The Report of an Investigation into the Characteristics, Operation and Protection Requirements of Civil Aeronautical and Civil Maritime Radar Systems

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Definitions of Acronyms and Abbreviations

ACR	………..	Airfield Control Radar
AEW	………..	Airborne Early Warning
AFC	………..	Automatic Frequency Control
AGC	………..	Automatic Gain Control (a method of CFAR)
AIS	………..	Automatic Identification System
ALARP	………..	As Low As Reasonably Practicable
AMASS	………..	Airport Movement Area Safety System
ARNS	………..	Aeronautical Radio Navigation Service
ASDE	………..	Airport Surface Detection Equipment
ASDE-3	………..	Airport Surface Detection Equipment - standard 3
ASDE-X	………..	Airport Surface Detection Equipment - X-band version
ASR	………..	Airport Surveillance Radar
ATC	………..	Air Traffic Control
ATM	………..	Air Traffic Management
AUT	………..	Antenna Under Test
AW	………..	Airborne Weather (Radar)
Bc	………..	Chirp Bandwidth
B_{imp}	………..	Impulse Bandwidth
B_{ref}	………..	Reference Bandwidth
B_{res}	………..	Resolution Bandwidth (interchangeable with RBw)
BITE	………..	Built In Test Equipment
Bw_m	………..	Measurement Bandwidth
C-Band	………..	IEEE Radar Band Designation (4 GHz - 8 GHz)
CAA	………..	Civil Aviation Authority
CAMRa	………..	Chilbolton Advanced Meteorological Radar
CDMA	………..	Code Division Multiple Access
CEPT	………..	Conférence Européenne des Administrations des Postes et des Télécommunications
CFA	………..	Cross Field Amplifier
CFAR	………..	Constant False Alarm Rate
CFIT	………..	Controlled Flight Into Terrain
COTS	………..	Commercial Off The Shelf
CP	………..	Circular Polarisation
CW	………..	Continuous Wave
dB	………..	Decibel
dBi	………..	Decibels above an Isotropic Antenna
DME	………..	Distance Measuring Equipment
DME/N	………..	Distance Measuring Equipment narrow
DME/P	………..	Distance Measuring Equipment precise
DPC	………..	Digital Pulse Compression
ECM	………..	Electronic Counter Measures
EIRP	………..	Equivalent Isotropically Radiated Power
ENG/OB	………..	Electronic News Gathering/Outside Broadcast
ESM	………..	Electronic Surveillance Measures
ESTEC	………..	European Space Research and Technology Centre
EUT	………..	Equipment Under Test.
FAA	………..	Federal Aviation Administration
FM-CW	………..	Frequency Modulated Continuous Waveform
FRUIT	………..	False Replies Unsynchronised In Time
FSS	………..	Frequency Selective Surface
GCA	………..	Ground Controlled Approach

GHz	………..	Giga Hertz
GLONASS	………..	Global Navigation Satellite System (Russian equivalent to US GPS)
GMDSS	………..	Global Maritime Distress and Safety System
GPR	………..	Ground Probing Radar
GPS	………..	Global Positioning System
HMCG	………..	Her Majesty's Coast Guard
HP	………..	Hewlett Packard
HRR	………..	High Range Resolution
HYREX	………..	Hydrological Radar Experiment
Hz	………..	Hertz
I/N	………..	Interference to Noise Ratio
ICAO	………..	International Civil Aviation Organisation
IEEE	………..	Institute of Electrical and Electronic Engineers
IFF	………..	Identification Friend or Foe
IMO	………..	International Maritime Organisation
ISLS	………..	Interrogator Side Lobe Suppression
ITU	………..	International Telecommunication Union
kHz	………..	Kilo Hertz
kW	………..	Kilo Watts
Ku-Band	………..	IEEE Radar Band Designation (12.4 GHz - 18 GHz)
L	………..	Linear
L-Band	………..	IEEE Radar Band Designation (1 GHz - 2 GHz)
LATCC	………..	London Area Traffic Control Centre
LNA	………..	Low Noise Amplifier
LP	………..	Long Pulse
LPI	………..	Low Probability of Interception
LVA	………..	Large Vertical Aperture SSR ground antenna
MCA	………..	Maritime and Coastguard Agency
MDS	………..	Minimum Discernible Signal
MTD	………..	Moving Target Detector
Met	………..	Meteorological
MHz	………..	Mega Hertz
MLS	………..	Microwave Landing System
MMS	………..	Modular Measurement System
MoD	………..	Ministry of Defence (UK)
MoD PE	………..	Ministry of Defence Procurement Executive (UK)
MP	………..	Medium Pulse
MRNS	………..	Maritime Radio Navigation Service
MSR	………..	Maritime Surveillance Radar
MSSR	………..	Monopulse Secondary Surveillance Radar
MTBF	………..	Mean Time Between Failures
MTD	………..	Moving Target Detector
MTI	………..	Moving Target Indication
MST	………..	Mesosphere, Stratosphere and Troposphere Radar
NA	………..	Not Applicable
NATS	………..	National Air Traffic Services
NB	………..	Necessary Bandwidth
NDA	………..	No Data Available
NERC	………..	Natural Environment Research Council
NL	………..	Non Linear
nm	………..	Nautical Mile
NTIA	………..	National Telecommunications and Information Administration

OACC	………..	Oceanic Area Control Centre
OB	………..	Occupied Bandwidth
OFDM	………..	Orthogonal Frequency Division Multiplex
OFHC	………..	Oxygen Free High Conductivity
OOB	………..	Out of Band
P0N	………..	Unmodulated pulse transmission (ITU classification of modulation)
PA	………..	Power Amplifier
PAR	………..	Precision Approach Radar
PC	………..	Personal Computer
PCL	………..	Passive Coherent Location
Pd	………..	Probability of Detection
PEP	………..	Peak Envelope Power
P_{fa}	………..	Probability of False Alarm
PFD	………..	Power Flux Density
PFN	………..	Pulse Forming Network
POEMS	………..	Pre-Operational European Mode S
PP	………..	Peak Power
PPI	………..	Plan Position Indicator
Ppm	………..	Parts per million
pps	………..	Pulses per Second
PRI	………..	Pulse Repetition Interval
PRR	………..	Pulse Repetition Rate
PSD	………..	Power Spectral Density
PSR	………..	Primary Surveillance Radar
PW	………..	Pulse Width
RA	………..	Radiocommunications Agency
RACON	………..	RAdar beaCON
RAF	………..	Royal Air Force (UK)
RAP	………..	Recognised Air Picture
RAPIER	………..	Relocatable Auroral Polar Ionospheric Experimental Radar
RASS	………..	Radio-Acoustic Sounding System
RBw	………..	Resolution Bandwidth (interchangeable with B_{res})
RCA	………..	Range Cell Averaging (a method of CFAR)
RCS	………..	Radar Cross Sectional area
RF	………..	Radio Frequency
RLAN	………..	Radio Location and Navigation
RLS	………..	Radio Location Service
RMS	………..	Root Mean Square
RN	………..	Royal Navy (UK)
RNSS	………..	RadioNavigation-Satellite Service
RNS	………..	Radio Navigation Service
RSS	………..	Root of the sum of the squares
RTE	………..	Radar Target Enhancer
Rx	………..	Receive or Receiver
S-Band	………..	IEEE Radar Band Designation (2.6 GHz to 3.9 GHz)
SABRE	………..	Sweden And Britain Radar Experiment
SACC	………..	Scottish Area Control Centre
SART	………..	Search And Rescue Transponder
SASS-C	………..	Surveillance Analysis Support System for ATC Centers (Eurocontrol's System Analysis Software Tool)
SAW	………..	Surface Acoustic Wave
SCV	………..	Sub-Clutter Visibility
SE	………..	Spurious Emissions

SIF	………..	Selective Identification Feature
SIL	………..	Safety Integrity Level
SL	………..	Side Lobe
SNL	………..	System Noise Level
S/N	………..	Signal to Noise Ratio
SOL	………..	Safety of Life
SOLAS	………..	Safety Of Life At Sea
SORAD	………..	Short Range Air Defence
SP	………..	Short Pulse
SRA	………..	Surveillance Radar Approach
SRE	………..	Surveillance Radar Element
SSR	………..	Secondary Surveillance Radar
STANAG	………..	Standard NATO Agreement
STC	………..	Sensitivity Time Control (Swept Gain)
TCAS	………..	Traffic Collision Avoidance System
TE	………..	Transverse Electric
TEM	………..	Transverse ElectroMagnetic wave
TI	………..	Transmission Identifier
TM	………..	Transverse Magnetic
TMA	………..	TerMinal Area
TNN	………..	Thales Naval Nederlands
TNR	………..	Threshold to Noise Ratio
TOA	………..	Time of arrival
TRSB	………..	Time Reference Scanning Beam
TWS	………..	Track-While-Scan
TWT	………..	Travelling Wave Tube
Tx	………..	Transmit or Transmitter
UE	………..	Unwanted Emissions
UHF	………..	Ultra High Frequency (300 MHz to 1 GHz) (IEEE)
VHF	………..	Very High Frequency (30MHz to 300MHz)
VSORAD	………..	Very Short Range Air Defence
VSWR	………..	Voltage Standing Wave Ratio
VTMS	………..	Vessel Traffic Management System
VTS	………..	Vessel Traffic System
W	………..	Watts
WF	………..	Wind Finder
X-Band	………..	IEEE Radar Band Designation (8.2 GHz to 12.4 GHz)
YIG	………..	Yttrium-Iron-Garnet

ITU-R Recommendations referred to in this report

ITU Document No.	Title
ITU-R Recommendation SM.329-9	Spurious emissions.
ITU-R Recommendation P.452-8	Prediction Procedure for the Evaluation of Microwave Interference between Stations on the Surface of the Earth at Frequencies above about 0.7 GHz.
ITU-R Recommendation SM.853	Necessary bandwidth.
ITU-R Recommendation SM.1138	Determination of necessary bandwidths including examples for their calculation and associated examples for the designation of emissions.
ITU-R Recommendation M.1177-2	Techniques for measurement of unwanted emissions of Radar Systems.
ITU-R Recommendation M.1313	Technical characteristics of maritime radionavigation radars.
ITU-R Recommendation M.1372	Efficient use of the radio spectrum by radar stations in the radiodetermination service
ITU-R Recommendation M.1460	Technical and operational characteristics and protection criteria of radiodetermination and meteorological radars in the 2900-3100 MHz band.
ITU-R Recommendation M.1461	Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services.
ITU-R Recommendation M.1462	Characteristics of and protection criteria for radars operating in the radiolocation service in the frequency range 420-450 MHz.
ITU-R Recommendation M.1463	Characteristics of and protection criteria for radars operating in the radiodetermination service in the frequency band 1215 to 1400 MHz.
ITU-R Recommendation M.1464	Characteristics of and protection criteria for radionavigation and meteorological radars operating in the frequency band 2700-2900 MHz.
ITU-R Recommendation M.1465	Characteristics of and protection criteria for radars operating in the radiodetermination service in the frequency band 3100-3700 MHz.
ITU-R Recommendation M.1466	Characteristics of, and protection criteria for radars operating in the radionavigation service in the frequency band 31.8-33.4 GHz.
ITU-R Recommendation SM.1539	Variation of the boundary between the out-of-band and spurious domains required for the application of ITU-R Recommendations SM.1541 and SM.329.
ITU-R Recommendation SM.1541	Unwanted emissions in the out-of-band domain.

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I

Preface

The value of the radio spectrum has been vividly demonstrated by the results of the auction for 3rd generation mobile telecommunications licences. However, there are a number of users of the spectrum not directly involved in commercial use, including civil aeronautical and maritime radionavigation services, which account for a significant percentage of the total usable radio spectrum.

This report has been prepared by AMS (formerly BAE Systems (CaRS)) to address several issues related to the operational characteristics and current uses of civil radar within the UK.

The report addresses the following issues:

- Information on the present and future uses of civil radar systems in the UK operating in the bands from 1 to 16 GHz;
- The specific transmission characteristics and operational parameters of current civil radars;
- The details of the measured, transmitted spectra of a number of civil radars;
- Receiver design and required protection levels;
- Possible mitigation options to reduce unwanted emissions;
- Improvements to the recommended measurement methods for unwanted emissions as specified in ITU-R Recommendation M.1177-2.

It is expected that information in this report will provide inputs to further studies investigating sharing and compatibility issues, both between separate radar systems and between radar and other technologies.

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II

Executive Summary

Civil radar is extensively used in the UK for aeronautical, maritime and weather surveillance on both fixed and mobile platforms. Other more specialised uses such as radar altimeters, vehicle speed measurement and ground probing radar have also been identified in this report. The UK also has a comprehensive network of Secondary Surveillance Radar (SSR) systems used for Air Traffic Control (ATC). The military also make extensive use of radar, and some military applications have also been identified. Military uses of radar fall into two types those that replicate the civil use and those that are exclusively military and have no civil application. Some radar applications such as ATC, SSR and Maritime Surveillance are clearly identified as "Safety of Life" services. Other radar applications, such as ground based weather radars, provide a safety-related function. This report covers in detail civil radars operating in the frequency range 1 GHz to 16 GHz. An analysis is made of the factors affecting the ability of a radar to reuse frequencies already allocated to a radar in a different geographical location. The situation pertaining to frequency reuse in the current civil radars used within the UK is analysed and the results presented. Whilst it is the case that the ability to reuse frequencies is very much related to the specific radar type, its use and local topological features, some indications are given on how frequency reuse can be improved.

This report documents the main roles of civil radar within the UK. The associated radar types are identified and typical data presented. Using information available in the public domain, this report also identifies various military and experimental uses of radar within the UK. The use of radar, band by band, is examined and presented in both tabulated and geographical distribution formats. The report gives an estimate of the total number of radars operating within the UK by band and by application. The largest number within a single band are the X-Band marine radar, airborne weather radar and radar altimeters. Within these classes, the largest numbers are associated with the small radars used by pleasure and fishing vessels.

Primary radar detects targets by looking for the reflections from the surface(s) of the targets, i.e. its receiver is optimised for the detection of the transmitted pulses. The prime outputs are the range and bearing of the target; and height in the case of 3-D radars. The degree of resolution of these parameters is defined by the pulse length and the antenna beamwidth. The target size and velocity can also be determined by measuring the amplitude of the echo and the Doppler frequency shift. A succession of echoes from the target can then be used to determine the target's track. In the limit, the bandwidth occupied depends to a first order on the resolution required between two objects and the technology used to implement the transmitter. The closer the objects to be resolved are to each other, the larger is the bandwidth that is required. It has not proven possible to identify reliable techniques that operate in the presence of noise that can resolve two targets using a bandwidth less than $1/\tau$ where τ is the pulse length of the radar. Historically, in order to generate the short pulses required to resolve two targets with sufficient RF power to achieve the detection range required, spectra much wider then $1/\tau$ were required due to the limitations of the transmitting valve. Improvements in the design of transmitters however can now achieve output spectra much closer to the theoretical $1/\tau$ bandwidth limit. The

achievement of this goal however may be at the expense of much higher cost or loss of other features such as frequency agility, because of, for example, the requirement to use high "Q" fixed tuned filters. The spectrum used is only one of the trade-offs that has to be considered by the designer. However in the current climate of scarce spectrum resource and changes to international regulations, coupled with band sharing etc., much greater account needs to be taken of minimising spectrum occupancy of radars. The report presents a set of design rules to achieve the minimum bandwidth occupied. Methods to reduce the transmitted spectrum are discussed and recommendations are given for a design process to reduce the transmitted spectrum close to the theoretical limit. The use of filters to restrict the bandwidth of the system is one solution to meeting the tighter limits, however this solution is generally only applicable to single frequency radars.

Consideration is given to the information content of the radar signals compared to the bandwidth used and hence their spectral efficiency. In practical radars the spectral efficiency is related to how much bandwidth is used compared to the range cell size used. Improving the spectral efficiency is best carried out by constraining the spectrum, by the use of spectrally efficient waveforms or filters.

Radar systems do employ certain methods within their receivers and signal processing that have the effect of reducing the probability that an interference signal will cause corruption to the received data. These methods fall into two types, those that have the effect of reducing interference as a by-product of their radar function and those which are specifically designed to reduce interference. These techniques are not 100% effective and if they are biased too heavily towards an increase in their interference rejection attributes then performance of the radar may suffer. It is a general rule that the more that interference rejection techniques are employed, the greater is the loss of information collected by the radar. In many cases these techniques are expensive and in some cases are not appropriate for introduction into older systems or for use in civil radar.

The report analyses the effects interfering signals have on the performance of the radar. The signals analysed are predominately noise-like and the effect on the radar is generally to cause the constant false alarm circuitry in the radar to raise the detection thresholds thus reducing probability of target detection (normally referred to as desensitisation). There are some indications however that those interference signals that depart from a noise-like characteristic can give rise to an increase in false alarms.

Interference effects need to be fully analysed and correctly specified, as each interference scenario may cause a reaction that is system dependent. This 'system dependent' reaction to interference will mask the effect of the interference when applied to one system and amplify its effect when applied to another. The multitude of radar systems available makes the process of the definition of the effect of interference and specification of acceptable levels of protection requirements a difficult one.

This report also makes recommendations as to the protection requirements required by some radar systems and recommends a reduction in the level of interference that is currently allowed and also recommends where in the system the protection requirement should best be defined. It is also recommended that a specific PFD limit is imposed with respect to the protection of ARNS radars from interference from RNSS systems in the band 1215 to 1300 MHz.

The study involved the measurement of a sample of civil radars currently in used in the UK. These measurements showed that there was a wide range of different transmitted spectra that are dependent on the type and role of the radar in question. These ranged from the wide, uncontrolled spectra produced by the magnetron radars to the relatively well controlled spectra produced by the pulse compression radars.

The results indicate that the pulse compression radars come close to, or meet the latest appropriate ITU Category A and Category B spurious emission limits. These limits will be applicable to radars installed after 1st January 2003 and for all transmitters after 1st January 2012. Of the types measured, solid state pulse compression radars gave the best performance. For these pulse compression systems, the non-compliances are minor and could be accounted for by in service modifications.

The in service magnetron radars however generally do not meet the new requirements and may require more substantial modifications. Single frequency, fixed site magnetron radars, such as ground weather radars, will have the most difficulty in meeting the latest requirements as they will be required to meet the more stringent ITU Category B emission limits that apply to this type of radar. Category B imposes a limit of -100 dBc as opposed to the Category A limit of -60 dBc.

Some work has recently been reported which could result in an improvement in some classes of magnetrons against the new Class A limits. However it is very likely that the main approach to be adopted for these fixed single frequency radars will be the provision of high "Q" band-pass filters centred on the operating frequency and low pass filters to provide the suppression of harmonic signals.

The problems with all radar types in meeting the ITU emission limits are further exacerbated by proposals to further restrict the OOB radiation by the introduction of a new design aim in ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain". This has increased the roll off in the OOB region from 20 dB/dec to 40 dB/dec. The plan is to start work on the adoption of the new aim after 2006. It is very likely that many categories of radars will have to be exempted from this design aim if it is adopted as a recommendation. However the final timescales for the adoption of such new recommendations is unclear and could be up to 20 years.

The measurement campaign also involved an assessment of the measurement methods specified in ITU-R Recommendation M.1177-2 "Techniques for measurement of unwanted emissions of Radar Systems" on how to measure the wanted and unwanted emissions of radar systems. Based on this assessment, the report makes some detailed recommendations for modifications of ITU-R Recommendation M.1177-2.

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Section 1

Introduction

This report has been produced under the Radiocommunications Agency (RA) study contract AY4051(510007288) by AMS Cowes (formerly BAE SYSTEMS (Combat and Radar Systems)). It contains inputs from AMS Radar Systems, Chelmsford and QinetiQ, Funtington.

A number of questions have been raised at both national and international levels which require an understanding of the current and future application of radars and their operational characteristics.

The value of the radio spectrum has been vividly demonstrated by the results of the UK auction for 3rd generation mobile telecommunications licences. However, there are a number of users of the spectrum not directly involved in commercial use, including civil aeronautical and maritime radionavigation services, which account for a significant percentage of the total usable radio spectrum. It should be recognised that there are a considerable number of civil radar frequency bands to be considered with radars operating in the UHF, L, S, C, X & Ku bands (IEEE Designations).

The RA commissioned this study to obtain information on such users of the spectrum. Such information provided in this report includes:

- Information on the present and future use of civil radar systems in the UK operating up to 16 GHz.
- The specified transmission characteristics and operational parameters of current civil radar.
- Details of the measured, transmitted spectra of a number of civil radars.
- Receiver design and required protection levels.
- Possible mitigation options to reduce unwanted emissions.
- An assessment of the proposed measurement techniques specified in the draft revision of the International Telecommunication Union's ITU-R Recommendation M.1177-2 "Techniques for measurement of unwanted emissions of Radar Systems." (document 8B/Temp/72-2) dated 30th October 2001.

It is expected that information from this report will provide inputs to further studies investigating sharing and compatibility issues, both between separate radar systems and between radar and other services (e.g. Radio Location and Navigation (RLAN), etc) as well as providing input to national and international technical groups. The results of this study are also expected to be used as input for ITU work, such as Conference Preparatory Meeting text and to provide input to World Radio Conference 2003.

In the past there have been many proposals made on how to overcome the perceived problems caused by the characteristics of radars. These proposals have generally been associated with applying a simple solution "fix" to one part or another of the radar, for example pulse shaping or filtering. Many of these proposals also made very simplistic or "text book" assumptions as to how the radar systems were engineered and implemented. These proposals have generally failed because they did not address all the detailed aspects of the radar design.

As well as being spectrally efficient and/or resistant to interference, radar also has to fulfil its operational role. Any changes to the implementation must still allow the radar to carry out its task; this is particularly important where the radar is fulfilling a safety of life role.

This type of design trade-off can only be made by those who have detailed understanding of how radar systems are engineered and how any potential changes will affect the operation of the existing technology, or how proposed new technologies would operate when used in a radar system.

As well as skills in the design of radar hardware, it is also necessary to be able to predict how changes would affect the overall system performance of the radar. Again a simplistic approach based on textbook designs could be taken, however the performance of the radar is generally much more complex than this approach would suggest. To predict the operations of radar in environments that are limited, for example by clutter, requires detailed systems knowledge.

Generally the performance of a radar in terms of the generation of unwanted emissions and its susceptibility to interference both at the RF level and at the outputs (plots, tracks, display) varies widely depending on the detailed implementation of the electronics and the signal processing.

There is no such thing as a generic "text book" or standard radar. In order to carry out this study efficiently and to give meaningful results, a breadth of detailed radar engineering knowledge has been utilised. This study has addressed several radar types.

Part of this report (section 3.1.3) contains the results of a measurement programme carried out on a number of radar systems in their working environment. Measurements that can demonstrate that the radar is performing to the latest requirements are not straightforward and specialist measurement equipment and skills have been used.

Section 2

Summary of Work Packages

The study was divided into six Work Packages, each intended to address a specific requirement of the Radiocommunications Agency. The work packages consisted of the following:

Work Package a) The Wanted Transmission characteristics of civil radar systems.

An investigation into the actual published transmission characteristics and operational parameters of existing and state-of-the-art civil radar systems including:

- Transmitter characteristics; including frequency, frequency tolerance, tuning range, bandwidth, Pulse Repetition Rate (PRR), pulse width, mean and peak power levels, and any enhancement techniques used (e.g. chirp, etc.).
- Antenna characteristics; including beamwidth (in both azimuth and elevation), gain, sidelobe performance and scan patterns.

Work Package b) Measurement Programme

A programme to measure the levels of radio emissions in the range 1 to 30 GHz from a number of radar types with operating frequencies between 1 and 16 GHz. The systems measured ranged from 'mature' magnetron technology through to the latest state-of-the-art, Solid-State radar systems operating in a number of civil frequency bands. The systems were selected in consultations between the Radiocommunications Agency , BAE SYSTEMS and QinetiQ.

Work Package c) Mitigation options in the design of radar systems.

A study of mitigation options which could be considered in the design and implementation of radar systems to reduce unwanted emissions and/or occupied bandwidth, (e.g. the choice of output device, antenna type, use of frequency selective surfaces/materials etc.).

This work package took into account the associated impact on performance parameters (bandwidth, coherency, resolution, etc.), expected life of the system, relative cost, weight, size and mechanical robustness. Calculations of the achievable emission levels using the above techniques were made. The effects of any mitigation options (including the use of Continuous Wave (CW) or Frequency Modulated (FM) radar) on existing RAdar beaCONs (RACONs) and Search And Rescue Transponders (SARTs) were considered.

Work Package d) Radar Receiver characteristics and protection criteria.

An investigation into the radar receiver characteristics and the criteria required for the protection of radar services. This took into account the radar mission (e.g. safety of life, radionavigation, etc.) and the technology used within the radar systems. This work package included details of characteristics and/or operational practices which might improve the ability of a radar system to fulfil its required function in the presence of a potential interference source, including co-frequency use by other radar installations and the operational and relative economic effects of these measures.

Work Package e) The present use of radar in the UK

A study of the present use of radar (including military radars where known) by frequency band, application, technology, numbers of operational systems, areas of usage, usage density, location of fixed stations and details of frequency re-use distances.

Work Package f) An assessment of the latest draft of ITU-R Recommendation M.1177

An assessment of the measurement techniques described in the latest draft of ITU-R Recommendation M.1177 including details of limitations of these techniques and any practical improvements that may be made.

The measurements and studies were conducted on sample radar units from the major application areas (aeronautical land based, maritime shipborne, maritime land based and ground based meteorological). The study covered all civil aeronautical and civil maritime radar bands, taking into account the radar mission (safety, navigation, tracking, etc), the available technologies (e.g. magnetron, Travelling Wave Tube (TWT), solid-state, etc.), and the type and size of the platform. Consideration was taken of work carried out in the SE 21 and SE34 Spectrum Workings Group of CEPT and Task Group 1-5 of the ITU.

2.1 Work Package Details

2.1.1 Work Package a) An investigation into the wanted transmission characteristics and operational parameters of existing and state-of-the-art civil radar systems.

Background

There are many important performance parameters that affect the transmission characteristics of a radar. The most obvious is the need to detect the wanted object, usually an aircraft, but in some specialist radars other objects such as rain or coastlines. Having detected the object, it is necessary to determine its position in space in at least the two dimensions of range and azimuth (bearing) and in some cases elevation. It also must be possible to determine the number of objects detected, so resolution is also important. All of these requirements result in a radar performance that can often be satisfied by different technologies that can result in different spectral usage and different antenna types.

Different transmitter technologies require different forms of transmission characteristics (duty cycle, pulse length, pulse modulation) for optimum operation but, for the same detection capability, the same mean power must be transmitted. For example magnetrons produce narrow pulses of high peak power while solid state devices produce low peak power and so require longer pulses for the same detection capability. Short pulses inherently give good accuracy and resolution in the range domain but these parameters can be recovered from long pulses if the pulses are coded. The spectrum of the pulse is made up of two parts, the pulse envelope (especially the rise and fall time) and the pulse coding.

The transmitter cannot however be considered in isolation. The antenna and microwave feeder elements and components are equally important as they provide a filtering and transmission function. For example, waveguide acts as a filter preventing the radiation of signals below the fundamental. There may be physical restrictions on the antenna size that affect the beamwidths and there may be information update rate considerations that affect the scan pattern. The accuracy and resolution in azimuth (and elevation if this is measured) is partly determined by the antenna beamwidth and partly by the pulse pattern. Although a narrow beam may appear optimum, it can create difficulties in separating wanted and unwanted returns, like separating an aircraft return from reflections from the ground. The aircraft detections are separated from the ground reflections by Doppler filtering which requires a set of pulses within a beamwidth for the processing.

Work Package Content

Using the wide radar experience within the group as well as published data, the study has collated the parameters for existing and state of the art radars operated within the UK. The radars have been reduced to generic radar types with typical parameters for their transmission and antenna characteristics. The wanted transmission characteristics of different types of transmission waveforms have been modelled to show their spectral usage. This has been carried out in the light of operational requirements.

Output

The output of this work package forms part of section 3.1.2 of the final report and contains the wanted transmission characteristics and operating parameters of mature and state-of-the-art civil radar systems, categorised in terms of the radars' operational roles.

Annex 1 of this report lists the various operational parameters gathered, calculated or estimated, for the civil radars and some military radars operating in the UK.

2.1.2 Work Package b) An investigation into the measured unwanted emission levels from 1 GHz to 30 GHz. Systems studied included mature and state-of-the-art civil radar systems operating in the civil frequency bands.

Background

There are various bands used for civil radar applications in the UK that were candidates for measurements, these include:

Aeronautical Radio Navigation Radars Ground Based (UHF, L & S-Bands)

Aeronautical Radio Navigation Radars Airborne (X & C-Band Weather)

Meteorological Radars Ground Based (C-Band Weather)

Marine Navigation Radars Land Based Vessel Traffic System (VTS) (X-Band)

Marine Navigation Radars Ship Borne (S & X-Bands)

Airport Surface Detection Equipment (ASDE) (X & Ku-Bands)

Within these classes there are also various differing implementations of radars using a mixture of technologies.

In order to measure the characteristics of such radars, extensive specialist equipment, experience and knowledge is required. In order to make these measurement with the required dynamic range of between 85 and 100 dB a specialised receiver is required. The receiver consists of a computer controlled network analyser operating in zero sweep mode. To achieve the dynamic range the spectrum analyser is augmented with a low noise amplifier, a computer controlled attenuator and a Yttrium-Iron-Garnet (YIG) preselector filter. The computer is used to continually adjust the filter and attenuator to maintain an optimum signal to noise level into the Spectrum Analyser. A high gain antenna is used to reduce the effects of multi-path and ambient interference. This technique has been proven by use in the USA by the National Telecommunications and Information Administration (NTIA) over many years.

The measurement work in this study was sub-contracted to QinetiQ at Funtington, who have experience of the development and use of such equipment. The QinetiQ equipment was capable of measuring over the frequency range of 1 to 30 GHz. The equipment was housed in a screened vehicle to provide a mobile test facility.

Work Package Content

Following consultation between the RA, QinetiQ and BAE SYSTEMS, the following radars were identified and measured as part of this study:

A Solid State "S-Band" Air Traffic Control (ATC) ground radar;

A magnetron "X-Band" maritime surveillance radar;

A coaxial magnetron "C-Band" Weather radar;

A magnetron "Ku-Band" ASDE;

A TWT "L-Band" ATC ground radar;

A TWT "S-Band" ATC ground radar[1].

As was expected, the majority of measurements had to be made on in-service radars and this made it necessary to measure the radars in their normal operational modes. Whilst this precluded the application of definitive specification masks, it provided a representative measurement in interference/interoperability terms. The X-Band maritime surveillance radar was tested at the QinetiQ Test Range at Funtington. All the other radar measurements were made by QinetiQ using their mobile test facility.

Various measurements were made using different bandwidths to investigate their effect upon the final results. Having to undertake most of the measurements in the radars' operational environment required QinetiQ to identify and eliminate the transmissions of other services operating in the vicinity of the measured radars.

For this work package, the version of ITU-R Recommendation M.1177 used was the Preliminary Draft Revision (document 8B/Temp/72-2) dated 30th October 2001.

Output

The output of this work package forms section 3.1.3 of the final report, detailing a representative set of measured transmission characteristics and operating parameters of the measured radar systems. The section includes a detailed description of the measurement method, the conditions in which the measurements were taken and a commentary on the results.

Further results from the measurement programme are also included in section 3.4 to illustrate and support the assessment of ITU-R Recommendation M.1177.

2.1.3 Work Package c) A study of mitigation options that could be taken into consideration in the design and implementation of radar systems to reduce unwanted emissions and/or occupied bandwidth.

Background

Having produced examples of spectral usage and its relationship to radar performance, methods of achieving the same performance with reduced spectra need to be considered. The rise and fall times of the pulse which affect the far out portion of the spectrum are not necessarily tightly related to the range accuracy and resolution so techniques can be used to reduce the far out power without degrading radar performance. The ability to realise such out of band control can depend on the final stage in the transmission chain. For transmitters based on tube technology (e.g. magnetron, travelling wave, cross field amplifier etc.), it may only be possible to reduce out of band emissions by filtering. The use of frequency selective surfaces can be regarded as a form of output filter that may be

[1] The contract required the measurement of five radars only. The measurement of the TWT based S-Band radar was funded separately by BAE SYSTEMS and these results are included in this report for completeness.

applicable to some types of antenna structure. For transmitters based on solid state devices, the spectrum can be controlled either by filtering or by modifying the drive waveforms. The effects of all these options need to considered.

Once the transmitted energy has been controlled as well as possible, undesirable effects can result from the antenna structure.

There is considerable work in the open literature that defines the maximum accuracy and resolution for a specific beamwidth and signal-to-noise ratio and analysis of super-resolution algorithms which attempt to improve the resolution for a specified beamwidth or pulse length. These algorithms often only function well at high signal-to-noise ratio so these trade-offs need to be considered.

Work Package Content

This study used the experience within the group as well as information from the open literature to identify and discuss the various mitigation options. It has taken into account the associated impact on performance parameters (bandwidth, coherency, resolution, etc.), expected life of the system, relative cost, weight, size and mechanical robustness. A calculation of the achievable emission levels using the above techniques has been provided. These mitigation techniques have been considered for their effect on the whole radar system performance. The effects of the proposed mitigation options on associated equipments such as Radar Beacons (RACONs) and Search and Rescue Transponders (SARTs) have also been considered.

Output

The output of this work package forms section 3.2 of the final report. It covers the various parameters important for radar performance and then expands the possible mitigation options that could be considered in the design and implementation of radar systems to reduce unwanted emissions and/or occupied bandwidth. The options are categorised as to their effect on the overall radar system performance and the operational role.

2.1.4 Work Package d) An investigation into the radar receiver characteristics and protection criteria required for the protection of radar services.

Background

A radar system is characterised by the requirement to detect radio echoes from targets at range. The well-known 'Radar Equation' demonstrates the $1/R^4$ characteristic of target echoes. In order to provide detection performance, primary radars typically use powerful transmitters and very sensitive receivers.

Co-frequency use by other radar installations and communication systems sharing the spectrum introduces possible interference with the radar system and the increased risk of a degraded radar service. In a noise limited environment there will be a minimum value of wanted-to-unwanted signal ratio below which the radar receiver performance will be adversely affected. Different systems will perform differently in this respect, for instance, a pulse compression system can detect a lower signal-to-noise ratio for the target echoes by using signal processing to improve the system gain. However, even a weak interfering signal with similar characteristics can have a significant effect on the system. Depending on the waveforms used and the signal processing applied, some systems that are clutter-limited may be more robust in the presence of an interferer than the equivalent noise limited systems.

Work Package Content

This study began with a review of current methods of protection used in the types of radar systems under consideration in this study, including both the technology aspects and current operational practices. There has been consideration of the performance of the radar systems that results when these protection methods are called into use in the current interference and sharing environment.

Following this, an investigation into the challenges involved for a radar system, operating in an interference and sharing environment based on possible future use of the spectrum, has been conducted. A number of sharing and interference scenarios, incorporating various types of system, have been considered along with the impact of such scenarios on current operational radar systems. This leads to an understanding of the scope of any modifications to the technology and practices required to deal with such scenarios. Clearly the radar mission is important in such considerations and there will be limits to the amount of interference to the radar service acceptable for different missions. For example where safety of life is an issue, availability and performance of the radar system has a very high priority and degradation of service should be minimised. Indeed in these cases both radar systems and communications systems requirements should be written to preserve an appropriate service.

The study includes an investigation into the possible technology and practices that could be implemented which may improve the ability of the radar systems to fulfil their required function in the presence of a potential interference source, and the operational and economic effects of these measures.

There is a trend in radar technology towards active phased array systems. Such systems provide very good protection against jammers and interferers, however, the active components in the front end of the system could be vulnerable to signals outside the radar's normal operating spectrum and may saturate in the presence of an off-tune interferer.

Output

The output of this work package forms section 3.3 of the final report. This section documents the radar receiver characteristics and protection criteria required for the protection of radar services. This includes a discussion of technology and practices which may improve the ability of the radar systems to fulfil their required function in the presence of a potential interference source and the operational and economic effects of these measures.

Under this work package, an interim paper was produced covering a discussion on the protection requirements for L-Band radars from interference from RadioNavigation-Satellite Service (RNSS). This output formed the basis of a UK paper submitted to ITU Working Party 8B. The UK paper is presented in full in Annex 3 of this report.

2.1.5 Work Package e) A study of the present use of radar.

Background

Radar was originally developed to meet the needs of the military, and it continues to have significant application for military purposes. It is used to detect aircraft, missiles, artillery and mortar projectiles, ships, land vehicles, weather and satellites. In addition, radar controls, guides, and fuses weapons; allows one class of target to be distinguished from another; aids in the navigation of aircraft and ships; performs reconnaissance; and determines the damage caused by weapons to targets. Attempts to degrade military radar capability include electronic warfare (jamming, deception, chaff, decoys, and interception of radar signals), anti-radiation missiles that home-in on radar transmissions, reduced radar cross-section targets to make detection more difficult (stealth), and high-power microwave energy transmissions to degrade or burn out sensitive receivers. A major objective of military radar development has been to ensure that a radar system can continue to perform its mission in spite of the various measures that attempt to degrade it.

Radar supports civil Air Traffic Control (ATC) by providing surveillance of aircraft and weather in the vicinity of airports as well as enroute between airports. Airport Surveillance Radars (ASR) are designed to detect both commercial aircraft and general aviation aircraft and sometimes precipitation, in the area around an air terminal. Longer range ATC systems, (out to 200 nm), track aircraft enroute. Many major airports also employ Airport Surface Detection Equipment (ASDE), which is a high-resolution radar that provides the airport controller with the location and movement of ground targets within the airport, including service vehicles and taxiing aircraft. Radar also has been used to “talk down” pilots to safe landings in adverse weather conditions. This is called Ground Controlled Approach (GCA) by the military.

Weather radars make measurements of the rate of precipitation and integrate it to calculate the rainfall level. In conjunction with the strength of the reflected signals they can indicate the severity of storms, as well as providing other important information for reliable weather forecasting.

The radar altimeter measures the height of an aircraft above the local terrain, Doppler navigation radar determines the plane's own speed and direction, and high-resolution radar mapping of the ground contributes to its navigation. Radars carried aboard aircraft also provide information about the location of dangerous weather.

Small, relatively simple radar systems on board ships aid in piloting and collision avoidance. Similar radars on land provide harbour surveillance.

The familiar police radar is a relatively simple, low-power continuous-wave system that measures the speed of vehicles by detecting the Doppler frequency shift introduced in the echo signal by a moving vehicle.

Each one of this wide range of radars have been optimised for their particular application which results in differences in frequency, waveform and transmitter etc.

Work Package Content

This work package has used the experience within the group, as well as information in the open literature, to identify and discuss the current use of radar. Subject to the availability of data and security considerations, radar usage was considered by frequency band, application, technology, numbers of operational systems, areas of usage and usage density, and location of fixed stations, including details of frequency re-use distances.

A short résumé of the military use of radar has also been included.

Output

The output of this work package is included in section 3.1.1 of the final report. It presents the uses of radar to meet different applications within the UK (including military radars where the information is in the public domain) and is accompanied by a discussion as to why the requirements of certain applications have lead to particular methods of practical implementation.

2.1.6 Work Package f) An assessment of the measurement technique described in the latest draft of ITU-R Recommendation M.1177.

Background

ITU-R Recommendation M.1177 describes the measurement methods for radar unwanted emissions and is currently under review.

Work Package Content

This work package consisted of an appraisal of the methods proposed in the draft Revision of ITU-R Recommendation M.1177-2 (document 8B/Temp/72-2) dated 30th October 2001.

The appraisal has been based on several sources of data/knowledge:

- Experience gained during the measurement campaign.
- Published analysis of the proposed methods.
- The team's experience of making similar measurements.
- Knowledge of the current and future technical aspects of radar electronics and their associated antenna systems.
- Practical limitations associated with the methods including issues relating to the practical aspects of the measurement, the applicability to the ITU Recommendations and the applicability to current and future radar designs.

Output

The output of this work package consists of section 3.4 of the final report. It provides comments as to the practicality and limitations of the proposed methods, recommendations for modifications to the methods, and the operational modes of the radar during the measurements. Comments on the appropriateness of the methods in terms of demonstrating compliance with the ITU regulations and recommendations are also provided.

A supplementary interim paper was produced in the early stages of the study and this formed the basis of a UK input to ITU Working Party 8B. The UK paper is presented in full in Annex 2 of the final report. The interim paper has been revised and forms the basis of section 3.4 of this report.

Section 3

Outputs of the Work Packages

Section 3 of this report includes the outputs of the various work packages completed under the contract. It is divided up into the following sections:

Section 3.1 UK Radar Systems in Use

Section 3.2 Mitigation Options

Section 3.3 An Investigation into the Radar Receiver Characteristics and Protection Criteria Required for the Protection of Radar Services.

Section 3.4 An Assessment of the Measurement Techniques described in ITU-R Recommendation M.1177-2

Notes on radar parameters presented in tables within this report.

There are four types of tables of radar parameters presented in this report:

The parameters given in the tables in Section 3.1.1 are figures relating to radars available in the world-wide market place that are in classes of radars used in the UK. They are intended to give background information. The figures in the tables are derived from individual manufacturer's data.

The parameters given in Section 3.1.2 are generic values that represent typical figures for the classes of radar operating in the UK. These are generally based on data pertaining to the most common type of radar in use or represent a mean of systems in use. They are intended to give information as to the general classes of radar in use and their performance parameters. They represent the average or typical UK system.

The parameters given in Section 3.1.3 are parameters measured on specific installed radars that were measured. The figures in these tables are given only to allow interpretation of the results and to provide the basis of any emission masks presented.

The parameters given in Annex 1 represent the best data available on specific systems in use or, in the case of mobile radars, possibly in use in the UK. The figures represent manufacturers published data, figures derived from published data or best engineering estimates taken from measurements or similar systems. These figures are given to allow a comparison with the generic systems given in 3.1.2.

Whilst the figures given in the different areas of this report can be expected to be close for radars of similar types and within a similar class, they will not necessarily be identical.

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Section 3.1

UK Radar Systems in Use

Section 3.1 of this report addresses the Radar Systems in use within the UK, the section is divided into the following

Section 3.1.1	Report of the Survey into the uses of Civil Radar in the UK.
Section 3.1.2	The Wanted Transmission Characteristics and Operational Parameters of Commercial Radars in use in the UK.
Section 3.1.3	The Measured Characteristics of a Sample of Commercial Radars in use in the UK.
Section 3.1.4	Summary

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Section 3.1.1

Report of the Survey into the uses of Civil Radar in the UK

Contents:

Figures:

Tables:

Maps:

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3.1.1 Report of the survey into the uses of civil radar in the UK

3.1.1.1 Introduction

This section discusses the Civil uses of Radar in the UK.

Civil Radar equipment can be divided into several categories, the majority of which provide a safety function. Some services are more critical than others in terms of the potential consequences of that service being unavailable. The following applications have been identified:

- Secondary surveillance radar (SSR)
- Radar altimeters
- Airport surface detection equipment (ASDE)
- Airborne weather radar (AW)
- Maritime vessel traffic systems (VTS)
- Air Traffic Control primary radar (ATC)
- Maritime navigation radar
- Maritime RAdar beaCONs (RACONs), Search And Rescue Transponders (SARTs) and Target Enhancers
- Ground based meteorological radar
- Police vehicle speed measurement radar
- Ground Probing Radar (GPR)
- Precision Approach Radar (PAR)
- Microwave Landing Systems (MLS)
- Distance Measuring Equipment (DME)

Each of these applications is discussed in turn.

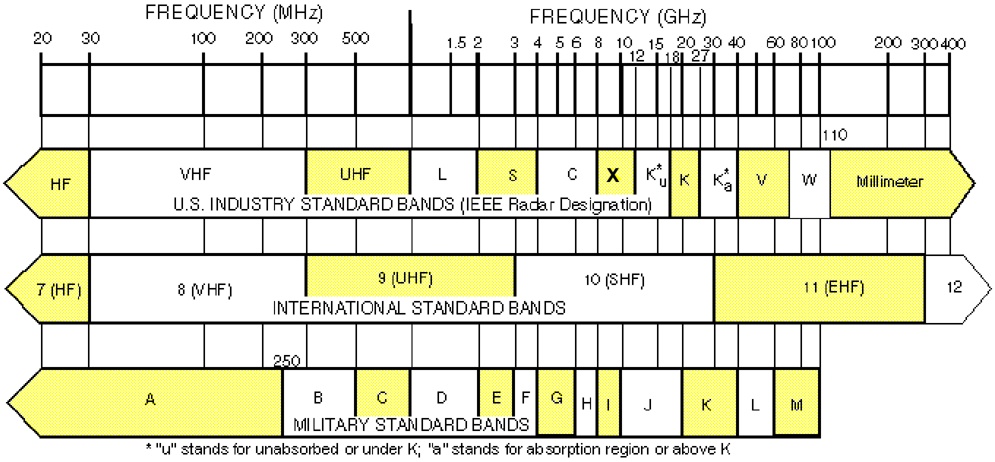
The use of experimental radars is discussed, as are military radars within the bounds of public domain knowledge. Finally a discussion on the geographical distribution of civil radar along with a description of frequency re-use in the UK is provided.

3.1.1.2 Reference information

3.1.1.2.1 Diagram of radar bands

Figure 3.1.1-1 is useful for reference purposes. The designations have not been formally adopted by the International Telecommunication Union (ITU), however they are in common use within the radar community. This report will adhere to the Institute of Electrical and Electronic Engineers (IEEE) designations or quote the actual frequencies where considered more appropriate. For a more precise definition see the table 3.1.2-1.

Figure 3.1.1-1 Radar Band Designations [1]



3.1.1.2.2 Definition of azimuth and elevation beamwidths

A radar beam exists in three dimensions, however, it is useful to describe its characteristics in two orthogonal planes:

- The azimuth plane (horizontal)
- The elevation plane (vertical)

The azimuth plane concerns the horizontal rotation of the radar beam through 360° parallel to the ground, whilst the elevation plane concerns the vertical scanning of the radar beam up to a possible maximum of 90°.

Figure 3.1.1-2 Representation of a radar beam described in azimuth (φ) and elevation (θ) planes

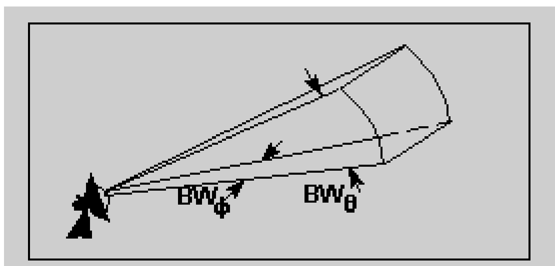


Figure 3.1.1-2 shows a representation of a radar beam where Bw_{φ}, is the azimuth beamwidth and Bw_{θ} is the elevation beamwidth.

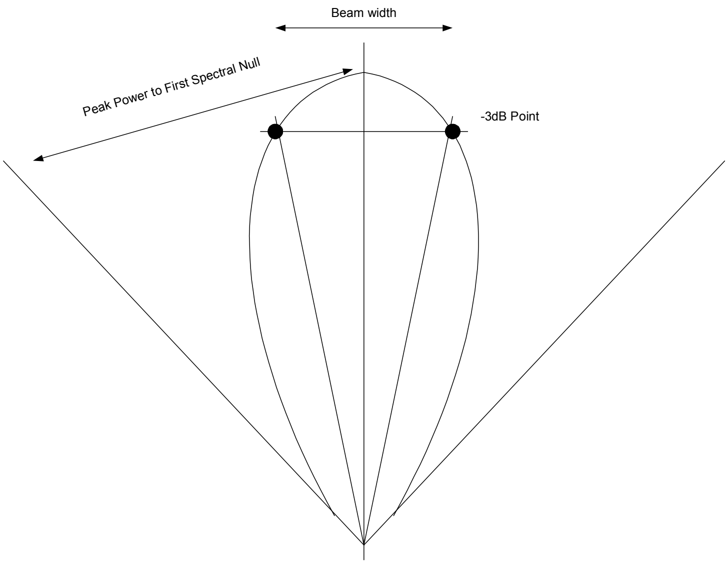
The beamwidth is related to the wavelength, λ, of the radar system and the antenna size, D, in the plane of interest.

$$Bw \approx 60\frac{\lambda}{D} \text{ degrees} \qquad \text{Equation 3.1.1-1}$$

This varies with the antenna shape and the power distribution across its aperture.

In general, the term 'beamwidth' is taken to be the width of the beam at the one way half power points, or -3 dB. This is illustrated in Figure 3.1.1-3 below.

Figure 3.1.1-3 -3 dB beamwidth [1]



Most of the Civil systems described here are 2D only and, unless explicitly stated, the term 'beamwidth' is used to describe the Azimuth beamwidth of the system. The geometry of the antennas of such systems and the fact that they are not steered in elevation means that elevation beamwidth has little meaning in a 2D system.

3.1.1.3 Secondary Surveillance Radar (SSR)

3.1.1.3.1 Description

Secondary Surveillance Radar is the main method of controlling aircraft in civil Air Traffic Control (ATC). The system on the ground (referred to as an interrogator) transmits a coded signal to a transponder on the aircraft, which then replies with a second code. The transmission from interrogator to transponder (known as the uplink) is on a frequency of 1030 MHz, and the replies (downlink) are on a frequency of 1090 MHz.

Ground based SSR antennas are often mounted directly on top of primary radar antennas. The possibility of interference from other sources has therefore been considered from the very early days of SSR. The situation is most severe when using a typical L-Band long range surveillance radar, which may be less than 200 MHz from the SSR receiver pass band, and can transmit several Megawatts.

The 1030/1090 MHz frequencies are also used for other aviation safety applications, the most safety critical being the Traffic Collision Avoidance System (TCAS). TCAS is a system whereby aircraft interrogate transponders of other aircraft and identify any that are close enough to be considered a threat to navigation. Information is presented to the pilots of the two aircraft involved, thus enabling evasive action to be taken. There have been many documented cases of TCAS systems actually preventing mid air collisions.

The 1030 / 1090 MHz frequencies are considered by many to be saturated, and not to be shared with any other application.

SSR has a lot of properties in common with a communications system, and for this reason it is often not considered to be a true radar system by primary radar engineers. It is however, defined as a radar under ITU definitions.

[1] Extracted from "EW and Radar System Engineering Handbook" http://ewhdbks.mugu.navy.mil/contents.htm

3.1.1.3.2 Transmission characteristics

3.1.1.3.2.1 Ground systems

The majority of systems in use in the UK transmit pulses at 1030 MHz that are 0.8μs wide. A typical interrogation consists of three of these pulses, two are transmitted from the main lobe of the antenna, and one pulse is transmitted from an omnidirectional antenna. If an airborne system receives the omnidirectional pulse at a higher level than the main lobe pulses then it is assumed that the aircraft is in a sidelobe and it does not reply to the interrogation. Pulse Repetition Rates[2] (PRR) of between 80 and 220 Hz are used, together with an antenna turning rate of between 6 and 15 rpm.

The transmitted power from a SSR system is much lower than that needed for a primary radar system as there is only a one-way path loss to cope with. A typical SSR transmitter, for a system with a range of 250 nautical miles (nm), outputs between 1 and 2 kW into the antenna.

3.1.1.3.2.2 Airborne systems

The airborne transmitters have a specified output power of 24 ± 3 dBW for commercial aircraft, and 18.5 dBW for light aircraft, whilst replying on a frequency of 1090 ± 3 MHz (as specified in Annexe 10 of the International Civil Aviation Organisation (ICAO) international specifications). However, in a study conducted recently in the USA, it was found that over 3% of commercial aircraft and over 9% of light aircraft failed the transmitter frequency limits[3].

3.1.1.3.3 Receiver characteristics

3.1.1.3.3.1 Ground systems

The ground receivers have a centre frequency of 1090 MHz, and a typical 3dB bandwidth of 8.1 MHz. There are additional attenuation limits intended to minimise the possibility of interference from other systems, notably co-located primary radar. These limits are:

- more than 40 dB attenuation outside the band 1078-1102 MHz
- more than 60 dB attenuation outside the band 1065-1115 MHz

The main antennas used for this type of radar are highly directional, with a -3dB beamwidth of approximately 2.5°. There is also an omnidirectional receiver channel, which is used to detect and thus reject replies received in antenna sidelobes. An aircraft must be detected at approximately the same location on two successive scans of the antenna before a track report is created and a plot output to the display.

3.1.1.3.3.2 Airborne systems

Civil aircraft typically have two antennas, one mounted on top of the fuselage and one mounted underneath. The antenna receiving the stronger interrogation is used to transmit the reply. These antennas are all omnidirectional, and hence, on receive, are vulnerable to interference from all directions.

3.1.1.3.4 Interference considerations

SSR systems do not use pulse compression or traditional Constant False Alarm Rate (CFAR) circuits to provide a measure of interference protection, however, a form of dynamic signal thresholding is implemented which has a similar effect to CFAR. Potentially the most damaging source of interference to a SSR system comes from other SSR systems. This appears as replies from transponders, which have been interrogated by other SSR ground stations (i.e. FRUIT (False Replies Unsynchronised In Time)). SSR systems do employ data processing techniques, such as de-fruiting described in section 3.3.2.1.13, and data fusion with primary radar, to reduce the impact of such interference. Other types

[2] ICAO Annex 10 limits the PRR to a maximum of 450Hz.

[3] Talotta, nicholas, j "A field study of transponder performance in general aviation aircraft" (DOT / FAA final report, December 5, 1997)

of interference, such as broadband noise and pulse Continuous Wave (CW) in the bandwidths of the up and down links, would have a serious effect on the operation of an SSR system.

When two aircraft are within 20μs of each other in range and within a beamwidth in azimuth, they both reply to the same interrogations and the replies overlap. If the 0.45μs pulses of one reply happens to fall in the 1μs spaces between the pulses of the second reply, the situation is called "Interleaving". If the pulses themselves overlap, they add coherently, and the result depends on the relative phase of the two pulses. This situation is known as "Garbling" and is more difficult to unscramble than interleaving.

Considering the directional nature of the radar antenna, it is tempting to predict the symptoms of interference to a single beamwidth, i.e. a 2.5° sector. However, the definition of the “system” must be extended to include the airborne transponders.

Most modern SSR Interrogator systems are fitted with Large Vertical Aperture (LVA) antennas and incorporate SideLobe Blanking to prevent aircraft transponders responding to interrogations from the interrogator antenna sidelobes; and also to prevent the SSR receiver processing replies received through the sidelobes.

There have been several recorded cases where interference has been radiated on the 1030 MHz interrogation frequency, triggering transponders on nearby aircraft to transmit replies. In some cases this has led to transponders being unable to detect the interrogations from the ground stations, and the aircraft effectively disappearing from the ATC radar.

SSR is used as the main, and in some cases the only, method of controlling aircraft in ATC systems, and therefore any possibility of interference must be minimised.

A new version of SSR called 'mode-S' is being introduced which will reduce the effect of interference between SSRs. Mode S normally uses selective addressing so that only the addressed aircraft responds to an interrogation, an 'all call' address is used intermittently to elicit replies from all aircraft in the coverage area. However mode-S also incorporates an extended duty cycle data link. The use of the data link and the ability to schedule messages is currently under study as part of the European ' Pre-Operational European Mode S' (POEMS) programme (see section 3.1.1.17.7).

3.1.1.4 Radar Altimeters

3.1.1.4.1 Description

Radar altimeters are used by aircraft to determine height above terrain, usually in the approach phase of flight. Their main use is to avoid Controlled Flight Into Terrain (CFIT) accidents caused by navigational errors. Automated voice messages from radar altimeters are also used during the later stages of final approach to inform the crew of their altitude at a time when they are unable to look at their instruments. In the case of auto-land approaches, the radar altimeter is the main sensor used to control the timing of critical events such as the flare prior to touchdown.

Figure 3.1.1-4 Typical radar altimeter cockpit display

3.1.1.4.2 Transmitter characteristics

Radar altimeters use Frequency Modulated Continuous Wave (FM-CW) transmissions. The frequency band allocated for this use is between 4.2 and 4.4 GHz. In order to reduce the possibility of interference with aircraft in close proximity, the transmitter power is kept to a minimum. A typical system will radiate less than 1 watt. In most radar altimeters a slow triangular wave (commonly 150 Hz) is used for the frequency modulation, causing a deviation in the output frequency of around 100 MHz.

The beamwidth of a radar altimeter antenna has to be relatively wide (at least 45°) in order to maintain operation while the aircraft is manoeuvring.

Table 3.1.1-1 Characteristics of a typical Radar Altimeter

Frequency (MHz)	4240 - 4360
Power output (mW)	210
Antenna gain (dB)	>10
Read out range (ft)	20 - 2500 (above ground level)
Operational altitude (ft)	0 - 45000

3.1.1.4.3 Receiver characteristics

The transmitted RF is slowly swept in frequency with a linear ramp. The frequency difference between the transmitted signal and the received signal is determined by the round-trip delay, neglecting the extreme ends of the frequency ramp. This frequency difference will therefore be proportional to the distance above ground level.

3.1.1.4.4 Interference considerations

In order to achieve the appropriate range/altitude performance the receiver has a front-end bandwidth greater than 100 MHz. There are two possible methods of interference, front-end saturation and false measurement. In the case of front-end saturation, any large signal within the front-end pass band will prevent the receiver from detecting the wanted signal at all.

In the case where the signal is within the pass band but does not saturate the front end, the effects will differ according to the make and model of the equipment. Most receivers employ a programmable band pass filter that is kept roughly in the frequency region where the reflected signal is likely to be. The rate of change of height of the aircraft will be within certain predictable limits, and so it is possible to assign a confidence level to the measurement, given the previous measurement. However, if the previous measurement was also wrong, the wrong height indication could be displayed by the system.

The radar altimeter is normally only used during the landing phase of flight, although it is permanently switched on to detect unexpected terrain. The vulnerability of the radar altimeter to interference is therefore limited to false terrain alarms during the cruise phase of flight.

The vulnerability to interference increases dramatically as the aircraft begins the approach to the destination airfield. Several factors combine to produce a potentially life threatening risk:

- The receiver could be physically close to the source of interference.
- The aircraft is travelling at slow speed.
- There is very little time to abort the landing and initiate a go-around.
- A “system failure” alarm could distract the crew at a critical phase of the flight.

Interference of any kind to this safety-critical system can therefore not be allowed.

3.1.1.5 Airport Surface Detection Equipment (ASDE)

3.1.1.5.1 Description

Airport Surface Detection Equipment is a type of radar used for the purposes of detecting the position of aircraft and service vehicles on the ground at airports. Typically mounted on top of the control tower, it has very low elevation cover (usually below the horizon), and short range (less than 5 miles).

The ASDE radar processing system uses a stored digital map of the airport to suppress targets and clutter from unwanted areas. Older types of equipment simply display a traditional Plan Position Indicator (PPI) for targets on the runways or taxiways.

Newer equipment uses plot extraction with data fusion techniques to merge data from several sensor types to display a data tag for each target, positively identifying the target. Such systems have the capability to “coast” a target, i.e. display a predicted plot if one or more of the sensors was not able to detect the target on a particular scan. Such equipment is known as an Airport Movement Area Safety System (AMASS), and provides automatic alert if an aircraft enters a 'protected' area such as a runway.

The demand for improved safety at smaller airports has led to a need for low cost surface movement monitoring solutions. The requirements of these smaller airports are far less stringent than the major airports, and in most cases all that is required is a confirmation that the runway is clear of traffic. An increasingly popular solution is to use marine radar technology to perform the surface detection function.

An example of a commercially available ASDE system is the Raytheon ASDE-X. It is a development of an X-Band marine radar product fitted with a new solid state transmitter in the band 9.0 to 9.2 GHz.

Figure 3.1.1-5 The Raytheon ASDE-X system installed at Logan Airport, Boston

3.1.1.5.2 Transmitter characteristics

There are two bands used in the UK for ASDE equipment, 9.3 - 9.5 GHz[4], and 15.7 - 16.2 GHz. Transmitters are often Magnetron devices, however solid state transmitters are starting to be used in the USA for FAA applications.

The short range requirement allows a very high PRR and fast turning rate to be used. Typically the antenna completes a scan in 1 second.

The characteristics of the ASDE -X, a USA X-Band airport surface radar, are given in Table 3.1.1-2.

Table 3.1.1-2 USA X-Band Tx characteristics

Frequency (MHz)	9000 - 9200
Pulse power (kW)	0.06
Antenna rotation rate (rpm)	60
Pulse widths (µs)	1 and 100
Pulse repetition rate (Hz)	4,000
Antenna Gain (dBi)	36
Azimuth Beamwidth (°)	0.4
Polarisation	Circular

[4] In the USA X-Band ASDEs operate in the band 9.0 to 9.2 GHz

The characteristics of a typical ASDE Ku-Band system are given in Table 3.1.1-3.

Table 3.1.1-3 Ku-Band Tx characteristics

Frequency (MHz)	15400 to 15700
Pulse power (kW)	3
Antenna rotation rate (rpm)	60
Pulse widths (μs)	0.04
Pulse repetition rate (Hz)	8000
Antenna gain (dBi)	44
Azimuth Beamwidth (°)	0.25
Polarisation	Circular

At Ku-Band, in order to achieve sufficient clutter rejection, frequency diversity must be employed.

3.1.1.5.3 Interference considerations

Since the main role of ASDE systems is to detect runway incursions, a loss in performance could have very serious safety consequences. A recent accident in Italy where an aircraft in bad weather collided with an airport building was attributed to the non-availability of the ASDE.

Noise-like interference is likely to be damaging to the operation of ASDE systems. The most likely symptom would be a loss of detection in one direction, caused either by the raising of the receiver noise floor, or saturation of the receiver front end.

In less sophisticated systems the raising of the receiver noise floor will, depending on the architecture of the system, cause either more missed detections or an increase in false alarms. The more sophisticated systems which fuse data from various sensors and use target tracking algorithms are able to coast tracks with missed detections so appear to be less vulnerable.

In all these systems, the very narrow beam width and low elevation angle would limit the extent of the interference.

3.1.1.6 Airborne weather radar

3.1.1.6.1 Description

Airborne weather radar is intended to detect and display hazardous weather systems that present a potential danger to the aircraft. The types of weather systems that present the greatest potential danger are wind shear and microbursts, which frequently exist in thunderstorms.

Wind shear is a term given to two wind currents blowing at different speeds or directions close to each other. This can cause eddy currents and areas of extreme turbulence in the space between the two wind currents.

Microbursts are sudden violent downward air currents that occasionally exist beneath thunderstorms. They tend to exist close to the ground, where they pose maximum risk to aircraft on final approach. There have been many fatal accidents attributed to microbursts, one of the best documented being the Delta Airlines I-1011 that crashed at Dallas Fort Worth Airport in February 1985.

Figure 3.1.1-6 Airborne weather radar display

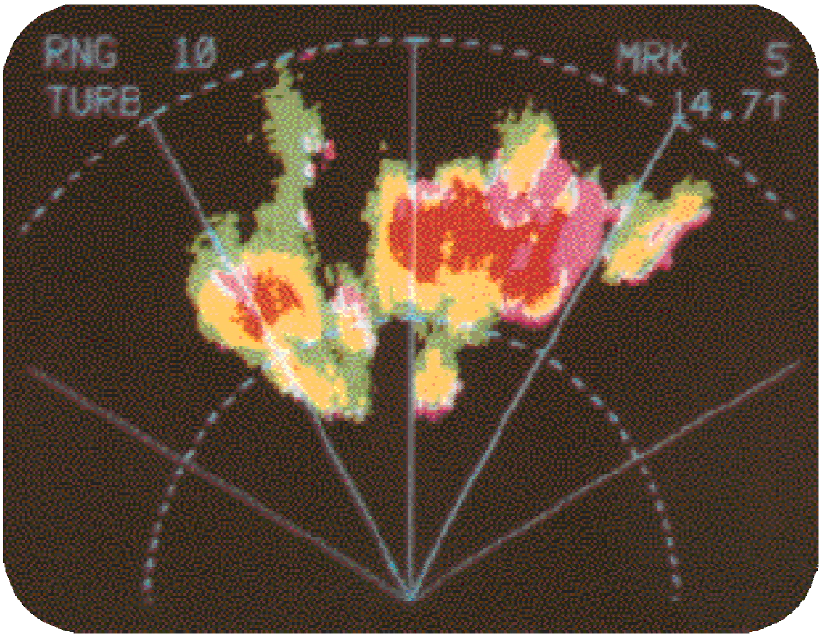


Figure 3.1.1-6 shows a typical display of an airborne weather radar, the weather targets are colour-coded by the intensity of the return. The display correlation to approximate rainfall is given in Table 3.1.1-4 below.

Table 3.1.1-4 Colour/rainfall correlation

Colour	Echo strength	Rainfall rate
Black	Very light or no returns	Less than 0.7 mm/hr.
Green	Light returns	0.7 - 4 mm/hr
Yellow	Medium returns	4 - 12 mm/hr.
Red	Strong returns	Greater than 12 mm/hr.
Magenta	Turbulence	N/a

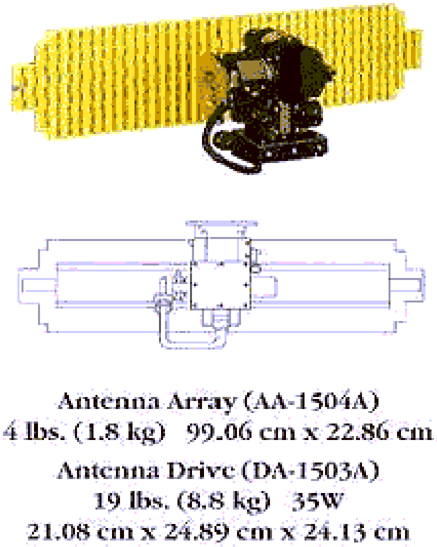
Weather radars used for search and rescue and in helicopters also can have the ability to display responses from SARTS & RACONs.

General aviation aircraft use ground returns from their weather radars as an aid to navigation.

3.1.1.6.2 Transmitter characteristics

Airborne weather radar transmitters operate at X-Band and may use either magnetron or solid state technology. Without exception airborne weather radar are forward looking systems. The antenna is usually of flat plate construction that is housed behind a radome on the nose of the aircraft. The antenna is fixed to a scanning mount that mechanically moves the antenna from side to side continuously. The pilot also has the ability to adjust the elevation axis of the antenna.

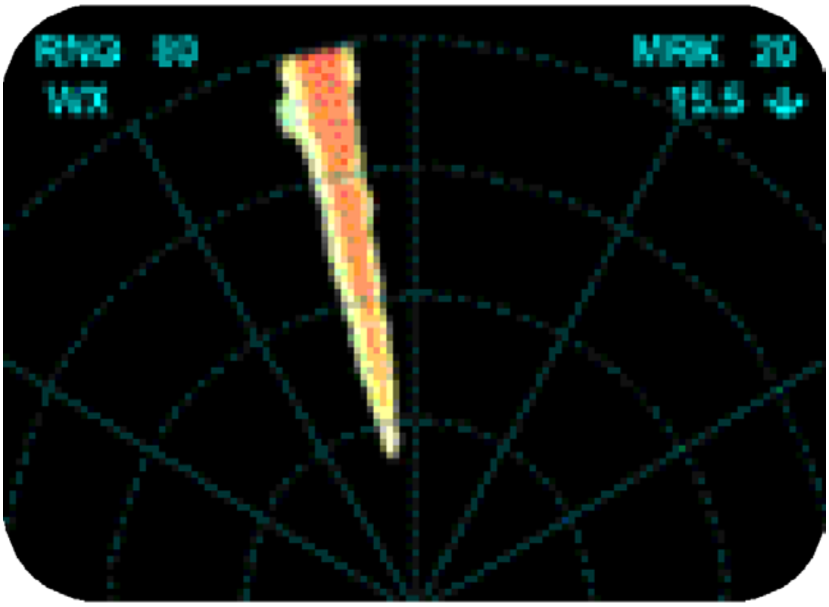
Figure 3.1.1-7 Airborne weather radar antenna and mount.



3.1.1.6.3 Interference considerations

An interfering RF source operating at a frequency close to the radar's operating frequency can create unusual return displays on the cockpit display (see Figure 3.1.1-8 below). These returns will appear as a single wedge of radar return that extends from very close range (< 5 nm) out to maximum range for the selected range scale. The wedge will typically cover from 3 to 5 degrees in azimuth.

Figure 3.1.1-8 Airborne weather radar cockpit display in the presence of an interferer



These patterns are caused by CW sources of interference. Types of CW RF source that can cause this effect include:

- military CW radar
- radar jamming equipment
- satellite uplink equipment

Adjusting the manual gain or the antenna tilt angle may help alleviate the effect of the interfering source but the effect will not completely disappear until the interfering source is no longer in the radar's field of view.

Aircraft are more susceptible to bad weather during the approach phase of flight. This is the time when weather radar is needed most. In this phase of flight the aircraft has a nose-down pitch attitude and hence the weather radar antenna points towards the ground. Some systems automatically adjust the antenna pitch if ground clutter is detected.

The downward direction of the antenna makes the system most susceptible to ground based interference in the most critical phase of flight (i.e. during landing). Interference that degrades performance and hence masks potentially dangerous weather cannot be accepted.

3.1.1.7 Vessel Traffic Systems (VTS)

3.1.1.7.1 Description

Vessel Traffic Systems are used in large ports and harbours to monitor the movement of surface vessels. These systems provide the harbour authorities with a large PPI display showing the positions and identities of the vessels in the port and surrounding area.

The typical VTS comprises a proprietary data processing system, which combines data from several sensor types for presentation on a single type of display. These sensor types include radar, video surveillance and Automatic Identification Systems (AIS). AIS systems are ship borne transponders that relay Global Positioning System (GPS) data and identity information from the vessel to the VTS via a VHF data link. In large ports several of each type of sensor are used to provide a large area of coverage.

The radar sensors employed in VTS systems are normally standard marine radars, usually with an appropriate data link to the data processing system. The technical characteristics of these standard marine radars are discussed separately in this document.

There is one major difference however, many VTS systems use much larger antennas than those used on ships, 13 foot and 22 foot open array antennas are common. More sophisticated systems make use of bespoke reflector antennas.

3.1.1.8 Air Traffic Control (ATC) primary radar

3.1.1.8.1 Description

For the last 60 years, ATC primary radar has played an important role in the safety of air traffic in and around airport airspace. One of the main advantages of a primary radar is that it does not rely on any co-operation from the target and can detect small targets such as light aircraft (or non-co-operating targets) which may not be fitted with SSR transponders.

The role of a primary radar system is being expanded to include the detection of rain systems, as well as the surveillance and detection of air targets. With the increasing complexity, functionality and popularity of SSR systems, the primary radar system also performs an integrated function, working in conjunction with data from an SSR system. This produces an accurate, and overall representation of the activity within airport airspace.

Some small airfields are only equipped with primary radar while other such airfields have no radar coverage at all.

Primary radar is still the main method of ATC at military airfields.

3.1.1.8.2 Transmitter characteristics

There are two frequency bands commonly used for ATC primary radar: L-Band (1215 to 1365 MHz), and S-Band (2700 to 2900 MHz).

There is a wide variety of technologies used for the transmitters of these systems. Older systems tended to use vast amounts of power (several Megawatts), and employed vacuum tube devices such as Magnetrons, Klystrons or Travelling Wave Tubes. More modern systems benefit from powerful signal processing techniques, and tend to require far less power than older types. Solid state transmitters are commonly (but not always) used in new installations.

L-Band radar is normally used for long range air surveillance and can easily achieve detection ranges of 250 nm.

The following parameters are given as an example of a modern solid state primary ATC L-Band system. This system is the Raytheon ASR-23SS solid state radar.

Table 3.1.1-5 Parameters of a modern solid state primary ATC L-Band system

Frequency (MHz)	1250 - 1350
Pulse power (kW)	40
Antenna rotation rate (rpm)	5
Pulse widths (µs)	1 and 100
Antenna gain (dBi)	36
Azimuth Beamwidth (°)	1.25
Polarisation	Linear and circular
Pulse compression ratio	100:1

S-Band radar is normally used for short range (<100 miles) air and weather surveillance.

The new solid state S-Band systems being installed in the UK are also Raytheon systems, the parameters given in Table 3.1.1-6 below reflect the options available from the manufacturer.

Table 3.1.1-6 Parameters of a modern solid state primary ATC S-Band system

Frequency (MHz)	2700 - 2900
Pulse power (kW)	15 or 30
Antenna rotation rate (rpm)	12 or 15
Pulse widths (µs)	1 and 100
Antenna gain (dBi)	35
Azimuth Beamwidth (°)	1.4
Polarisation	Linear and circular
Pulse compression ratio	100:1

Due to congestion in the 2700-2900 MHz band, the FAA is planning to allow systems currently using that band to expand into the 2900-3100 MHz band.

3.1.1.8.3 Receiver characteristics

ATC primary radar have relatively sophisticated receiver systems, which include the ability to perform many of the signal processing tasks described is section 3.3. These may include Sensitivity Time Control (STC), pulse integration, Constant False Alarm Rate (CFAR), Moving Target Indication (MTI) and automatic plot extraction. Many systems also employ pulse compression.

In addition to the signal processing functions, data processing on the target reports from the primary radar associates, or "combines" them with the target reports from the SSR system to form one target on the integrated ATC display. This provides a clearer view than simply overlaying the primary and secondary targets.

3.1.1.8.4 Interference considerations

When interference is present, the effects will depend on the nature of the interference, especially the modulation method. The most serious type of interference is likely to be wideband noise-like. This will have the effect of raising the receiver noise floor resulting in a reduction in the maximum detectable range of the radar or the Probability of Detection (Pd) of a given target. In severe cases this may completely saturate the front end of the receiver, preventing any detection. False alarms are relatively unlikely where techniques such as CFAR, STC and pulse compression are used.

The narrow antenna beamwidth, however, restricts the extent of the symptoms to a narrow sector in the direction of the interference source, provided the interference source is not so strong as to affect the receiver through the antenna sidelobes.

Pulsed CW-like interference may also prove dangerous to these systems since this type of interference is able to pass through the pulse compression circuits with less degradation than other types of interference.

The safety implications of interference to ATC primary radar systems are serious; however, with data processing and integration with SSR, providing there is not simultaneous interference to the SSR system, aircraft will continue to be tracked through the areas of reduced coverage. Similarly, tracking will be maintained if the SSR has interference and the primary radar does not.

3.1.1.8.5 X-Band ATC Airfield Radars

Some airfields operate X-Band Airfield Control Radars (ACR). These are used for local surveillance and Ground Controlled Approach (GCA) roles. These systems are short-range systems based entirely on Magnetron transmitters. The transmission characteristics of these systems are very similar to X-Band marine (see section 3.1.1.9) radars with the exception that they generally use horn fed reflector antennas to avoid coning[5]. These antennas do not squint in azimuth so no beam modulation occurs. Some systems have two beams, a “Control Beam” and a “Surveillance Beam”. The surveillance beam is used for general ATC surveillance whilst the Control beam is reserved for ground controlled landings.

The consequence of interference to these systems can be very severe particularly when they are being used to control landing aircraft.

3.1.1.8.5.1 Receiver characteristics

Some of the receivers in these systems use the so-called “Dicke Fix”[6] to reduce the effect of pulsed interference. In this type of receiver a wide-band limiting amplifier is followed by a narrow band filter. The gain of the wide-band limiting amplifier is set such that it ensures that it is always saturated by the system noise so that all signals are limited to the same level at this point in the receiver. The constant output is then applied to a narrow band filter, optimised for system pulse length *t* (i.e. bandwidth *b = 1/t)*.

The noise power appearing at the output of the narrow-band filter is less than the noise power at the output of the wide-band limiting amplifier by the ratio of the two bandwidths. An interfering input at any frequency inside the wide-band but outside the narrow-band, results in a higher power density at that frequency and a reduction in the power density over the rest of the wide-band, so that the total power remains constant as limited by the limiting amplifier. The interfering signal input thus causes the noise out of the narrow-band filter to reduce, the unwanted signal appearing as a hole in the normal noise background.

[5] Coning is a phenomenon that occurs in fan beams produced by squinting antennas. A principle elevation plane of a squinted fan beam lies on a cone not a great circle this results in the azimuth angle detected being a function of the height of the target. The error is generally acceptable for targets close to the horizon so is generally acceptable for surface movement applications but becomes unacceptable for systems that require high angle of elevation coverage.

[6] Watching the Skies J Gough HMSO ISBN 0-11-772723-7 Page 191

Due to the action of the limiter, the wide-band limiting receiver has an constant false-alarm quality and is much less sensitive to interference outside the narrow band.

3.1.1.9 Maritime navigation radar

3.1.1.9.1 Description

Marine navigation radar systems are carried on board vessels at sea to assist in the safe navigation of that vessel. The way in which the radar is used depends largely on the size of the vessel.

Small vessels (including yachts, motor cruisers and trawlers) use their radar for navigation in bad weather and poor visibility. These systems can detect navigational hazards, RACONs, and other vessels in fog, and are therefore vital to the safety of the host vessel. Due to the low cost of processing and display technology, these systems are now very affordable.

Large vessels also use their radar systems in good weather. Large ships are inherently difficult to manoeuvre, and stopping distances and turning radii of several miles are common. The radar systems carried by large ships are therefore capable of tracking surrounding vessels, and displaying the track history and prediction vector for these vessels. Automated alerts are generated whenever a risk of collision exists with another vessel. Figure 3.1.1-9 shows a typical display.

Docking radars are used by ships to aid berthing. Currently they operate at X Band and are effectively marine navigational radars operating in short range mode. The main difference when used as a docking radar is that the display is provided in the conning position from where the captain docks the ship. The scanner can be a separate radar positioned to give an optimum view or alternatively the docking radar display could simply be a repeater from the main navigational radar display. Electromagnetically the docking radar is identical to the navigational radar.

There are also references to docking radars used by ports and oil terminals. These are land based radars and are essentially short range VTS systems.

Historically docking radars were operated in the Ku-Band between 14.25 GHz and 14.3 GHz. However technical problems due to rain attenuation have meant that such radars are no longer used.

The following quote is from section 4 of DSI Phase III[7] *"The use of various radiodetermination bands for maritime radars is reviewed in Table B. This shows that the 12 GHz to 40 GHz bands have been tried in the past but are not usable due to absorption and attenuation problems which limit range performance severely."*

[7] DSI Phase III :United Kingdom Comments on EROs Preliminary Conclusions

Figure 3.1.1-9 Typical large vessel radar display. The track history of surrounding ships can be clearly seen

3.1.1.9.2 Transmitter characteristics

The transmitter devices are most often Magnetrons. Two frequency bands are commonly used for marine radar; known to operators as the 3 cm and 10 cm bands. The 3 cm radar systems typically operate in the band 9.3 to 9.5 GHz, and 10 cm radars are allocated the 2.9 to 3.1 GHz band.

The transmitter characteristics for a typical 3 cm (X-Band) small yacht radar are shown in Table 3.1.1-7.

The transmitter characteristics for a typical 3 cm (X-Band) radar for a large commercial vessel are shown in Table 3.1.1-8.

The transmitter characteristics for a typical 10 cm (S-Band) radar for a large commercial vessel are shown in Table 3.1.1-9.

Table 3.1.1-7 Typical transmitter characteristics of a 3 cm small yacht radar

Frequency (MHz)	9410 ± 30
Transmitter type	Magnetron
Pulse power (kW)	2
Antenna rotation rate (rpm)	24
Pulse widths (μs)	0.08 / 0.25 / 0.7
Pulse repetition rate (Hz)	2250 / 1200 / 750
Beamwidth (°)	Azimuth: 5.2 Elevation: 25
Polarisation	Horizontal
Maximum range scale (nm.)	24

Table 3.1.1-8 Typical transmitter characteristics of a 3 cm radar for a large commercial vessel

Frequency (MHz)	9410 ± 30
Transmitter type	Magnetron
Pulse power (kW)	60
Antenna rotation rate (rpm)	26
Pulse widths (μs)	0.08 / 0.2 / 0.4 / 0.7/ 1.2
Pulse repetition rate (Hz)	2200 / 100 / 600 / 500
Beamwidth (°)	Azimuth:1.23 Elevation: 25
Polarisation	Horizontal
Maximum range scale (nm.)	96

Table 3.1.1-9 Typical transmitter characteristics of a 10 cm radar for a large commercial vessel

Frequency (MHz)	3050 ± 30
Transmitter type	Magnetron
Pulse power (kW)	30
Antenna rotation rate (rpm)	24
Pulse widths (μs)	0.08 / 0.3 / 0.6 / 1.2
Pulse repetition rate (Hz)	1900 / 1100 / 600
Beamwidth (°)	Azimuth: 2.3 Elevation: 25
Polarisation	Horizontal
Maximum range scale (nm.)	120

3.1.1.9.3 Receiver System characteristics

Since the transmitter devices are most commonly magnetrons, techniques such as coherent pulse integration and pulse compression will not be used. Small vessel radars tend to be quite simple in design and will not include signal processing techniques such as CFAR, although some simple clutter suppression techniques, such as STC, will be implemented. Large vessels will be equipped with more complex systems that may implement more sophisticated signal processing.

3.1.1.9.4 Interference considerations

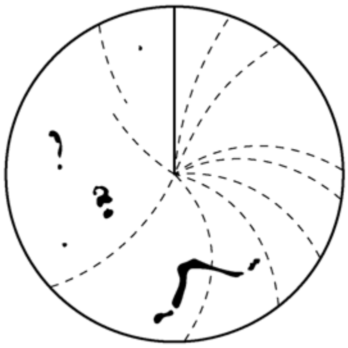
When interference is present, the effects will depend on the nature of the interference, especially the modulation method. In many cases the interference will be evident as a raising of the noise floor of the radar receiver. In severe cases this may completely saturate the front end of the receiver, preventing any detection. In certain situations noise from an interfering source may be approximately synchronous to the radar transmissions. This would lead to the generation of false targets.

The narrow beamwidth of the marine radar limits the consequences of interference in the same way as for ATC primary radar. The effects of this interference will vary according to the design of the equipment and the interferer, but the most likely symptom of interference will be a loss of range, or dead zone, on the same bearing as the interference source.

Mutual radar interference is likely when two or more radar-equipped vessels are operating within range of each other. This usually appears as a series of small dots moving to and from the display centre in a straight line or a long, sweeping curve. This type of interference is most noticeable at long ranges and is shown in Figure 3.1.1-10. Some systems have the option to reduce this effect in signal processing.

Techniques such PRR jitter, "pulse-to-pulse correlation" and "scan-to-scan correlation" allied with good receiver and display design, along with how the radar is set-up, can significantly reduce the effect of mutual interference between these types of systems. These techniques are discussed in ITU document 8B/72-E[8].

Figure 3.1.1-10 Mutual interference between two marine navigation radars



For systems on larger ships, interference could cause problems with target tracking. As a vessel moves into the dead zone, its track file would be dropped (usually after a couple of scans). The vessel would then emerge out of the dead zone with no heading or velocity information. As the dead zone would be relatively narrow, this is unlikely to compromise safety.

One of the useful features of modern maritime radar systems is the ability to define a “guard zone” around the vessel. This is essentially a range threshold alarm, which is activated if a target comes within a certain range of the vessel. The hidden danger with interference is that it can cause false targets and hence trigger false alarms. Unreliable warning equipment and false alarms inevitably lead to operators ignoring the warnings, and sooner or later a genuine warning will be ignored.

3.1.1.9.5 FM-CW Radars

There are two maritime surveillance radars available that use FM-CW techniques. These are the Scout and Pilot radars from Thales Naval Nederlands and Celsiustech. These radars claim to be Low Probability of Interception (LPI) systems and operate with very low peak powers (1 W to 1 mW peak/mean [9] power). They use a FM CW waveform with a chirp of around 50 MHz. The transmitters used are solid state devices.

The Scout radar makes use of a dedicated scanner. The Pilot radar can be integrated with an existing marine radar. It must be remembered however that these radars are designed for LPI as their inherent detection range is limited even on the largest targets.

3.1.1.10 Maritime RACONs, SARTs and Radar Target Enhancers

3.1.1.10.1 Description

These devices are all used to detect radar pulses and provide an enhanced return providing more visibility of the target to the radar operator.

[8] Factors that mitigate interference from radio location radars to maritime and aeronautical radionavigation radars in the 2900 -3100 MHz band 8B/72-E 15th May 2001. See also ITU-R Recommendation M.1372(11/98) Efficient use of the radio spectrum by radar stations in the radiodetermination service.

[9] In CW radar peak power = mean power

RAdar beaCONs (RACONs) are transponders designed to be located in fixed positions. Their purpose is to positively identify a navigational feature such as a buoy, lighthouse, etc on a vessel's radar display. They transmit in response to being illuminated by a marine navigation radar. They may respond in one of two ways. Older systems will respond by a series of sweeps covering the entire frequency band of the receiver in which the signal was received, while newer systems will respond on the frequency of the interrogating signal. Swept frequency RACONs are obsolescent and are not recommended for new installations.

The reply is a pulse train representing a morse code letter, and usually starts with a dash. The beacon appears on the radar display as a morse letter extending from the beacon outwards in range. The length of the RACONs reply message will vary depending upon the triggering radar, the length of message will be such that it will appear on the radar display over approximately 20% of the display range up to a maximum of 5 miles. The RACON achieves this by use of a proportional scaling function which monitors the interrogating radar pulse length and pulse repetition rate, and adjusts its response so that the length of trace appearing on the radar screen will be generally uniform on all range settings.

By the nature of their locations, RACONs usually operate from a solar charged battery, and are hence on a tight power budget. It is normal for buoy-mounted RACONs to operate 50% of the time in order to conserve power.

A similar system is also used for marine emergency use. The Search And Rescue Transponder (SART) is a small portable radar beacon. Operating in exactly the same way as a RACON, the SART is designed to be carried aboard a vessel, and activated only in the event of an emergency. Once activated, the SART indicates its position as a series of 12 dots spaced at 0.6mm on 3cm (9GHz) radar displays.

The SART has slightly different transmitter characteristics to the RACONs, due to a different set of design constraints. They are designed to be activated in an emergency situation, and have to operate continuously for as long as possible on a single set of batteries.

Figure 3.1.1-11 A typical SART

The Radar Target Enhancer (RTE) is a device designed to replace a passive radar reflector and is designed to "enhance" the radar return from a small vessel that might otherwise be undetected by the radar. When it is illuminated by a radar signal, the RTE amplifies the signal and retransmits it with a minimum delay. The result is a very large radar return from a relatively small object.

3.1.1.10.2 Transmitter characteristics

Because they must interact with marine navigation radars RACONs can operate in the marine radionavigation bands: 9300 - 9500 MHz and/or 2900 - 3100 MHz. (9300 - 9320 MHz from 01 January 2001)

Although most vessels have radars that operate in the 9 GHz band, an increasing number are fitted with both 9 GHz and 3 GHz band radars. The provision of dual band RACONs is important, since at times, particularly during bad weather, many vessels use 3 GHz band radars in preference to 9 GHz band radars because the former produce better clutter rejection. A vessel equipped with a radar for each band will tend to use the one that produces the better display in any given situation. Therefore RACON service will be expected to be available at all times in both the 3 GHz and 9 GHz bands.

The RACON will attempt to reply on the same frequency as the radar signal that triggered it. In practice this frequency measurement becomes more difficult if the received pulse is short. The requirements for RACONs allow the transmission frequency tolerance of ± 3.5 MHz if the received pulse is less than 200ns wide, or ± 1.5 MHz if the received pulse is more than 200ns wide.

The typical transmission parameters from a RTE are given in Table 3.1.1-10 below.

Table 3.1.1-10 Typical transmission parameters from a RTE

Operating Frequency	9300 to 9500 MHz
Minimum Conversion Gain	56 dB (RCS[10] of $32m^2$)
Equivalent Isotropically Radiated Power (EIRP)	1 W
PRR Range	250 - 5000 Hz
Input Protection	250 W peak / 3 W CW

3.1.1.10.3 Receiver characteristics

The RACON uses an omni-directional antenna to ensure it can be seen from all directions. This also makes the receiver susceptible to interference from all directions.

Some RACONs use a swept frequency homodyne receiver that slowly (over several seconds) sweeps across the radar band. The transmitter then replies on the same frequency as the detected pulse. If any interference pulses are detected anywhere in the radar band, transmissions will be triggered.

One of the disadvantages of the swept frequency architecture is that the front end of the receiver must have a very wide pass band. This must cover (and can extend beyond) the radar band. One of the weaknesses in this design is therefore the possibility that this front end can become saturated. No signals will be detected if this occurs, and the RACON will effectively disappear from the radar displays.

RACONs, SARTs and RTEs typically have a sensitivity of -50 dBmi (decibels below 1mW if received through an isotropic antenna).

3.1.1.10.4 Interference considerations

Like the airborne SSR transponder, the effects of interference will be false triggering of the beacon, possibly by strong pulsed interference. This will manifest itself as a loss of detection of the RACON on the ships' radar display.

The worst case scenario is that the failure to detect the RACON could lead to a navigational error. With modern navigational equipment (i.e. GPS equipment), this should be a small risk. There are however vessels that do not have this modern equipment.

For SARTs, false triggering is a particular problem since they are battery powered. Continuous false triggering will drain the batteries and the transponder will cease to operate, making the task of locating the distressed vessel significantly more difficult.

In the case of RTEs the main problem would be front end overload. High level signals close to the RTE could cause the front end to limit, preventing the RTE from replying to other signals.

[10] Radar Cross Sectional area.

3.1.1.11 Ground based meteorological radar

3.1.1.11.1 Description

There are a number of types of weather radar which, by virtue of their different characteristics, can measure various weather properties.

Air traffic control primary radar (particularly S-Band) systems receive reflections from precipitation, this is potentially useful information for air traffic controllers. Since weather data is a useful by-product of the air surveillance function, it can be output on the same screen as the aircraft plots. This enables a controller to vector aircraft around a storm. Civil ATC radar, however, are 2 dimensional systems and can give no indication of the elevation (height) of the precipitation.

In the UK the Met Office operate a number of radar systems that are designed specifically for meteorological use and provide far more information than their ATC counterparts. These fall into two categories:

- Ground Based Weather Radars
- Wind Profiler Radars

3.1.1.11.2 Ground Based Weather Radars

The UK Met Office, together with Met Eireann and the Jersey State, operates an integrated network of C-Band weather radar sensors across the British Isles.

The UK and Jersey parts of this network are composed of Type 45C weather Radar sensors as supplied by the former Siemens Plessey Systems company (now part of AMS). Data is transferred from each installation to the Central Forecasting Office at Bracknell, where a composite National Weather database is prepared for distribution across the UK and continental Europe.

Figure 3.1.1-12 The Type 45C weather radar antenna

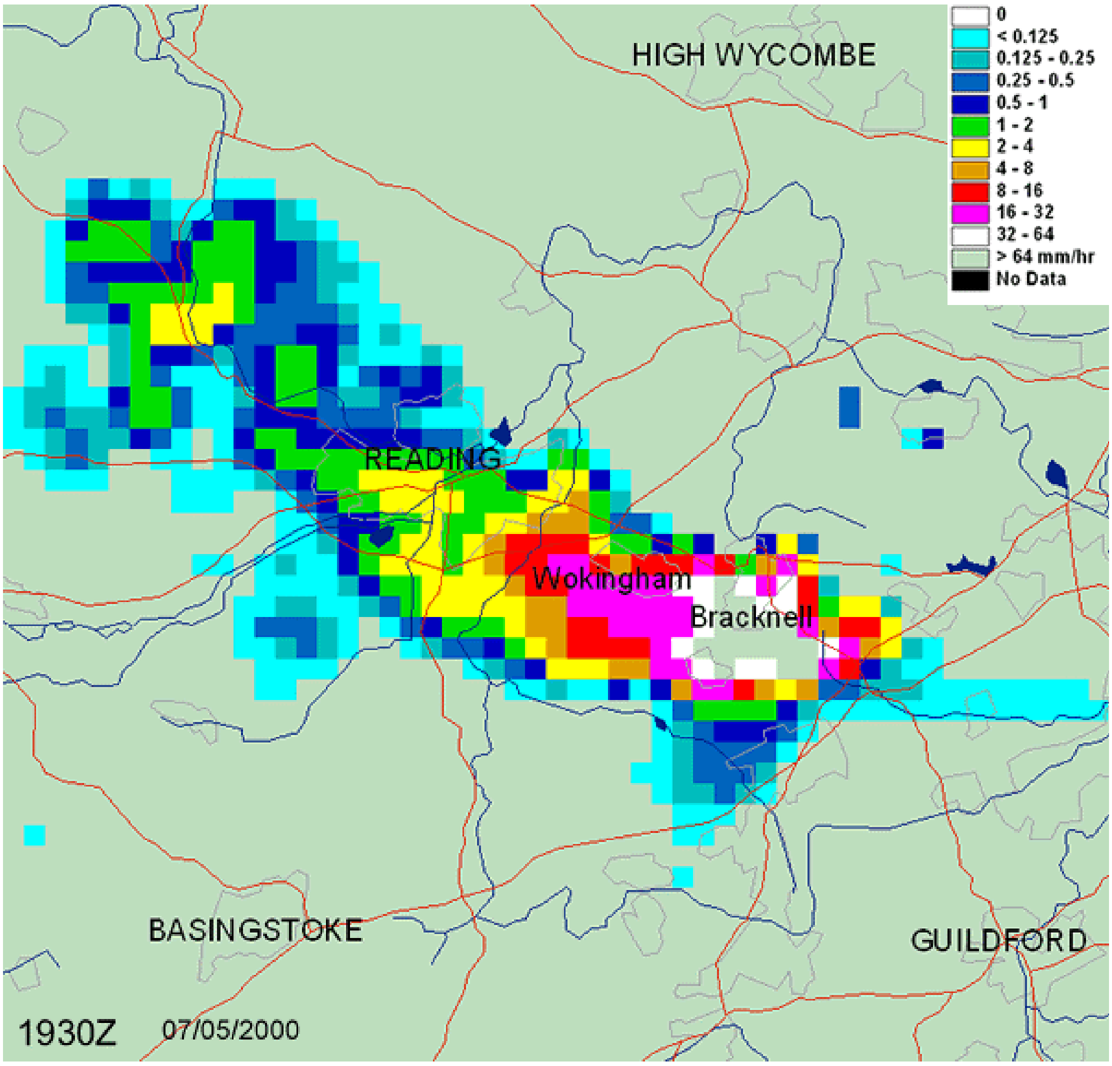
The Type 45C is a powerful C-Band weather radar sensor capable of detecting all significant precipitation within a range limited only by the radar horizon. Some of the weather radars have a Doppler mode which provides the capability of discriminating precipitation echoes from underlying ground clutter echoes and provides velocity data on precipitation echoes. The system employs a large (nominally 3.66m) diameter parabolic reflector antenna giving a 1° pencil beam, with 43dB gain with respect to an isotropic radiator, at a nominal working frequency of 5625MHz. The sidelobe levels do not exceed -25dB. The antenna can be positioned in both azimuth and elevation allowing either azimuth or elevation weather cross sections to be produced.

In addition to the Met Office weather radar network, an experimental weather radar station is operated at Chilbolton in Hampshire by the Radio Communications Research Unit of the Rutherford Appleton Laboratory in Oxfordshire. This 3 GHz installation is described in section 3.1.1.17.2 of this report.

3.1.1.11.2.1 Precipitation

Precipitation is detected by simply measuring the amount of power reflected at a given range. This produces a false colour picture display showing the density of the precipitation. Figure 3.1.1-13 shows the picture of a storm over Bracknell.

Figure 3.1.1-13 A storm over Bracknell [11]



The greatest rainfall rate depicted on the Bracknell area image is above 64 mm/hr; this is a limitation of the encoding and data transfer method.

The empirical relationship between radar reflectivity and rainfall rate is fixed, whereas in reality this is highly dependent on precipitation type and is very different for rain and hail.

[11] Picture from the UK Met Office web site - www.metoffice.gov.uk.

The familiar rainfall profile commonly presented during TV weather forecasts, is the result of fusing the data from all the radars in the weather network.

3.1.1.11.2.2 Transmitter Characteristics

The Type 45C Doppler weather radars use a coaxial high stability magnetron, tuneable in the band 5450-5825MHz. This operates in two modes:

- Normal (Precipitation intensity) : pulse width of 2μs ± 0.2μs at 50% amplitude with 300Hz PRR.
- Doppler : pulse width of 0.5μs ± 0.1μs at 50% amplitude with variable PRR up to 1200Hz using pairs of PRR for velocity ambiguity resolution.

Table 3.1.1-11 Transmitter characteristics of the 45C Weather Radar

Frequency (MHz)	5625
Transmitter type	Coaxial magnetron
Peak Power (kW)	250
Pulse Width (μs)	2, 0.5
Pulse Repetition Rate (Hz)	300, 1200
Beamwidth (degree)	1 (pencil beam)
Polarisation	Vertical
Maximum range (km)	200

3.1.1.11.2.3 Interference considerations

The narrow elevation of the beam pattern makes the meteorological radar less sensitive to interference than ATC radars. It spends most of its time looking at positive angles of elevation, and so is only likely to have an interference source directly in the beam when the antenna is pointing close to the ground.

There is however another mechanism by which a meteorological radar can receive interference. Any RF power that is radiated from an interference source into the air will be scattered by the moisture in the air, and might be picked up by the receiver. This is an important phenomenon to take into account if a point to point communication system is to be used on the same frequency.

Front-end saturation and false measurements are likely consequences of interference, depending on the characteristics of the interfering transmission.

3.1.1.11.3 Wind Profiler radar

3.1.1.11.3.1 Description

During the last 20 years, Doppler radars were systematically developed to probe the atmosphere and derive the wind profile (i.e., the speed and direction as a function of height) from echoes of the transmitted radio waves produced by turbulence in the clear air. A wind profiler is the operational application of a radar originally developed by scientists for measuring the echo intensity and the wind profile up to about 30 km with height resolutions from 100 to 250 m. Sequences of high power pulses are radiated in the vertical and in oblique directions. By analysing the received echoes, the radial velocity and the turbulence intensity can be computed. Observations from at least three directions are necessary to determine direction and speed of the wind.

The maximum reachable height of a wind profiler radar depends, among other parameters, on the operating frequency. To monitor atmospheric processes up to 30 km, 16 km and 5 km, wind profiler systems with operating frequencies at about 50 MHz, 400 MHz and 1000 MHz are used.

Wind profiler radars can be adapted to measure temperature profiles up to about 5 km when they are used in conjunction with a Radio-Acoustic Sounding System (RASS). This is achieved by transmitting a strong but short acoustic "beep" vertically upwards. This tone burst travels as a compression wave with the speed of sound upwards in the atmosphere. The wind profiling radar is now used to measure the speed of propagation of this sound burst, which also produces an echo of the radar signal. Since the speed of sound depends on the air temperature, this latter value can then be computed.

Figure 3.1.1-14 '15 LAP'®-3000 Wind Profiler

The Wind Profilers operated by the UK Met Office have the operating characteristics as shown in Table 3.1.1-12 through to Table 3.1.1-15 below.

Table 3.1.1-12 Characteristics of Wind Profiler at Camborne (Radian LAP)

Frequency (MHz)	915
Height resolution (m)	200
Range (km)	0.6 to 5.0
Beam Angle (°)	15.0

Table 3.1.1-13 Characteristics of Wind Profiler at Dunkeswell (Radian LAP3000)

Frequency (MHz)	1290
Peak Power (kW)	1
Height resolution (m)	60 / 210
Range (m)	108 to 2015 / 253 to 7937
Beam Angle (°)	15.5

Table 3.1.1-14 Characteristics of Wind Profiler at Aberystwyth (NERC MST[12] radar at Aberystwyth)

Frequency (MHz)	46.50
Height resolution (m)	300 sampled at 150m intervals
Range (km)	1.7 to 20.0
Beam angle (°)	6

[12] Natural Environment Research Council, Mesosphere, Stratosphere and Troposphere Radar

Table 3.1.1-15 Characteristics of Wind Profiler at Wattisham, (Radian LAP3000)

Frequency (MHz)	1290
Peak Power (kW)	1
Height resolution (m)	102 / 205
Range (m)	239 to 2060/ 347 to 8239
Beam Angle (°)	15.5

3.1.1.11.3.2 Interference Considerations

Because of the physical principle used, wind profiler radars require a large amount of bandwidth in the electromagnetic spectrum already crowded by television and radio stations, as well as by two-way radio and wireless telephones. Further, the choice of the operating frequency is not entirely free, because the processes producing the echoes occur only at certain frequencies.

3.1.1.12 Police vehicle speed measurement radar

3.1.1.12.1 Description

The use of roadside RF speed detectors is decreasing, due to the widespread use of laser speed measuring devices. Laser devices have a much narrower beamwidth than RF guns, and hence they are better at picking out a single target from several. Because of this narrow beamwidth, laser devices are also far more difficult to detect. There are however, several circumstances in which laser devices are not suitable, such as in fog or heavy precipitation, and so radar doppler measurement equipment is likely to continue to have some applications for the foreseeable future.

3.1.1.12.2 Transmitter characteristics

In January 1997, an English court ruled that the use of radar detectors was not an offence. With the resulting proliferation of commercially available radar detectors, the transmission characteristics of police doppler radars are evolving.

Most recent police radar guns now use a pulsed modulation system, controlled by a trigger type operating switch. This minimises the amount of time for which the transmitter is active, and hence reduces the probability of it being detected.

There are three frequency bands defined for traffic radar in the UK: X-Band, K-Band and Ka-Band.

X-Band radars operated between 10.500 and 10.550 GHz, but are no longer used in the UK. The band has been opened up for a variety of other civil microwave transmitter applications (i.e. Alarm systems, etc.).

K-Band systems operate between 24.05 GHz and 24.25 GHz. At this frequency signals are highly attenuated by moisture in the atmosphere, and hence are ideal for short-range radar applications. Most traffic radar in the UK uses this band. Gatso speed cameras are one such system. These use a beamwidth of 5° pointing across the road at an angle of 22.5°. The resulting doppler measurement is divided by the cosine of 22.5° to give the true speed of the vehicle. The output power from this type of transmitter is very low (typically 2.5 mW).

Ka-Band systems operate in the band between 33.4 GHz and 36 GHz. This band is divided between 13 channels of 200 MHz each. Some systems use a single channel, and some hop between several channels to avoid detection and/or jamming.

3.1.1.12.3 Interference considerations

Traffic radar systems are inherently unlikely to suffer from accidental interference. Their narrow beamwidth, low elevation angle, and in some cases brief operation reduce the likelihood of an interference source being detected. However, unlike rotating radar systems, the presence of interference will prevent the operation of the radar completely.

The two obvious consequences of interference are failure to convict a speeding motorist, and convicting an innocent motorist. Both these events are very unlikely.

3.1.1.13 Ground Probing Radars (GPR)

3.1.1.13.1 Description

Ground Probing Radar is becoming an important and growing field of radar systems design. A list of current uses is provided:

- Landmine, pipe and cable detection.
- Mineshaft and tunnel location.
- Measurement of structure thickness.
- Locating hidden objects.
- Investigating areas of archaeological interest.
- Investigating areas of geophysical interest.
- Mapping landmasses and glacial areas.

When compared to other forms of non-radar probing systems, the ground probing radar system is lightweight and relatively manoeuvrable. There is a disadvantage associated with this type of radar system, namely the level of radio propagation. Good radio propagation is only achieved through a suitably dry material, whereas penetration into wet material limits the detection range to a few metres.

3.1.1.13.2 Operational characteristics

Essentially, GPR is governed by mission. The correct transmission frequency cannot be selected until the transmission medium has been correctly specified, and in keeping with the tradition of radar, a compromise must be struck between the detection depth and resolution required.

A high transmission frequency provides good resolution but does not propagate well through the transmission medium leading to poor depth of penetration, whilst the lower transmission frequencies provide deeper penetration but lack the required resolution.

The reason behind this compromise lies within the transmission medium itself. Each type of material or medium has an associated dielectric loss associated with it. In the case of ground probing radar, this loss manifests itself as an attenuation factor that acts as a low pass filtering function. As the water content of the specified medium increases, so does this attenuation factor. This can be demonstrated by comparing the dielectric loss of water (80) and that of dry soil (2 - 6). The maximum detection range decreases with any increase in dielectric loss.

The low pass effect of each medium places an immediate limitation on the available range of transmission frequencies. In general, to locate buried objects the transmission frequency is kept below 1 GHz. The higher frequencies provide good resolution but are poor in terms of detection depth. To conduct geological ground probing the transmission frequency is kept below 100 MHz. These lower frequencies provide excellent detection depth but give poor resolution results. In general, propagation losses keep the transmission frequency below 1 GHz, whilst antenna constraints keep the transmission frequency above 1 MHz

3.1.1.13.3 Interference considerations

The most damaging form of interference to a ground probing radar is likely to be wideband noise-like, which will raise the noise floor in the receiver and reduce the detection capability of the system. Safety critical areas include the location and detection of electrical cabling, gas pipes, tunnels, mineshafts and, of course, landmines. Interference on these particular frequencies could cause missed detections. This could prove dangerous when attempting to detect sub-surface landmines or high voltage cabling structures.

Due to the usage of such systems, the likelihood of destructive interference is greatly reduced.

3.1.1.14 Precision Approach Radar (PAR)

3.1.1.14.1 Description

Some military airfields in the UK are fitted with Precision Approach Radar (PAR). These are used to control the landing of aircraft from the ground on a Ground Controlled Approach (GCA). The main feature of these radars is the requirement to display an aircraft's elevation and azimuth positions separately with respect to the glide slope.

The early PARs used two mechanically scanned antennas one rotating in azimuth to provide the azimuth glide slope data and one scanning vertically (nodding) up and down to provide the elevation data. Antennas based on slotted waveguide arrays later replaced these systems. Mechanical means were used to form a scanning beam from fixed antennas. Modern systems use electronic scanning and active arrays to produce the beam. PAR installations come with a GCA surveillance (rotating beam) or with just the sector scanning beams as required. The GCA surveillance beam is generated by the so-called Surveillance Radar Element (SRE)

When a PAR installation is equipped with a SRE, it is referred to as a "PAR *System*". The update rate on the SRE and PAR must be less than 1s, resulting in a rotation rate of greater than 60 rpm being required for the SRE.

Most of the PARs currently in service are slotted waveguide types, however, the UK is currently undergoing a replacement programme to replace its PARs with modern electronically scanned versions.

Figure 3.1.1-15 below shows a modern PAR produced by Raytheon.

Figure 3.1.1-15 Raytheon FBPAR Fixed Base Precision Approach Radar

3.1.1.14.2 Transmitter characteristics

The older systems use magnetrons with short pulses, with a transmitted waveform similar to that produce by a marine radar (see section 3.1.1.9).

The modern systems use solid state transmitter/receiver modules in an active array configuration with peak power typically around 500 W. To achieve the required range and range accuracy (< 100 ft), multiple pulse lengths and coding and processing schemes are used.

3.1.1.14.3 Interference considerations

PARs operate in a different part of X-Band spectrum from the ATC and marine radars and this protects them to some extent. However any interference to such critical systems could be serious. The use of active array technology may suggest that the low noise front end has limited selectivity, however the mission of the PAR means that it only needs to operate at fixed frequencies and there may be some case for the provision of extra protection.

3.1.1.15 Microwave Landing Systems (MLS)

3.1.1.15.1 Description

The Microwave Landing Systems operates in the C-Band part of the spectrum and is capable of providing landing guidance down to ICAO CAT 3. The system is called Time Reference Scanning Beam (TRSB) and operates by measuring the time taken for a scanning beam to move to and fro across the receiver in the aircraft. Two scanning beams are used, one for azimuth and one for elevation.

The azimuth antenna has a pencil beam in azimuth and a shaped elevation pattern to provide constant EIRP with range at a given height. The elevation antenna has a fan beam in azimuth and a pencil beam in elevation.

The system also has the ability to generate data and out-of-coverage beams using wide beamwidth antennas.

By measuring the time for the two beams to pass the receiver, the computer in the receiver can calculate the position of the aircraft relative to the glide slope. If the receiver has knowledge of the range to touchdown then curved or offset approaches are possible. The range can be provided by a precision Distance Measuring Equipment (DME/P).

Experimental systems have been operating in the UK for several years, currently only one system is still in use. There are plans to introduce the system at major UK airports and procurement is under way.

Figure 3.1.1-16 MLS Azimuth Antenna

3.1.1.15.2 Transmitter Characteristics

The system operates on a $1/R^2$ law so the transmitter power required is low. The signals in space are fully defined in ICAO annex 10[13] which gives the parameters of representative systems as follows:

- Scanning Rate = 0.02 degrees per microsecond
- EIRP = 33.8 dBW @ 41.7 km (22.5 nm)
- Transmitter = 20 W

[13] ICAO Annex 10 Aeronautical Telecommunications Vol 1 5th Ed July 96 Table G-1 page 199.

3.1.1.15.3 Interference Considerations

MLS ground equipment essentially comprises just a transmitter and hence would generally be expected to be immune to interference However each MLS ground system is fitted with an executive monitor. This is a MLS receiver situated in the near field of the ground equipment. This receiver constantly measures the MLS beam and determines whether it is operating within its prescribed limits. Interference could cause this monitor to falsely conclude that the system has gone outside of the prescribed limits. This would result in the Built In Test Equipment (BITE) of the monitor producing an executive trip and the system will shut down. Such a shutdown could have severe consequences if it occurred during a landing under MLS control.

The airborne receiver however could be seriously affected by interference. The system is defined as safety critical particularly in the later stages of the landing where the pilot has committed to the landing. Interference could in principle cause the receiver in an aircraft to calculate the wrong position. However the system design is such, and is monitored, that it should not be able to provide a false guidance signal. Again however the system could shut down. The shut down of any part of the system during a landing could prove very hazardous. The frequency band used by MLS is also subject to special protection requirements under the ITU regulations.

3.1.1.16 Distance Measuring Equipment (DME)

3.1.1.16.1 Description

The Distance Measuring Equipment (DME) system is a transponder-based system used by an aircraft to measure the distance from a fixed point. The aircraft interrogates a ground station "transponder" that replies with a specified delay. By measuring the time of the received reply and knowing the delay, the distance to the transponder can be calculated. There are two types of DME, the normal DME/N and the precision DME/P[14].

Figure 3.1.1-17 DME display

3.1.1.16.2 Transmitter Characteristics

The DME system operates with Interrogation channels covering the band 1025 to 1150 MHz, the reply channels cover the band 962 to 1213 MHz. The system operates on a $1/R^2$ law so the transmitter power required is low. The signals in space are fully defined in ICAO

[14] ICAO Annex 10 definitions are:

DME/N - DME narrow

DME/P - DME precise

Annex 10[13]. The pulses used by the DME system are Gaussian in amplitude to reduce the necessary bandwidth these are specified in detail in ICAO Annex 10.

The characteristics of DME transmitters are shown in Table 3.1.1-16.

Table 3.1.1-16 DME Transmitter Characteristics

Parameter	Transponder	Interrogator
Tx Peak Power (W)	100 or 1000	700
Power Density (dBW/m^2)	-83	-100
Pulse Width (µs)	3.5	3.5
Rise Time (µs) DME/N DME/P	<3 <1.6	<3 <1.6
Fall Time (µs)	2.5	2.5
Spurious Emissions (dBm/kHz)	-40	
Inter Pulse Emissions (dB)	-50	-50
Harmonic Emissions (dBm EIRP)	10	
Frequency Accuracy (kHz)		+/- 100
Frequency Accuracy (%)	0.002	

3.1.1.16.3 Interference Considerations

Interference is likely to affect the receiver in the interrogator and could prevent the system from correctly measuring the distance. Less likely is the production of a false range. Measures have to be taken to prevent interference from co-located SSR systems affecting the DME.

The most critical period would be when the DME/P is being used with an MLS for an offset or curved landing approach. Like the MLS the DME/P has an executive monitor that could shut the system down. In the UK, the National Air Traffic Services (NATS) are not proposing to use the DME/P for offset landings. The DME/Ps in the UK are thus only used in an advisory role and have no safety classification.

3.1.1.17 Radars in the UK used for experimental purposes

3.1.1.17.1 Introduction

There are several non-military radars operating within the UK for various experimental purposes. They are associated with topics such as weather and rainfall measurements, atmospheric or astronomical observations. Many are funded by the various science research councils and are controlled by Universities.

Listed below are a selection of the larger systems:

3.1.1.17.2 Chilbolton Radar Facility

The Chilbolton radars are experimental in the sense that they are used for experimental measurements of propagation phenomena. The main facility is the 25 metre fully steerable paraboloidal antenna, which is used by the 3 GHz Doppler-Polarisation radar, Chilbolton Advanced Meteorological Radar (CAMRa). A 35 GHz radar, Rabelais, on loan from the University of Toulouse, is also mounted on the edge of the antenna, together with the 94 GHz Galileo radar, which is on loan from European Space Research and Technology Centre (ESTEC). These radars provide a powerful combination of instruments for studies of cloud and precipitation. Currently, a ceilometer, also on loan from ESTEC, provides further information on cloud structure.

The first S-Band ex-air surveillance radar was installed on the 25 metre antenna at Chilbolton for studies of precipitation and clear-air phenomena over 20 years ago. Since then, the original radar has been improved many times to measure new parameters. The current system and its capabilities are described below.

3.1.1.17.2.1 The CAMRa Radar System

The CAMRa operates at 3 GHz, where propagation effects are generally so small they can be neglected. At this frequency, the use of a large antenna provides the good sensitivity and high resolution needed for long range observations of precipitation. The majority of funding for the radar has come through the Radiocommunication Agency of the DTI, and is used for developing and testing propagation models for terrestrial and satellite communications systems design. A large meteorological radar is also sited at Chilbolton, where it is used for research into the measurement of rainfall and radio-wave propagation.

Figure 3.1.1-18 The CAMRa Radar Chilbolton

The parameters of the CAMRa radar are given in Table 3.1.1-17.

Table 3.1.1-17 The parameters of the CAMRa radar

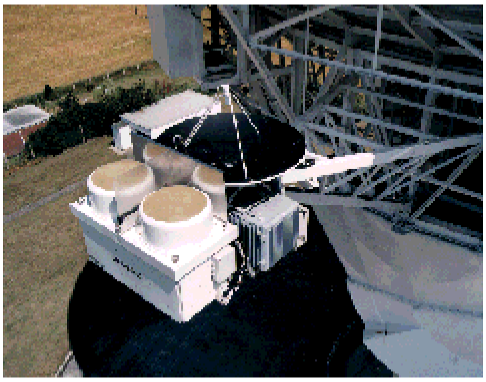
Frequency (GHz)	3.075
Power (kW)	600
Pulse Width (μs)	0.5
Repetition Rate (Hz)	610
System Noise Figure (dB)	1.3
Antenna Diameter (m)	25
Antenna Gain (dBi)[15]	56
Maximum Scanning Rate (degree per second)	1
Beamwidth @ 3 GHz (degree)	0.25

[15] Estimated from quoted beamwidth

3.1.1.17.2.2 Rabelais & Galileo

Research at the Chilbolten site makes use of other radars from time to time, for example, Figure 3.1.1-19 shows the 35 GHz Rabelais radar (on loan from the University of Toulouse) with its single, black surfaced dish, and the 94 GHz Galileo radar (on loan from ESTEC), contained in the white box with twin radomes.

Figure 3.1.1-19 Rabelais & Galileo



3.1.1.17.2.3 S-Band Experimental Low Power Weather Radar

An experimental low power weather radar has been installed at St Andrews University[16]. It operates at 3 kW peak power with a 2μs pulse and PRR of 2.5 kHz. The radar uses a 3m dish with a gain of 37dBi[17].

3.1.1.17.3 The UK Mesosphere, Stratosphere and Troposphere Radar (MST)

The MST is primarily a Wind Profiler measuring vertical profiles of the wind.

The UK MST Radar is situated at Capel Dewi near Aberystwyth in Wales. It was developed and is operated jointly by the University of Wales and the Rutherford Appleton Laboratory and is now funded by the UK Natural Environment Research Council (NERC).

The MST Radar measures horizontal and vertical wind velocities above the site, in the height range from 2 km to about 20 km. It can also receive daytime echoes from mesospheric heights between about 75 and 90 km.

The Radar is designed as a flexible research instrument. It operates at 46.5 MHz using the Doppler beam swinging method.

Figure 3.1.1-20 The UK MST Radar Capel Dewi

[16] IEE Colloquium Aviation Surveillance Systems 23rd Jan 2002 Page 6/1

[17] Estimated from antenna size.

3.1.1.17.4 Sweden And Britain Radar Experiment (SABRE)

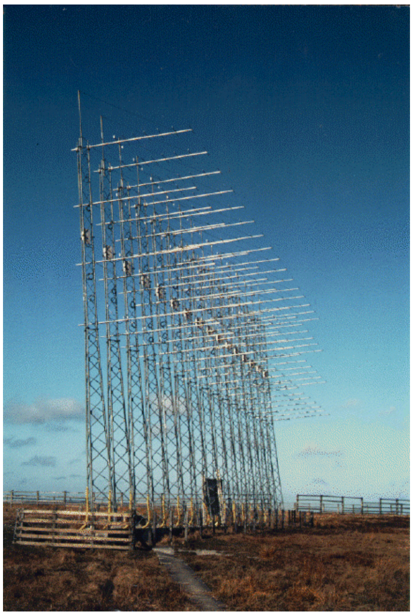
SABRE was a bistatic phased array radar. It was designed and built jointly by Leicester University, UK and the Max Planck Institut fur Aeronomie, Lindau, Germany. The two radars were located in Wick, Scotland and Uppsala, Sweden.

The amplitude and Doppler frequency shifts of the signals backscattered from the E-region radar aurora were measured. By combining the data from the two stations, the magnitude and direction of the current flow and electric field vector were determined.

The combined viewing area of the two radars was approximately 200,000 square km located in the sub-auroral region off the coast of Norway. The spatial resolution was about 20 km by 20 km. and data were normally recorded at 20 sec. resolution.

The Uppsala radar ceased operation on the 28th October 1986. The Wick radar ceased operation on the 31st of March 1994

Figure 3.1.1-21 SABRE Radar



3.1.1.17.5 Relocatable Auroral Polar Ionospheric Experimental Radar (RAPIER)

The RAPIER operates on a campaign basis at Wick when not required elsewhere. When operating at Wick data from this system is retrieved each day for processing at Leicester.

RAPIER is a development of the SABRE system intended to provide coherent radar measurements in a variety of high latitude locations. It consists of an eight-channel phased array radar operating at approx. 145 MHz.

The antenna array combines transmission with reception to provide a significant improvement over the ‘floodlight’ transmission employed in the SABRE radar. The total transmitted power is only a few hundred Watts as opposed to the 50 kW peak pulse power necessary in SABRE.

The system thus has only a single beam but this may be electronically steered to any direction. In normal operation the beam is swept through 8 beam directions to emulate the SABRE arrangement. Other modes of operation include a single beam with high temporal resolution and several combinations of 2 and 4 beams.

The complete system is thus much more compact and it is practical to operate in a campaign mode in different locations. Setting up the system requires 3-4 people and may be achieved in a few days.

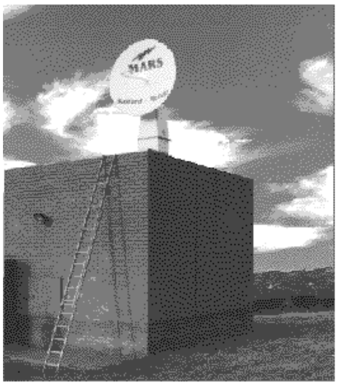
The system is controlled by a multi-processor computer system based on Motorola 68X00 processors in a VME rack. This provides considerable flexibility in operation.

3.1.1.17.6 Hydrological Radars (HYREX)

The HYREX was a UK Natural Environment Research Council (NERC) Special Topic which ran from May 1993 to April 1997. The broad aim of HYREX was to gain a better understanding of rainfall variability, as sensed by weather radar, and how this variability impacts on river flow at the catchment scale. Part of the study was to deploy at least two high resolution vertically pointing X-Band radars to obtain vertical reflectivity profiles of rainfall systems. Two X-Band radars were deployed in the Lake District.

This programme is now complete but it is typical of the smaller types of radars used for experimental purposes. Figure 3.1.1-23 below shows a C-Band Hydrological radar developed by Salford University.

Figure 3.1.1-22 C-Band Hydrological Radar



3.1.1.17.7 Pre-Operational European Mode S (POEMS)

The POEMS program, managed by UK NATS on behalf of Eurocontrol, is a research program for the implementation of Mode S SSR in Europe. There are three Mode S SSR stations in the UK taking part in this program, two in Southern England and one in the Midlands. The Mode S systems operate at a lower PRR than conventional MSSR but at a much increased duty cycle. Peak power and antenna parameters are identical to conventional MSSR systems.

POEMS, although experimental, is controlled by the UK SSR committee as are all SSRs in the UK.

3.1.1.18 A Short Résumé of Military Radar Use In The UK

3.1.1.18.1 Introduction

Radar use in the UK is split between the three services together with some experimental, test, measurement or training radars operated directly on behalf of the MoD.

3.1.1.18.2 The Army

The Army has several radar types in service, these are generally related to Weapon Location, Missile or Gun Control. Their use in peacetime is generally limited to training.

Figure 3.1.1-23 Portable Surveillance Radar Associated with a Missile Battery

3.1.1.18.3 The Royal Air Force (RAF)

3.1.1.18.3.1 RAF Ground Radars

The Royal Air Force are responsible for the Air Defence of the UK and for the Air Traffic Control of RAF aircraft flying outside of controlled airspace.

The ATC role of the RAF is very similar to that of the civil ATC authority. They use radars very similar in design to traditional Aeronautical Radio Navigation Service (ARNS) radars as described in section 3.1.1.8. The radars used however have extra facilities that are not used in peacetime. In peacetime these radars co-ordinate closely with the civil ATC authorities. The RAF also operate Precision Approach Radars (section 3.1.1.14) for the landing of aircraft. The Royal Navy and Army Air-Stations operate radars essentially the same as the RAF for these applications.

The RAF also operate the UK's Air-defence radars. These radars generally operate in the L or S-Band regions of the spectrum but are much larger and more powerful than the ATC types.

There are also radars that are associated with short-range air defence missiles used for the defence of airfields. These systems include both surveillance and tracking radars and are generally not used within the UK apart from training and trials.

The RAF also operates the large, UHF band, land based early warning radar at RAF Fylingdales.

Figure 3.1.1-24 Tactical Long-Range Air Defence Radar

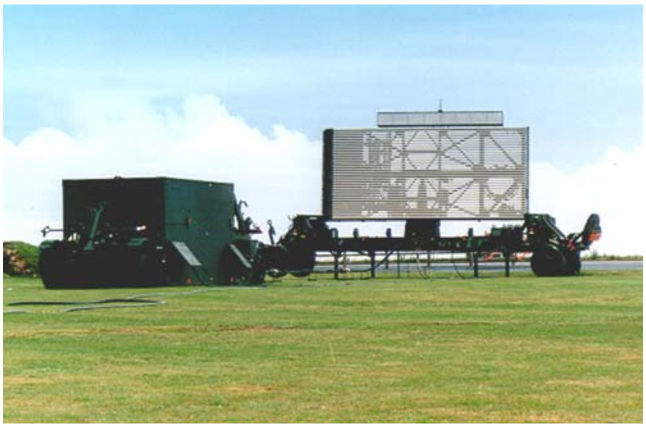


Figure 3.1.1-25 Tactical ATC Radar

3.1.1.18.3.2 RAF Airborne Radars

Airborne radars are used in several roles by the RAF, including:

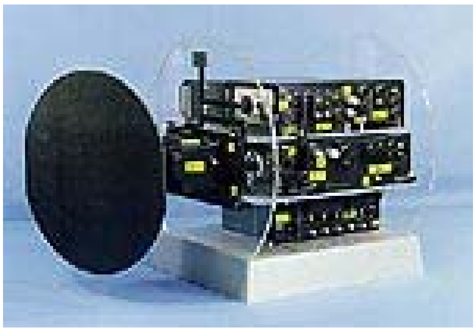
- Airborne Interceptor;
- Terrain Following;
- Airborne Early Warning (AEW);
- Maritime Surveillance;
- Battlefield Surveillance;
- Airborne Weather;
- Missile Approach Warning.

Figure 3.1.1-26 Airborne Stand-off Battlefield Radar

Most of the airborne radars operate towards the upper end of the spectrum with the exception of the AEW radar that operates around S-Band.

Some types of RAF air-launched missiles also use radars as part of their “seekers”; these are expendable radars which only operate for a matter of seconds.

Figure 3.1.1-27 Airborne Interceptor Radar



3.1.1.18.4 The Royal Navy (RN)

The Royal Navy operates radars on their ships, aircraft and on-shore establishments.

3.1.1.18.4.1 Ship-borne Radar

RN ships operate with both L and S-Band surveillance radars which are used to compile a recognised air picture. S-Band radars are also used for Transmission Identifiers (TI) and queuing and laying-on the missile tracking radars. The air surveillance radars can be of 2 or 3D types with scanning or fixed elevation beams. Tracking radars are used by both the area and point defence missile systems. Very Short Range Air Defence (VSORAD) systems consisting of rapid firing guns, also make use of autonomous tracking radars. The tracking radars tend to operate in X, Ku or Ka-Bands.

The RN also use traditional Maritime Surveillance radars for surface search and navigation. These types are generally very similar to SOLAS vessel radars.

Figure 3.1.1-28 RN Naval Surveillance Radars

The next generation of RN radars will be a single multifunction type carrying out many of the functions currently carried out by several radar types. The Type 45 Frigate shown below will be fitted with two multifunction radars.

Figure 3.1.1-29 Type 45 Frigate

3.1.1.18.4.2 RN Airborne Radars

Airborne radars are used by the RN in several roles, these include:

- Airborne Interceptor;
- Maritime Airborne Early Warning;
- Maritime Surveillance;
- Missile Approach Warning;
- Helicopter Beacons.

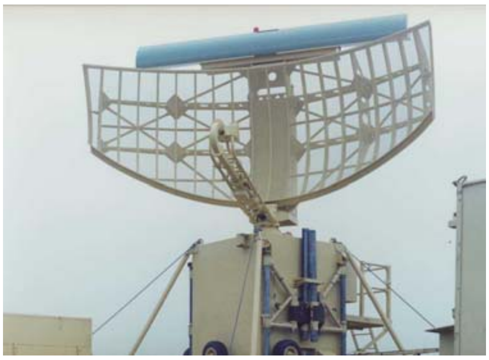
Figure 3.1.1-30 RN Naval AEW Helicopter

Figure 3.1.1-31 RN Naval Maritime Surveillance Helicopter

3.1.1.18.5 Military SSR/IFF Usage

The military operate both IFF[18] and SSR systems at various sites. Within the UK the use of IFF and SSR is co-ordinated in terms of allowable EIRP and available PRR by the UK SSR committee. The aim of this is to reduce the amount of unnecessary interrogations and to reduce transponder blocking and FRUIT. RN ships are fitted with SSR/IFF systems and some SORAD/VSORAD weapon systems for use on land and sea have IFF interrogators fitted.

Figure 3.1.1-32 Military Radar Fitted With IFF Interrogator "Hog-Trough" Antenna



3.1.1.18.6 The UK Ministry of Defence (MoD)

The UK MoD own/operate several radars either directly or by the use of third parties.

These include:

- Experimental Radars;
- Range Safety Radars;
- Range Tracking Radars;
- Training Radars;
- Reference sets;
- Measurement Radars.

An example shown in Figure 3.1.1-33 is the MESAR2 experimental radar operated by QinetiQ.

[18] Identification Friend or Foe - the Military equivalent of civil SSR.

The range safety radars are used to provide surveillance on military test ranges. These tend to be coastal radars very similar to civilian VTS systems. Some test ranges also have dedicated tracking radars to provide "ground truth" data for use in system trials.

Several MoD establishments have radar sets used for training operators and maintainers. There are several land based versions of RN systems used for this purpose.

Equipment Manufacturers are sometimes required by the MoD Procurement Executive to keep a reference set at their premises to support logistics and Post Design Services work. There are several of these systems in the UK.

There are also several measurement radars owned by, or operated by commercial establishments for the benefit of the MoD. These radars are typically used for target or clutter measurements.

Figure 3.1.1-33 Military Experimental Radar

3.1.1.19 Geographical Considerations of Radars within the UK

3.1.1.19.1 Introduction

The geographical distribution of Civil radars within the UK is not even; it varies greatly for the different functions of the radar. In order to get an idea of the geographical distribution, it is necessary to consider the radars by function.

3.1.1.19.2 Radars Associated with Airports, Airfields & ATC Activity

Airports and Military Airfields operate radars for the control of aircraft in the vicinity. The complexity and types of the radars depend on the type and amount of air-traffic. Some sites require more radar coverage than others. Military airfields are included in this appraisal because, in peacetime, they operate a pseudo-civilian function and co-operate with civil ATC authorities. The following radar types are associated with Airports and Airfields:

- Primary Surveillance Radar (PSR);
- Airport Surface Detection Equipment (ASDE);
- Secondary Surveillance Radars (SSR);
- Precision Approach Radar (PAR).

3.1.1.19.2.1 Primary Surveillance Radar

In the UK most of the civil regional airports have S-Band PSR coverage with a range of 60nm. Some of the airfields operate X-Band PSRs as well as, or instead of, the S-Band radars. These X-Band systems have a range of typically 30 nm.

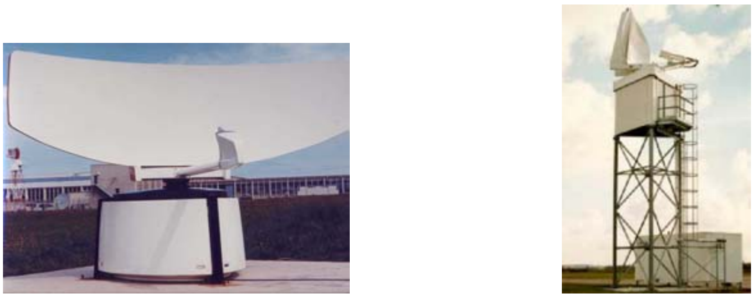
In the UK S-Band PSRs are the most numerous with the majority in the band 2.7 to 2.9 GHz. The paper "Capacity for Sharing in the 2.7 to 2.9 GHz Band (UK Data)"[19] discusses

[19] Conférence Européenne des Administrations des Postes et des Télécommunications (CEPT) SE34 Paper SE34(99)39

the distribution of S-Band systems in the UK. Many of the civil systems are located in Southern England, the Greater London area having a particularly high concentration with civil S-Band radars at Heathrow (2), Gatwick (2), Stansted, Luton, and Farnborough. The paper gives details of 10 S-Band radars (both civil and military) in the London area. There are 43 S-Band radars (civil & military) located in Southern England. There are 46 civil PSR airport radars in the UK.

Figure 3.1.1-34 below shows two typical examples of airport radars, one X and one S-Band.

Figure 3.1.1-34 Examples of Airport PSRs



Heathrow airport is unique in the UK in that it has an L-Band radar optimised for TerMinal Area (TMA) operations.

As well as covering TMA operations there are some S-Band sites providing cover out to the North Sea oil and gas rigs. These radars are optimised for helicopter detection.

As well as radars covering airfields there is also a network of radars covering Enroute traffic, into, over and out of the UK. These systems operate at a much longer range then the TMA radars, 200 nm rather than the 60 nm of TMA systems. These are L-Band radars and all have associated SSR radars. There are 9 L-Band Enroute radars covering the UK (another L-Band radar is configured for TMA operation at a UK Airport, and another one is used only for training purposes).

3.1.1.19.2.2 Airport Surface Detection Equipment

The larger airports associated with major cities also have ASDE. London Heathrow, Stansted and Edinburgh Airports have Ku-Band ASDE. Other airports, such as Gatwick & Birmingham International, have X-Band ASDE systems. There are a total of 8 ASDEs in the UK.

Figure 3.1.1-35 shows a typical X-Band ASDE scanner.

Figure 3.1.1-35 Raytheon X-Band ASDE open array scanner

3.1.1.19.2.3 Secondary Surveillance Radars

SSR is used in the UK for both airport and Enroute coverage. The SSR system can be either co-mounted with the primary radar or mounted on a separate tower. Figure 3.1.1-36 shows a typical co-mounted system.

Figure 3.1.1-36 Co-mounted PSR/SSR Raytheon ASR11

There are 31 fixed civil SSR systems in the UK network. These are split between Enroute type (15) and Airport type (16)[20]. In the UK the use of SSR is strictly controlled to prevent the generation of excess FRUIT. PRR's and transmitter power are allocated on a central basis.

3.1.1.19.3 Precision Approach Radar

Military airfields operated by the three services are generally equipped with S-Band PSR, some have also local SSR coverage. In the UK the use of PAR is restricted to military airfields only and little information is in the public domain. The U.K. MoD has recently placed an order for replacement PARs with ITT Gilfellan, their publicity states:

"The Modern active array, and fully solid-state radars will replace obsolete CR-62 PARs at Royal Air Force (RAF), Royal Navy (RN) and Defense Evaluation and Research Agency airfields in the UK....."

Figure 3.1.1-37 shows such a PAR installation.

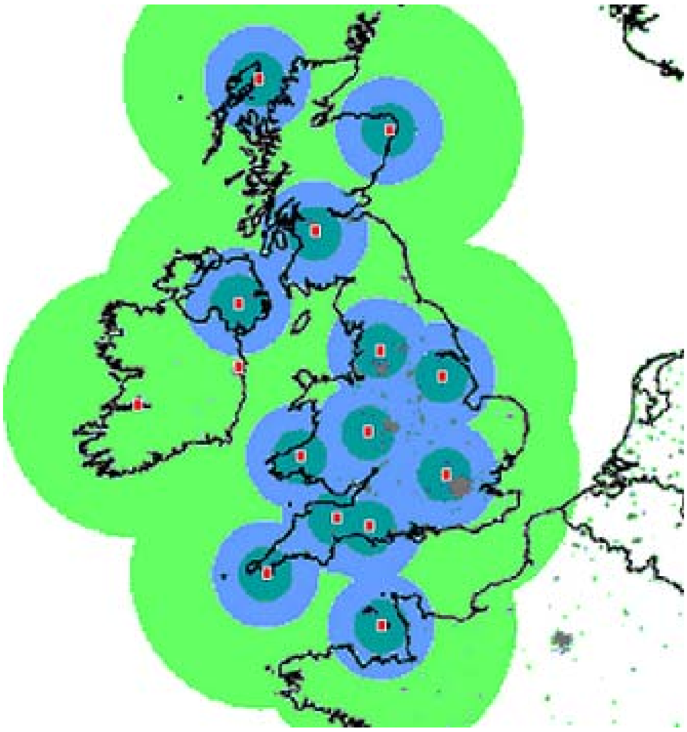
Figure 3.1.1-37 ITT Gilfellan PAR 2000

3.1.1.19.4 Meteorological Radar

The British Isles has a network of 15 C-Band radars providing weather prediction covering all the area and these are operated by the UK Met Office (12), Met Eireann (2) and the Jersey State (1), see Figure 3.1.1-38 (the different coloured areas indicate different data ranges (50, 100 and 200km) available from the individual sites). The UK Met Office also operate an experimental radar at their Bracknell research establishment. Figure 3.1.1-38 and Map 3.1.1-7 show the operational sites in the weather prediction network.

[20] See sections 3.1.1.17 and 3.1.1.18 for other applications in the experimental and military fields.

Figure 3.1.1-38 C-Band Weather Radars & Coverage on the British Isles [21]



The UK and Jersey weather radars operate at C-Band on a single frequency of 5.625 GHz.

There are discussions underway to possibly provide three more radars along the East Coast to augment the network.

Figure 3.1.1-39 45 C UK Weather Radar

[21] Picture from UK Met Office website - www.metoffice.gov.uk.

It has also been suggested that a special weather radar should be sited near London to provide high update rate weather data to the airports in the London area. A study[22] has been carried out into the parameters of such a radar. In order to reduce the interference potential, it is proposed to operate with a driven transmitter thus reducing its peak power and having more control over its spectrum. This radar would have the following parameters:

Frequency	C-Band
Peak Power	5 kW
PRR	1 kHz
Pulse Length	2 µs

3.1.1.19.5 Radars Associated with Ports & Harbours

Vessel Traffic Systems (VTS) radars cover many of the UK's ports, harbours and shipping lanes. They include Southampton Water, Dover, London, Liverpool, Milford Haven, Felixstowe and many more. They are operated by a mixture of Her Majesty's Coast Guard (Maritime and Coastguard Agency) (HMCG (MCA)) and local port authorities.

The radars used in these areas fall into three distinct types as discussed in sections 3.1.1.19.5.1 to 3.1.1.19.5.4 below.

3.1.1.19.5.1 Reflector Systems

The first type are large bespoke systems, fitted with large reflector antennas.

Figure 3.1.1-40 VTS Reflector Antenna

Figure 3.1.1-40 above shows a harbour radar fitted with an EASAT Systems antenna. These systems use antennas designed to provide inverse $Cosec^2$ coverage and direct energy preferentially towards the sea surface giving constant gain for targets on the sea surface.

3.1.1.19.5.2 Open Array Scanners

The smaller systems use modified marine radars with 8 foot, 13 foot or 22 foot slotted arrays. Figure 3.1.1-41 shows a TERMA installation with a slotted waveguide antenna.

22 IEE Colloqum on Aviation Surveillance Systems 23rd Jan 2002.

Figure 3.1.1-41 Slotted Waveguide VTS Installation

Generally these systems operate on a single frequency with transmitters in the range 25 to 30 kW, however proposals have been made to use frequency diversity systems operating on two frequencies.

It is estimated that there are 20 of the larger types (more than 12 foot) and 60 of the smaller types (less than 12 foot) in the UK distributed along the coast and at the major ports. The Port of London has four short range radars in the capital itself and others along the Thames and its estuary. Both X and S-Band systems are in use, however the X-Band are by far the more numerous.

3.1.1.19.5.3 VTS Marine Systems

The third type used are essentially simple marine radars mounted on a land site pole or building. These systems are associated with very small private ports, yacht havens, etc. It is not known how many of these types exist but several have been identified on the south coast. Figure 3.1.1-42 shows an example of the type of small radar scanner that is used.

Figure 3.1.1-42 Marine Navigational Radar 4 Foot Scanner

3.1.1.19.5.4 Range Safety Radars

The UK MoD (or in some cases, commercial organisations on the behalf of MoD) operate several coastal ranges, these are normally equipped with safety radars to ensure that vessels do not enter any danger areas. These radars generally operate at X-Band and have very similar performance figures to VTS systems.

3.1.1.19.5.5 Distribution of VTS systems

Table 3.1.1-18 gives a list of the VTS systems identified under this study.

Table 3.1.1-18 List of VTS Radars Systems [23]

Ref. no[24]	Port[25]	UK Grid	No of Scanners	Band	Coverage[26]	Notes
1	Aberdeen	NJ	1	NDA	NDA	There is a Navigation Control Service equipped with a surveillance radar which is operated 24 hours.
2	Avonmouth	ST	NDA	NDA	Steep Holm to Second Severn Crossing.	None
3	Belfast	N/A	2	X	Belfast inner and outer harbours and the greater part of Belfast Lough is under radar surveillance.	None
4	Bridgwater	ST	1	NDA	NDA	The Pilot Station is equipped with radar.
5	Bristol	ST	NDA	NDA	Radar surveillance is maintained from Second Severn Crossing to the Pilot Boarding Area N of Breaksea Light.	None
6	Clyde	NS	4	X	NDA	None
7	Douglas	SC	1	NDA	NDA	Maintained from radar on Douglas head.
8	Dover CMIS	TR	2	X	All channel Newhaven to Margate.	None
9	Dover Port	TR	3	S	NDA	None
10	Dover Port	TR	1	X	NDA	Back up.
11	Firth of Forth	NT	NDA	NDA	Radar surveillance is maintained throughout the area.	None
12	Fraserbrough	NJ	1	NDA	NDA	The port radar station will supply advice to vessels 24 hours when visibility is poor.
13	Harwich	TM	4	X	NDA	Radar advice is available on request.
14	Havengore Bridge	TQ	1	NDA	Radar surveillance is maintained while firing range is in use.	Range safety.
15	Holyhead	SH	3	X	NDA	None
16	Lerwick	HU	1	X	Radar coverage of the North entrance to South entrance and inner harbour.	None

[23] NDA = No Data Available

[24] The reference number is purely for identification purposes within this report.

[25] This list covers civilian ports only and those military facilities publicly listed in the open literature. In general military facilities such as test ranges are not listed.

[26] Admiralty List of Radio Signals Vol 6(1)

Ref. no[24]	Port[25]	UK Grid	No of Scanners	Band	Coverage[26]	Notes
17	Liverpool	SJ	4	X	NDA	None
18	London	TQ &TR	13	X	Radar assistance is available from Crayfordness to Greenwich. Radar assistance is available from Erith to seaward limits of the port of London.	None
19	Milford Haven	SM	2	NDA	Milford Haven port Authority operates a port control service which includes harbour surveillance covering Milford Haven up to the Cleddue Bridge and the seaward approaches for ranges upto 6 nm.	None
20	Peterhead	NK	NDA	NDA	NDA	Radar surveillance is maintained for the advice of shipping.
21	Portsmouth/ Southampton	SZ & SU	5	X	Radar coverage is from East Lepe Buoy, Western Solent to No Man's Land Fort, Eastern Solent. Also Portsmouth Harbour.	None
22	Scapa Flow	HY&ND	NDA	NDA	Radar surveillance is maintained over Scapa Flow and Pentland Firth.	None
23	Medway	TQ	2	X	NDA	Radar assistance is available on request
24	Sullom Voe	HU	NDA	S	Maintained in Yell Sound and Sullom Voe.	None
25	Tees	NZ	NDA	NDA	The port operations and information service which includes harbour surveillance radar covers the river Tees, Tees and Hartlepool Bays and approaches seawards for ranges up to 12 nm.	None
26	Tyne	NZ	1	NDA	NDA	None

The maximum concentration of VTS systems is in the part of the south and east coast running from the Solent through the Straits of Dover to the port of Felixstowe, including the port of London. The data indicates that there are at least 59 radar scanner associated with these systems. It is believed that approximately 6 are S-Band with the rest being X-Band.

It should be noted that the radars listed are those associated with the major UK ports. There may be some of the smaller marine type radars used in individual minor ports, mariners and sailing clubs. It has not proved possible to find a mechanism for identifying these.

3.1.1.19.6 Marine Navigational Radars

3.1.1.19.6.1 Introduction

These types of radars fall into several categories, many manufacturers refer to these types as follows: “Deep Sea (SOLAS)”, “Fishing”, and “Pleasure”. SOLAS vessels come under International Maritime Organisation (IMO) regulations and include all commercial sea going vessels of over 150 tons. Large ships operating in certain coastal areas are not covered by SOLAS but are regulated by local rules. The radars fitted to SOLAS ships have their number and performance controlled by international standards.

3.1.1.19.6.2 SOLAS Vessels[27]

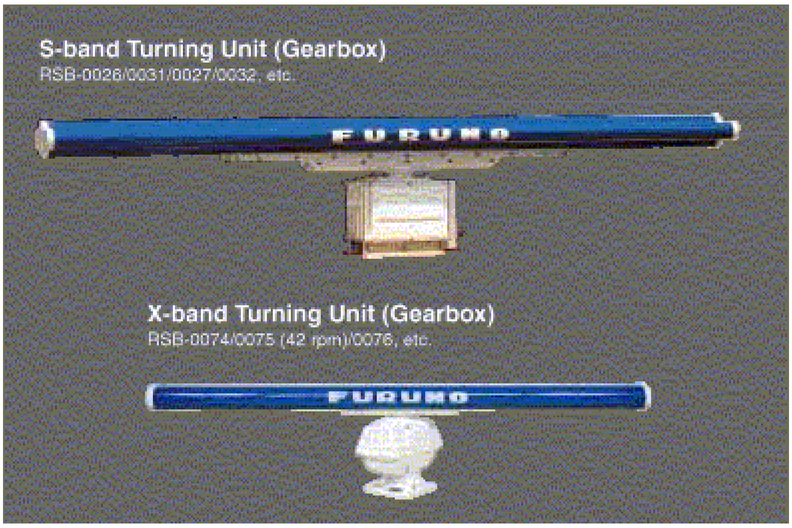
It is estimated that in UK waters there are about 1000 SOLAS type ships operating every day and each of these ships will be using radar. SOLAS ships over 10000 gross tons (or over 3000 gross tons if built after June 2002) are required to be fitted with two radars, larger vessels having S and X-Band radars, smaller vessels having two X-Band (for Ships using coastal waters, the use of the X-Band radar is more likely).

The MCA estimate that currently about 20% of SOLAS ships in UK waters need to be fitted with two radars. As it is common practice for ships to leave their radars operating all the time, the 1000 SOLAS vessels could be operating up to 1200 radars.

It is estimated that, at any one time, 80% of the SOLAS vessels in UK waters are in the Dover straits.

An example of a typical scanner fit for modern SOLAS ships is shown in Figure 3.1.1-43. Some very large ships also carry a third radar to cover the blind area in front of the bows that results when radars are mounted high-up close to the bridge. See Figure 3.1.1-44.

Figure 3.1.1-43 Example of a “SOLAS” Radar Fit



[27] SOLAS vessels are those covered by the Safety of Life at Sea regulations of the International Maritime Organisation

Figure 3.1.1-44 Typical two Radar Mounting SOLAS Ships

3.1.1.19.6.3 Fishing Vessels

Ships operating in UK coastal waters are not covered by SOLAS. They are however licensed by the Maritime and Coastguard Agency (MCA) and are required to carry radar very similar to SOLAS ships.

Unlike continental Europe, the UK has very little inland shipping traffic. However ships using waterways (i.e. Southampton Water, the Thames, the Mersey, and the Clyde) will be using their radars.

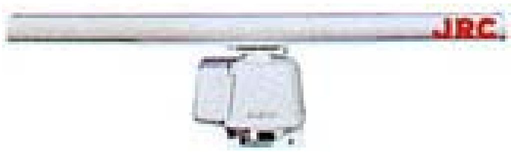
These are generally fitted with the medium to small marine radars depending on the size of vessel. Some of the larger vessels (greater than 150 tons) will be fitted with SOLAS radars. Table 3.1.1-19 gives the number of fishing vessels registered in the UK.

Table 3.1.1-19 UK Fishing Vessels

Registration	> 10 m	< 10 m
England, Wales & Northern Ireland	989	3056
Scotland	958	1622
UK Total	1947	4678

Figure 3.1.1-45 shows a medium size (7 foot scanner) that may be used on these types of vessels. These systems would be operating with transmitters of 6 to 25 kW for the smaller vessels, and possibly up to 50 kW for the bigger ships.

Figure 3.1.1-45 JRC 7 foot Scanner



3.1.1.19.6.4 Pleasure Craft

The coastguard does not license private pleasure craft, however there are codes of practice issued by the MCA. Pleasure craft used for commercial purposes (i.e. carrying passengers or leased) are controlled by MCA rules. Depending on their size, these craft may be required to have radar fitted. These radars would be of the smaller and less capable types than those used on SOLAS ships. Pleasure craft will almost certainly be fitted with X-Band radars. If they are carrying radar they must have a suitable radio licence.

These craft, when they have radars fitted, use the smaller lower power sets. The maximum concentration will be off the south and east coasts during the summer holiday period.

The smaller boats will have what are termed "Radome", these are small antennas mounted in radome enclosures to provide weather protection and to prevent the boats rigging from becoming snagged. These types of scanners vary between 1ft to 2ft in size and operate typically with powers of 1 to 4 kW. Figure 3.1.1-46 shows some examples of these types of scanners. Figure 3.1.1-47 shows a radome scanner installed on a yacht.

Figure 3.1.1-46 Examples of Radome Scanners used on Pleasure craft

Figure 3.1.1-47 Radar Scanner Fitted to a Yacht Mast

The larger pleasure craft will be fitted with "open array" scanners up to perhaps 4 foot to 6 foot as illustrated in Figure 3.1.1-48 below operating with powers in the range 6 to 12 kW.

Figure 3.1.1-48 Radar Scanner that may be used on a Larger Pleasure Craft

An unofficial estimate based on the manufacturers trade association BMF[28] and figures for world-wide use published by CIRM[29] is that in the UK there are between 50,000 & 100,000 pleasure craft fitted with radar of one type or another. Figure 3.1.1-49 illustrates the multiplicity of types in this class of radar.

[28] British Marine Federation

[29] Comité International Radio-Maritime

Figure 3.1.1-49 Multiplicity of radar types

3.1.1.19.6.5 Other Deployments of Marine Radars

There are maritime radars fitted on many land-based establishments such as training schools, colleges and universities. They are used for operator or servicing training, teaching or experimental purposes. These tend to be the lower cost/power versions.

3.1.1.19.7 RACONs, SARTS & Radar Target Enhancers

These devices are used in conjunction with Marine radars to enhance navigation or aid in search and rescue.

3.1.1.19.7.1 RACONs (**RA**dar Bea**CON**s)

These are fitted to navigation features such as Oil Rigs, Navigation buoys, Harbour entrances etc. In the UK they are controlled by Trinity House for England and Wales, and by the Commissioners of the Northern Lights in Scotland. These devices respond using a coded signal when illuminated by the radar. They come in either a swept frequency version or an agile version. The agile version is more modern and can detect the radar's specific frequency and replies accordingly. The swept version sweeps the whole of the allocated marine bands of 9.3 to 9.5 GHz and 2.9 to 3.1 GHz. There are approximately 100 RACONs situated around the UK. They are very low power devices. In terms of this report their only relevance is that currently Marine radars have to be designed to trigger RACONs, which limits the transmitted waveform and the frequency bands that may be used. This could affect the possible methods of mitigating the level of unwanted radar emissions.

With the introduction of Automatic Identification System (AIS), there is currently a debate as to whether RACONs could be replaced by AIS transponders operating at VHF frequencies and whether non-SOLAS radars should continue to have the requirements to trigger RACONs.

3.1.1.19.7.2 SARTS (Search and Rescue Transponders)

SARTS are carried on all SOLAS ships and used when the ship is in difficulty; they are hand held devices and can operate from lifeboats. The SART responds to the radar by producing a series of time delayed pulses, that produce a "line" of dots on the radar display indicating the bearing of the transponder. Geographically they can be used anywhere but their use is restricted to emergency use only. In terms of this report, their only relevance is that currently marine radars have to be designed to trigger SARTS and this limits the transmitted wave forms that may be used by the radar designer. This could affect the possible methods of mitigating the level of unwanted emissions.

3.1.1.19.7.3 Radar Target Enhancers

These are used to enhance the reflectivity of an object, however, unlike a conventional passive radar reflector these devices use an amplifier to enhance the reflected signal. These devices when triggered generate an EIRP of under 1 watt.

3.1.1.19.8 Airborne Weather Radar/Radio Altimeters

3.1.1.19.8.1 Introduction

Depending on the jurisdiction; aircraft have to be fitted with weather radar and altimeters. For all scheduled flights in the UK aircraft will be so fitted. Aircraft make use of weather radars to detect the presence of weather hazards such as storms, tornadoes, wind-shear and microbursts. Civil airliners are required to be fitted with weather radars. Some private or general aviation aircraft are also fitted.

3.1.1.19.8.2 Aircraft Movement Statistics

Table 3.1.1-20 through to Table 3.1.1-23 give statistics of aircraft movements over the UK handled by controllers at London (LATCC), Manchester, Scotland (SACC), and the Oceanic Air Control Centre (OACC).

Table 3.1.1-20 Movements handled by LATCC controllers

Year	1997	1998	1999	2000
Movements	1,631,064	1,747,290	1,870,475	1,913,730

Busiest Month: July 2000 - 185,537

Table 3.1.1-21 Movements handled by Manchester controllers

Year	1997	1998	1999	2000	2001
Movements	168,469	180,457	183,362	192,835	196,500

Busiest Day: 17 August 2001 - 706 movements

Table 3.1.1-22 Movements handled by SACC controllers

Year	1997	1998	1999	2000
Movements	439,820	467,763	489,253	483,314

Busiest Month: August 2000 - 47,816

Table 3.1.1-23 Movements handled by OACC controllers

Year	1997	1998	1999	2000
Movements	278,787	305,647	334,301	351,018

Busiest Month: July 2000 - 33,729

The total movements are given in Table 3.1.1-24. Some of these will be duplicated but the figures show the order of the number involved.

Table 3.1.1-24 Total UK Controlled airspace

Year	1997	1998	1999	2000
Movements	2,518,140	2,701,157	2,877,391	2,940,897

Thus on average (assuming 18 hours flying per day) this gives approximately 450 Flights/hour, however on busy days the peak could be as high as 1.5 times this figure. Thus as an estimate the maximum number of aircraft in controlled airspace at a given time could be 700. Most will have radio altimeters operating and the majority will also have weather radar operating.

These figures only cover controlled airspace. There are movements in non-controlled airspace and these are more likely to be general aviation aircraft.

3.1.1.19.9 Manufacturer's Test Facilities.

Radar equipment manufacturers normally have radar installations associated with their manufacturing, development or test facilities. The Following UK companies are known to operate radar systems at their sites:

- AMS
- BAE SYSTEMS Avionics
- Kelvin Hughes
- Thales
- Litton Marine
- Ray Marine

3.1.1.19.10 Summary

3.1.1.19.10.1 Totals of installed radars.

Table 3.1.1-25 below gives a summary of the number of fixed radars operating in the UK.

Table 3.1.1-25 Fixed Civil Radars operating in the UK [30]

Radar Type	Radar Band	Number[31]
SSR	L	31[32]
ATC	L	11
ATC	S	120[32,33]
ATC	X	9
ASDE	X	5
ASDE	Ku	3
Weather	C	13[32]

[30] Excludes test and development facilities

[31] Does not include military installations unless otherwise indicated

[32] Including installation(s) in the Channel Islands

[33] Number includes 84 Military S-Band radars (may not all be ATC) from information in the public domain

MLS	C	1[34]
PAR[34]	X	NDA
VTS	S	2 ports
VTS	X	11 ports
VTS	Unknown	13 ports

Table 3.1.1-26 gives a summary of mobile radars operating in the UK.

Table 3.1.1-26 Mobile Radars

Radar Type	Radar Band	Number
Airborne Weather	X	700[35]
Altimeters	C	700[35]
Pleasure	X	50-60,000
SOLAS[36]	X & S	1200
Fishing	X	6625

3.1.1.20 Frequency Reuse

3.1.1.20.1 Introduction

The concept of frequency reuse is based on the ability of two radar systems to operate co-channel; that is, on the same frequency. To operate in this manner the only methods available to reduce interference are to reduce the coupling between the systems, or to reduce the effect that the interference produces within the victim system.

In order to reduce the coupling, geographical separation, screening or other techniques must be adopted.

The distance required between two systems to operate in this way depends on several factors:

- The transmitter power and the gain of the antenna;
- The receiver sensitivity and gain of the antenna;
- The propagation loss:
    - The distance between the antennas;
    - Geographical and local screening;
    - Anomalous propagation issues.
- Receiver protection requirements.

In order to mitigate interference, if it is present, then the detailed effect the interference has on the radar must also be considered.

The ability to reuse frequencies depends a lot on whether the two systems are:

- Radars sharing with other services;

[34] Only used on military airfields, location not in public domain. NDA = No Data Available

[35] At a given time.

[36] Estimated per day

- Radars sharing with other radars;
- Radars sharing with other radars of the same type.

This section covers the conditions in the UK of frequency reuse between civilian radars.

3.1.1.20.2 Propagation Loss

One mechanism that makes frequency reuse possible is the propagation loss, this increases as the distance between the radars increases at a rate of $1/R^2$.

Consider two radars on the surface of the earth. Simple geometric considerations show that the distance to the horizon *d* for an antenna at height *h* above the sea level is approximately:

$$d = \sqrt{D \times h}$$ Equation 3.1.1-2

Where *D* is the Earth's effective diameter. The refraction of radar waves by the Earth's atmosphere makes the radar horizon somewhat longer than the normal optical horizon. The effective diameter is usually taken as 4/3 times the actual diameter for these purposes, although an approximation.

Thus the equation for *d* becomes:

$$d = 1.23h^{\frac{1}{2}}$$ Equation 3.1.1-3

where:

d	=	distance to horizon (nm)
h	=	height of antenna above sea level (feet)

or:

$$d = 4.1h^{\frac{1}{2}}$$ Equation 3.1.1-4

where:

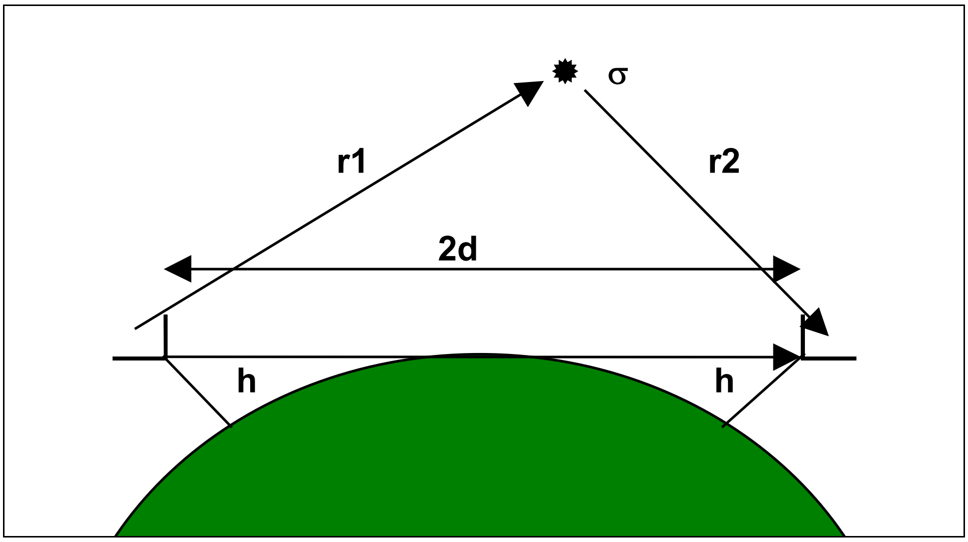
d	=	distance to horizon (km)
h	=	height of antenna above sea level (metres)

This is shown in Figure 3.1.1-50.

For antennas at the same height, the ground separation distance, *R , is approximately 2d*.

Thus for an antenna 12 m above the ground the distance to the horizon is 14.2 km. Thus for the second radar at the same height to be shadowed by the horizon, it needs to be at a distance of at least 28.4 km.

Figure 3.1.1-50 Coupling Between two Radars on the surface of the earth



The coupling between the two antennas falls with distance as *1/R²* *(*where *R is less than 2d)* up until the shadow point where *R equals 2d*. When *R is greater than 2d*, diffraction takes over and the coupling falls at a much faster rate with separation distance .

This approximation is for a "smooth earth" and is probably only valid over the sea. On land local topographical details provide much more local screening which tends to reduce the coupling.

There are however mechanisms that can increase the received signal over and above that which would be predicted using the approach above. For radars in line of sight of each other, then both multi-path and anoprop (anomalous propagation) can increase the level of receive signal. When the radars are shadowed by the horizon, anoprop alone can result in much higher received signal levels than is predicted from the simple diffraction approach.

There is however a further mechanism that can lead to interference between radars, this is the case when a target or clutter (i.e. hills, tall structures etc) are illuminated ("seen") by both radars at the same time, In this case the coupling is calculated by the following:

$$P_r = P_t G_1 G_2 \times \frac{\lambda^2 \sigma}{(4\pi)^3 r_1^{\,2} r_2^{\,2}}$$ Equation 3.1.1-5

where: P_r = Power Received

P_t = Power Transmitted

G_1&G_2 = the gains of the respective antennas

σ = Target Cross section in m^2

This compares to the line of sight free space coupling given by the Friis transmission equation.

$$P_r = P_t G_1 G_2 \times \frac{\lambda^2}{(4\pi)^2 (2d)^2}$$ Equation 3.1.1-6

In the limit when the target is close to the horizon:

$$r_1 \,\&\, r_2 \to d$$ Equation 3.1.1-7

and hence the coupling from the target scattering reduces to:

$$P_r = P_t G_1 G_2 \times \frac{\lambda^2 \sigma}{(4\pi)^3 d^4}$$ Equation 3.1.1-8

This form of coupling is much lower than the direct coupling as it contains an extra factor of :

$$\frac{\sigma}{\pi d^2}$$ Equation 3.1.1-9

which reduces as $1/d^2$.

Generally the interference from this type of coupling is not considered as significant a problem as direct coupling.

The equations above both contain terms related to the antenna gain of the transmitting and receiving antennas. The antenna gain is greatest in the main beam region so the highest coupling occurs when the two main beams intersect. Lesser coupling (≈ -30 to -40 dB) occurs for main beam to sidelobes and even less (≈ -60 to -80 dB) for sidelobe to sidelobe coupling. For line of sight coupling the period for which main beam coupling occurs and the repetition rate depends on the relative rotation rate of the two radars and how stable it is. In general systems do not have accurately controlled rotation speeds and the period of main beam coupling varies with time as the two rotation rates "beat" together. In the case of the two beams intersecting there also has to be a target or mutually visible clutter present in the zone of intersection. This further reduces the likely hood of interference.

3.1.1.20.2.1 Further Predictions of Propagation Loss

As has been shown, in order to calculate the propagation loss between two radars (path loss), several methods could be applied. The simple line of sight case[37] based on the Friis transmission equation given previously, or smooth earth analysis based on diffraction over the horizon are two options. These are simple models and take no account of multi-path, topographical screening or anoprop. In some models an extra 6 dB upgrade for multi-path is also included, and other more complicated models attempt to model other effects as well.

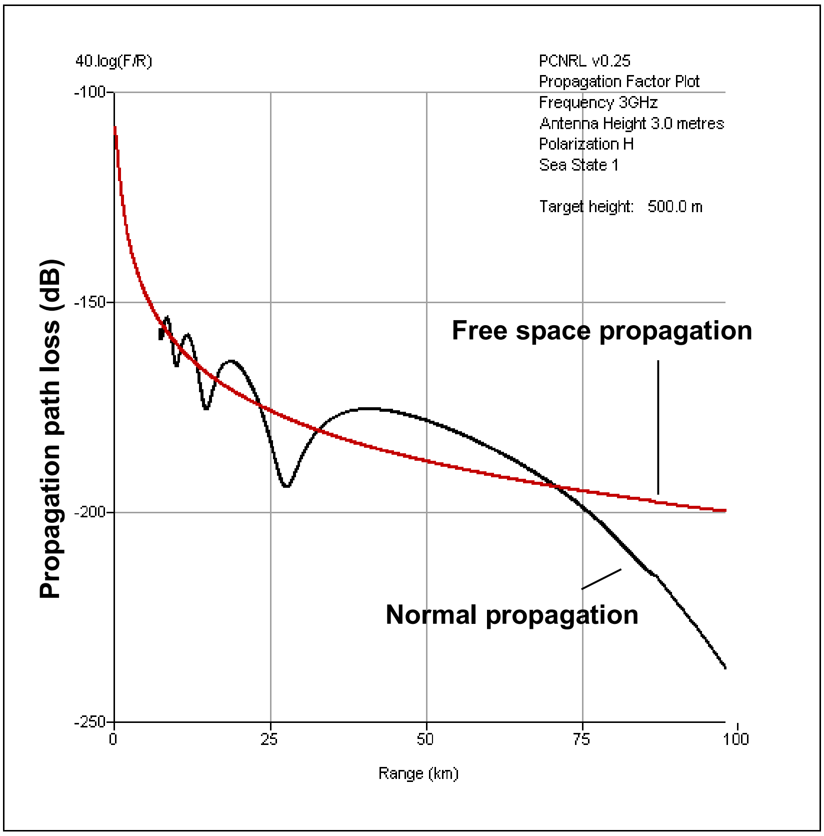
Figure 3.1.1-51 shows the output of a model, which uses a spherical earth with an allowance for multi-path. Anoprop can be included but is not used in this example. So in this case, the model is set to a standard atmosphere (4/3 earth). The two-way path loss is calculated as a function of range for a ground antenna 3 m above the ground and an air target at 500m[38]. The effect of the multi-path term can be seen in the ripples on the normal propagation curve[39]. This is the coherent sum of the direct path and the reflected path.

[37] A line of sight calculation with a 12 dB multi-path uplift which takes no account of horizon screening is probably a "worst" case approximation.

[38] The loss is the two way loss seen by a radar hence falls off as $1/R^4$.

[39] In radar terms this is referred to as lobing.

Figure 3.1.1-51 Example Output from a Radar Propagation Loss Model



Some workers in the field have suggested that the propagation path loss used to account for interference between radars is calculated as described in ITU-Recommendation P.452-8[40]. This model allows the path loss to be calculated between two points on the surface of the earth, taking into account all the mechanisms that are known to contribute to the propagation of RF signals.

This is essentially the generalised Friis equation with the path loss factor calculated using a statistical variable. The interference model invoked in document ITU-R Recommendation P.452-8 involves several distinct elements:

- It applies to radio frequencies in the range 0.7 to 30 GHz;
- It applies to time percentages in the range 50% and below; i.e. is aimed specifically at normal-to-interference type conditions, rather than reliability planning;
- It includes propagation models for several different modes of propagation:
    - Line-of-sight;
    - Diffraction;
    - Ducting and other anomalous propagation modes;
    - Troposcatter.

Which of these modes is important will vary, depending on the radio path length and the time percentage of interest. The dominance of one mechanism over the other depends on the time of year, day, climate, radio frequency, time percentage of interest, distance and path topology. At any given time, one or more mechanisms may be present.

[40] ITU-R Recommendation P.452-8, Prediction Procedure for the Evaluation of Microwave Interference between Stations on the Surface of the Earth at Frequencies above about 0.7 GHz.

The model was initially designed to allow the likely levels of interference signal between satellite earth stations and microwave links to be calculated on the basis of a time period over which a specific interference level will exist. It makes use of a geographical description of the transmission path to calculate points of diffraction, shadowing etc. It is not clear how representative it is for short-range propagation, where the fine detail of the topographical data, such as the position of specific buildings, could have a major influence.

The ITU-R Recommendation P.452-8 model considers two classes of interference:

- Long term interference;
- Short term interference.

Long term interference is caused by mechanisms that are essentially time invariant and consists of:

- Line of sight;
- Multi-path;[41]
- Diffraction;
- Troposcatter.[42]

Short term interference is caused by mechanisms that are highly time and weather dependent. The propagation path is generally caused by changes to the refractive index profile of the atmosphere due to temperature and water vapour effects. Mechanisms include:

- Multi-path;
- Ducting and other anomalous propagation modes;
- Elevated Layer reflection/refraction;
- Hydrometer scatter.

The model also predicts on the basis of interference that exists above a given level for a given period of time. For sources relatively close to the radars then this interference is likely to be very long lived. The model, however, does not predict what the peak level of interference could be and, for short periods of time, the interference could substantially exceed the levels predicted.

In predicting the effect that any interference may have on a radar and how critical it may be, many factors must be considered, these include:

- The level of the interference;
- The spectral & temporal nature of the interfering signal;
- The type of radar receiver;
- The type of radar signal processing;
- The type of radar display;
- The role of the radar.

It is thus very likely that interference considerations must be made on a radar by radar basis. There is no generic solutions both in terms of coupling between radars and the effect on individual installations.

[41] The long or short-term dependence of multi-path depends critically on the site topology.

[42] Generally only applies to high gain antennas at ranges >100 to 150 km.

3.1.1.20.3 Frequency Reuse Considerations for Civil systems in the UK

3.1.1.20.3.1 L-Band ATC

Frequency reuse is employed on only four civil frequency assignments in the UK. Four radar sites use two of the frequency assignments and three of these four use the further two assignments. Typically the antennas for these systems are mounted about 25 m above the ground which would give a maximum line of sight distance of typically 41 km. Currently the shortest frequency reuse distance between operational sites is 224 km but in this case the two systems use very different pulse patterns. For frequency reuse between two radars of the same model, 533 km is the closest distance currently used for the L-Band assignments.

3.1.1.20.3.2 S-Band ATC

Of the fixed radars within the UK, there are more S-Band ATC (ARNS) than any other type, both civil and military, and there are also military radiolocation radars. Of the civil S-Band assignments, 13 are reused by a maximum of 6 radars. It is not known how many assignments are reused with military radars. The closest spacing between civil radars is 70 km. This spacing is only possible when terrain screening allows, the typical reuse distance is much further. This issue is discussed in SE 34 paper [43].

3.1.1.20.3.3 X-Band ATC /ASDE

There are 11 X-Band assignments in the UK and of these eleven 7 are reused. The X-Band radars fall into two basic types airfield radars (ATC), and surface movement (ASDE) radars. The airport radar antennas are generally mounted close to the ground (approximately 2m) and have very good terrain screening. The ASDE radars are mounted much higher in order to get a good view of surface movement on the airport. Of the four X-Band ASDEs in the UK, three have the same frequency assignments. The closest spacing is 54 km for ASDE radars and 122 km for ATC types. Of the other assignments the shortest frequency reuse distance is 54 km.

3.1.1.20.3.4 PAR Radars

No details are available about the frequency reuse of the military PAR radars. However PAR radars operate on relatively low power over a short range. They are mounted close to the ground so will have good geographical screening.

3.1.1.20.3.5 Ku-Band ASDE

Ku-Band radars of this type are generally mounted high up in order to view the surface of the airport. The three Ku-Band ADSE radars in the UK all operate on the same frequencies and the closest distance between any two is 70 km.

3.1.1.20.3.6 C-Band Ground Based Weather Radars

All the ground based weather radars in the UK operate on the same frequency of 5.625 GHz. The shortest frequency reuse distance is approximately 50 km. In this case the radars are not in line of sight and there is high ground between the two radar sites.

3.1.1.20.3.7 X-Band VTS Radars

The majority of VTS radars in the UK operate on 9.375 and 9.465 GHz. The reuse distances can be very short (in the order of a few kilometres). Sector blanking is employed in these radars that have overlapping coverage.

3.1.1.20.3.8 Mobile Radars

The majority of civil mobile radars are maritime or airborne weather radar. In the case of these types it is not possible to plan frequency assignments to prevent co-channel operation. The problem is further compounded by the fact that the majority of mobile radars used in the UK have a very limited choice of operating frequencies.

[43] CEPT Spectrum Working Group SE34 (99) 39 Capacity for sharing in the 2.7 to 2.9 GHz Band (UK Data).

3.1.1.20.3.8.1 Maritime Radars

Table 3.1.1-27 gives the operating frequencies published by a selection of maritime radar manufacturers.

Table 3.1.1-27 Published Operational Frequencies of Maritime Radars

Manufacturer	9410 +/- 30MHz	9445 +/- 30 MHz	9415+/-30 MHz	3050+/-10MHz
Kelvin Hughes	✓			✓
JRC		✓		
Raymarine	✓			
Furuno	✓		✓	✓
Koden	✓	✓		
Si-Tex	✓	✓		
Raytheon		✓		
Anritsu	✓			

Other maritime radar manufacturers who do not publicly publish data operate on similar frequencies. One manufacturer offers a range of 9170 to 9490 MHz and standard frequencies of 9410 and 9375 MHz. Two frequency diversity systems, used to improve clutter cancellation, are also offered on more sophisticated systems.

3.1.1.20.3.8.2 Airborne Weather Radars

Table 3.1.1-28 shows the published operational frequencies of airborne weather radars.

Table 3.1.1-28 Published Airborne Weather Radar Frequencies

Manufacturer	Frequency
Bendix/King	9345+/- 30 MHz
Honeywell	9345 MHz
Rockwell Collins	9330 MHz
Telephonics[44]	9375 MHz

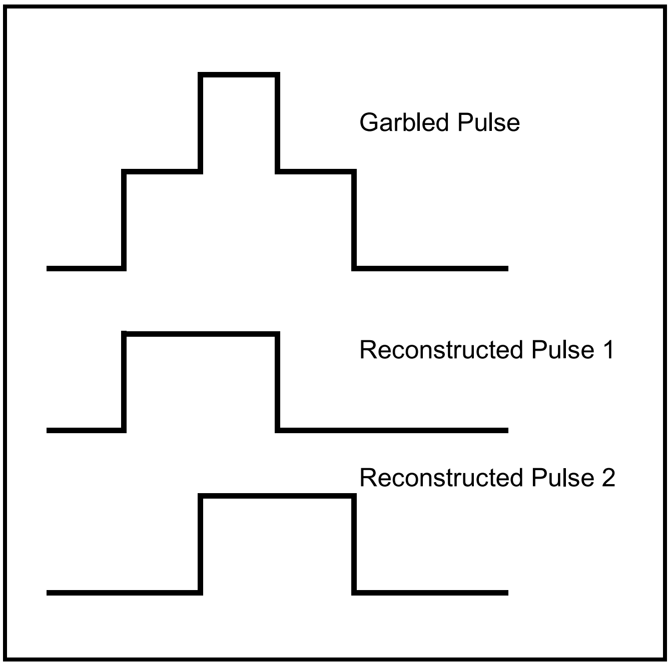
3.1.1.20.3.9 SSR Radars

SSR radars are a supreme example of frequency reuse, as all systems transmit (i.e. interrogate transponders) and receive replies from transponders on the same pair of frequencies. Because the SSR interrogator system transmits and receives on a different frequency, direct coupling between systems is not a cause of interference. The main cause of SSR interference is what is known as False Replies Unsynchronised In Time (FRUIT). FRUIT are replies received at an interrogator that are initiated by interrogations from other sites. SSR systems are designed to operate in the FRUIT environment and defruiting techniques are used to mitigate the effects of such interference. Defruiting involves removing replies that do not correlate with the PRR of the interrogator. Another significant cause of SSR interference is 'garbling'. Garble results from two transponders within an antenna beamwidth replying to the same interrogator, if the aircraft are close in range then the replies can overlap or "Garble". Degarbling involves "unscrambling" two or more overlapping replies.

[44] Military/Paramilitary System

These techniques are facilitated within the SSR by prior knowledge of the form of the interfering signal. This allows decisions to be made as to the presence of a garbled pulse and promotes the ability to disentangle the same types of overlapping replies. The SSR also has the ability to reconstruct pulses as information is contained only in the position of the pulses, not the pulse shape. This means that replies can be reconstructed from detection of leading edges. Figure 3.1.1-52 below illustrates this feature, in this the presence of the leading edges can be used to reconstruct two pulses from a garbled pulse.

Figure 3.1.1-52 Reconstructing garbled pulse



Monopulse SSR systems also have the ability to use angle discrimination to aid the degarbling. The received garbled pulses are sampled at a high data rate and monopulse bearing information is assigned to each of the samples. This anglular information can then be used to assign pulses to different bearings and hence degarble the pulses.

The ability to successfully defruit depends on how much FRUIT exists in the environment. Some specifications require the system to cope with FRUIT rates of up to 10,000 F/sec into the antenna main beam whilst still maintaining a low false detection rate.

Many SSR systems also use tracking to aid degarbling and reflection suppression. This can also be used to facilitate code repair on replies that cannot be successfully degarbled. Tracking can also be used to suppress interference that is not rejected by the defruiter by not outputting un-confirmed detections. This technique reduces the Pd of the SSR. SSR systems are, however, generally specified to achieve a very high Pd (of the order of greater than 95% in a mixed environment).

As a further measure within the UK, the use of SSR is controlled by the UK SSR committee that allocates operational parameters such as maximum transmitter powers and PRRs.

3.1.1.20.4 Methods to Improve Frequency Re-use

There are several strategies that can be adopted to decrease the reuse distance between radars these include:

- PRR Jitter
- Cross Polarisation
- Sector Blanking
- Synchronising Rotation
- Orthogonal Sweeps

3.1.1.20.4.1 PRR Jitter

By jittering or using different PRRs, the interfering signal will not correlate with wanted replies. Interference will thus tend to be suppressed.

3.1.1.20.4.2 Cross Polarisation

If radars are operated with orthogonal polarisation, then direct interference between main beams will be reduced by between 10 and 20 dB. Because cross polar sidelobes tend to be of the same order as co-polar, then main-beam to side-lobe and side-lobe to side-lobe interference will be substantially unaffected by using orthogonal polarisation.

3.1.1.20.4.3 Sector Blanking

If radars can be sector blanked in the direction of other radars, then coupling will be reduced. However each radar will have a blind arc over the blanked sector. Networking of the radars could help to facilitate this blanking by filling in the areas of missing coverage where the sectors overlap.

3.1.1.20.4.4 Synchronising Rotation

If the rotation rate of radars can be "locked" together such that they never both "look" directly at each other at the same time, then only main beam to sidelobe coupling would have to be considered. This will reduce the effect of interference considerably by about 30 dB.

3.1.1.20.4.5 Orthogonal Sweeps

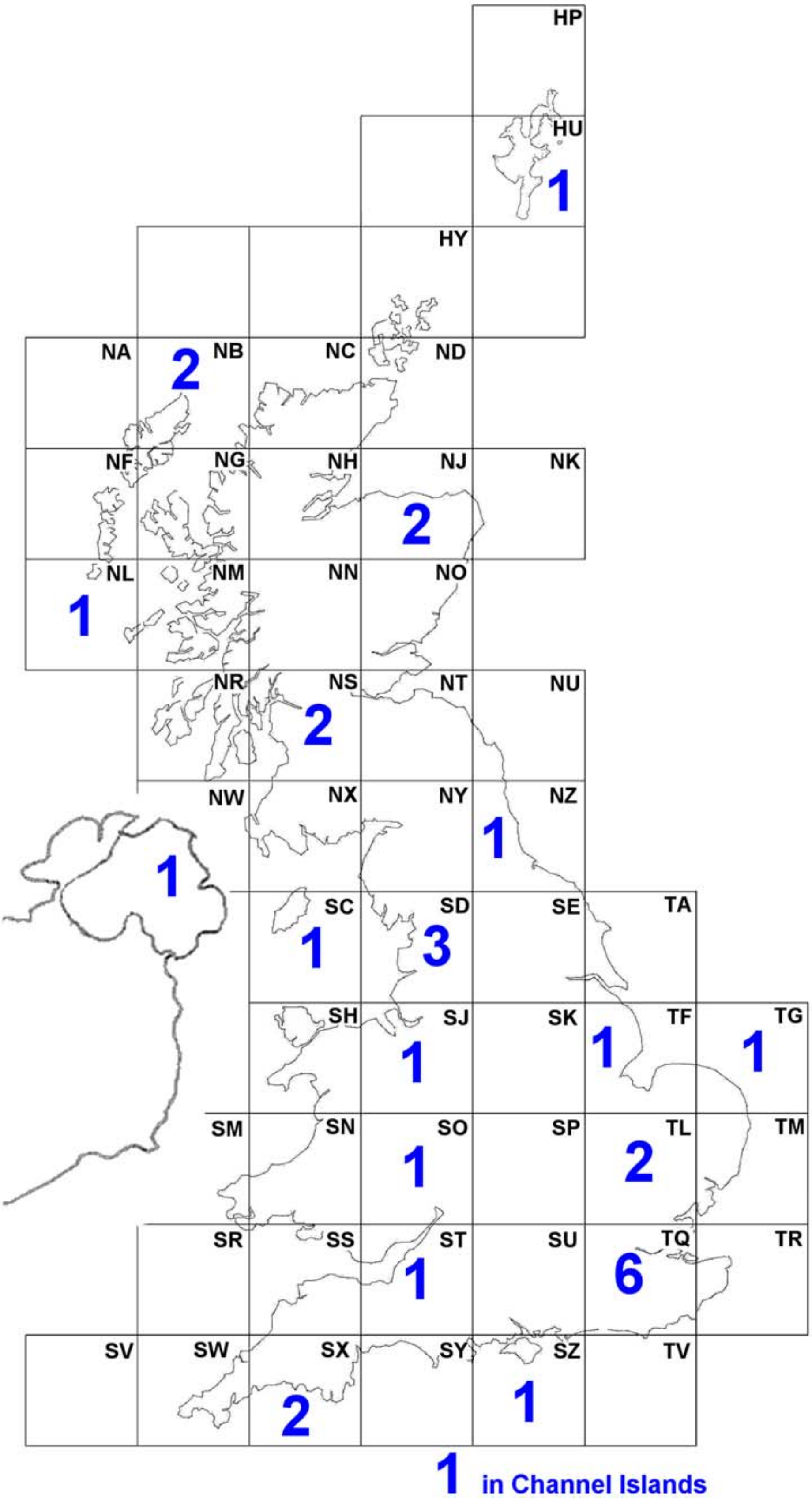
In a pulse compression system one method that has been proposed to reduce interference is to reverse the pulse compression sweep on adjacent radars. This results in the interference signal being further expanded or "spread out" on reception, as opposed to being compressed. In system terms, this would spread the interference over twice as many range cells, but at half the power level per range cell. Depending on the level of the interference, this could be considered a worse form of interference. However if combined with other measures which have already substantially reduced the interference then, it could provide the extra attenuation needed to reduce the interference to an acceptable level.

3.1.1.21 Maps of UK radar distribution

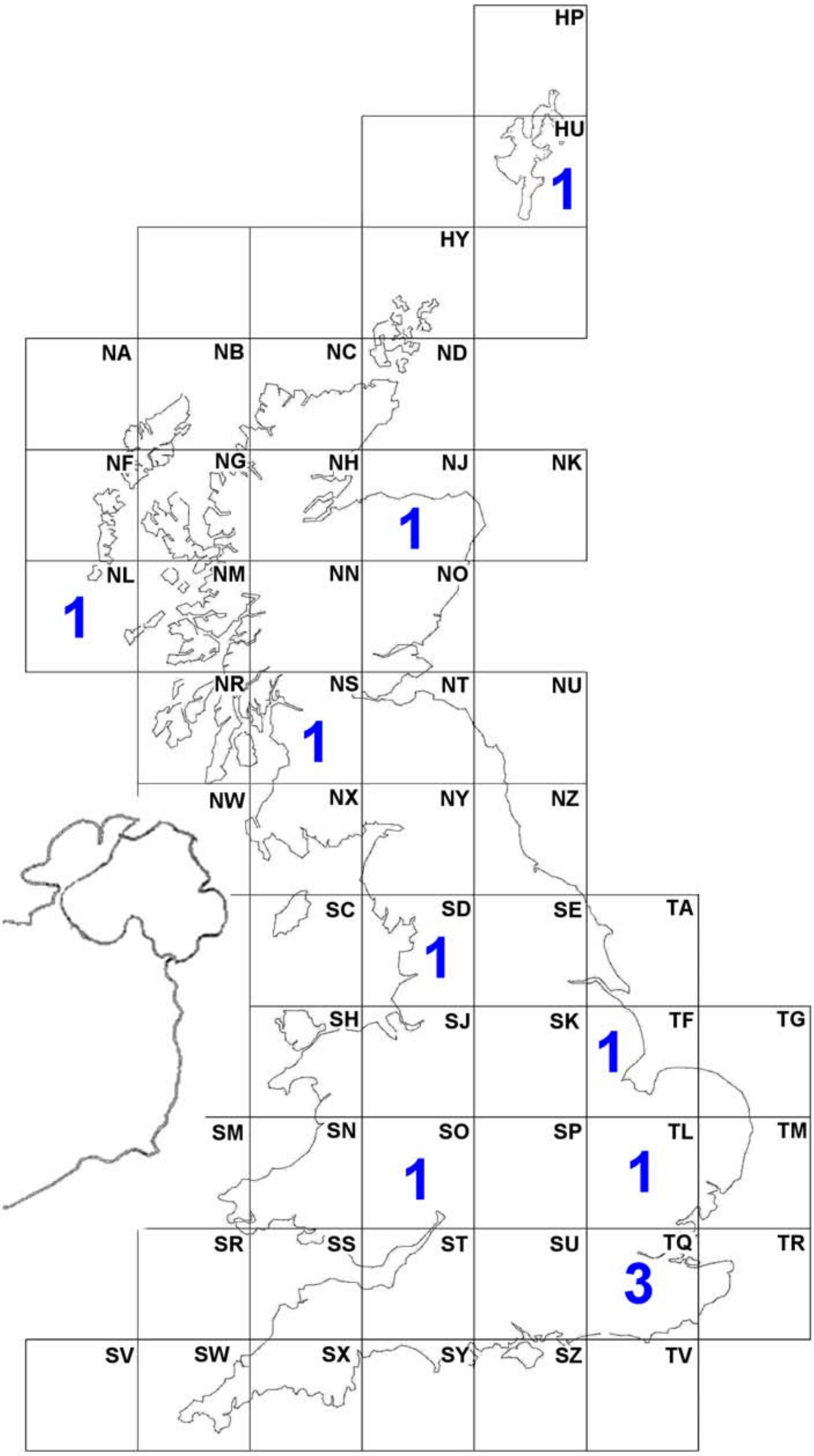
The following maps give the distribution of fixed civil radars operating in the UK.

These maps exclude military systems (except where indicated), experimental, training and development systems.

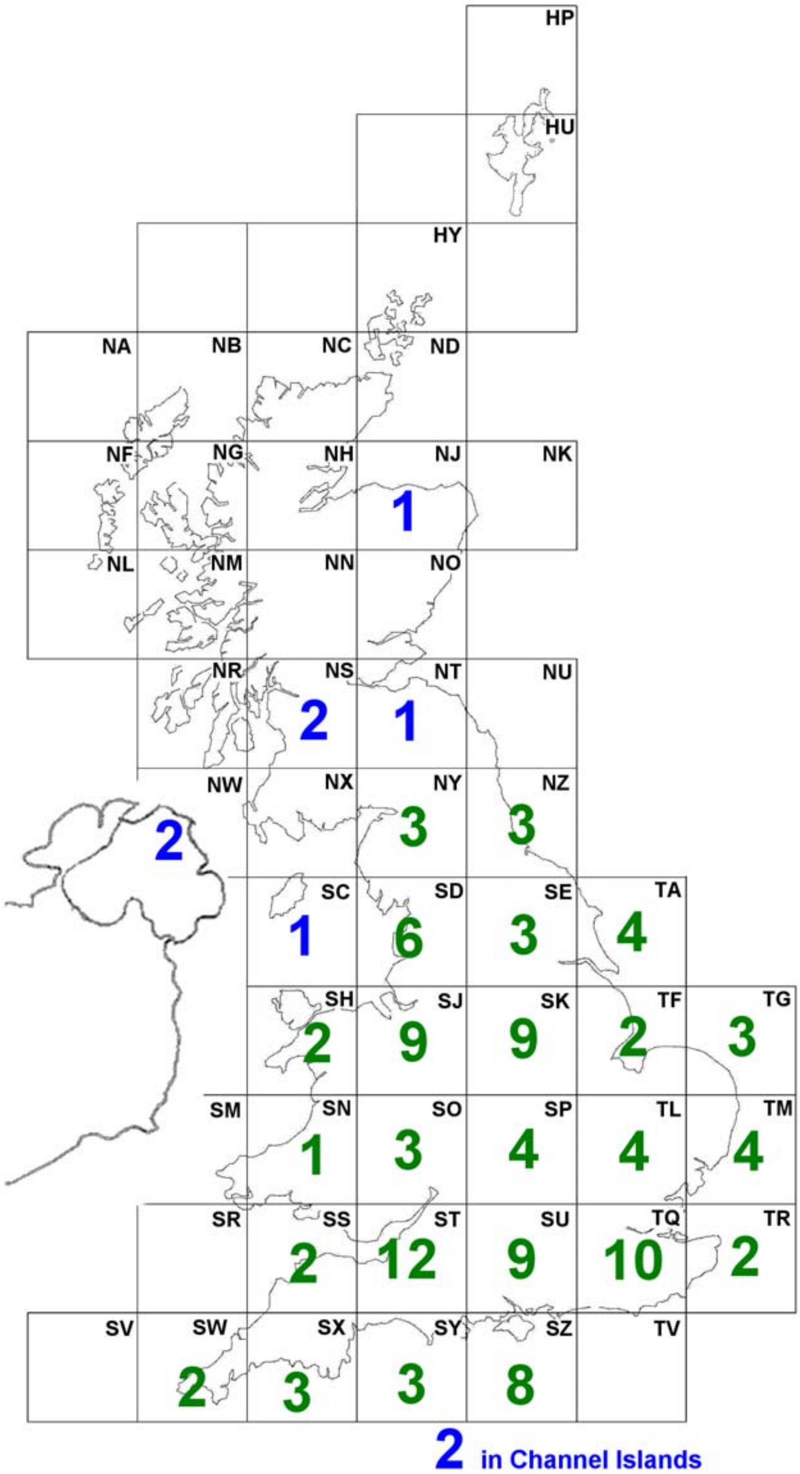
Map 3.1.1-1 Civil SSR Systems



Map 3.1.1-2 Civil L-Band 23 cm Systems



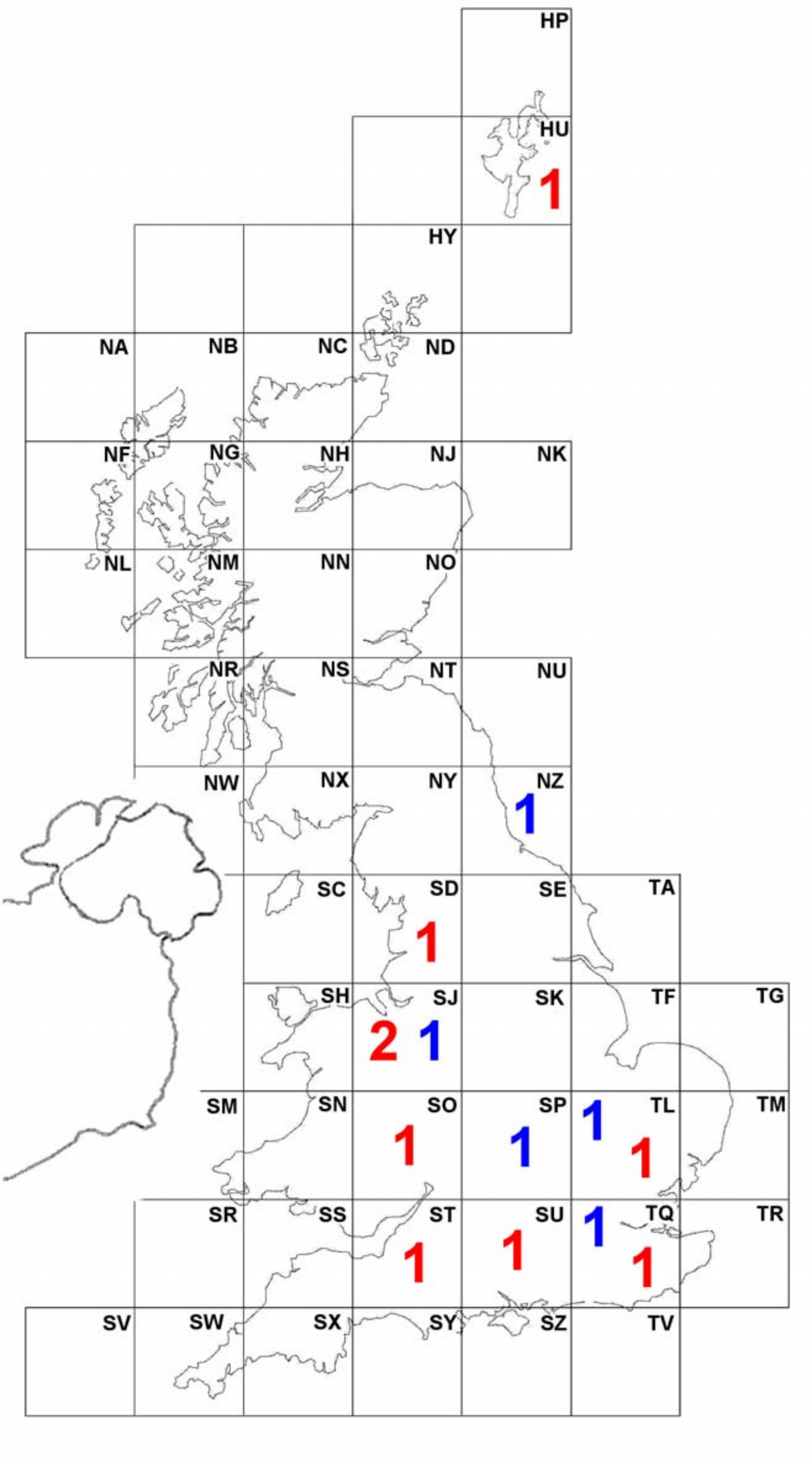
Map 3.1.1-3 S-Band 10 cm Systems



Blue - Civil ATC outside of England and Wales.

Green - Civil and Military Radars (This combined information covering England and Wales is in the public domain[43]. No Military radars are indicated outside of these areas, however this does not convey that such radars don't exist, only that such information is not available.)

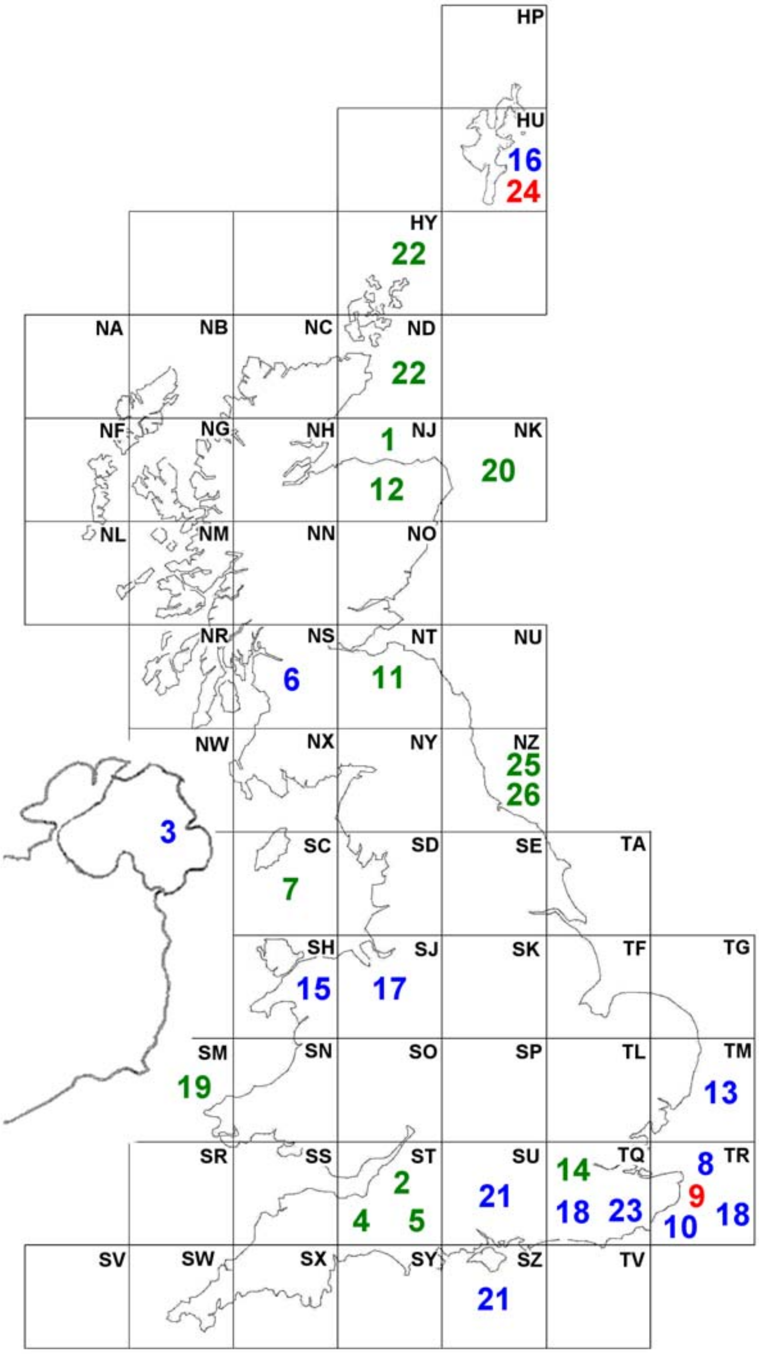
Map 3.1.1-4 X-Band ARNS 3 cm Systems



Red - ATC

Blue - ASDE

Map 3.1.1-5 VTS System Areas



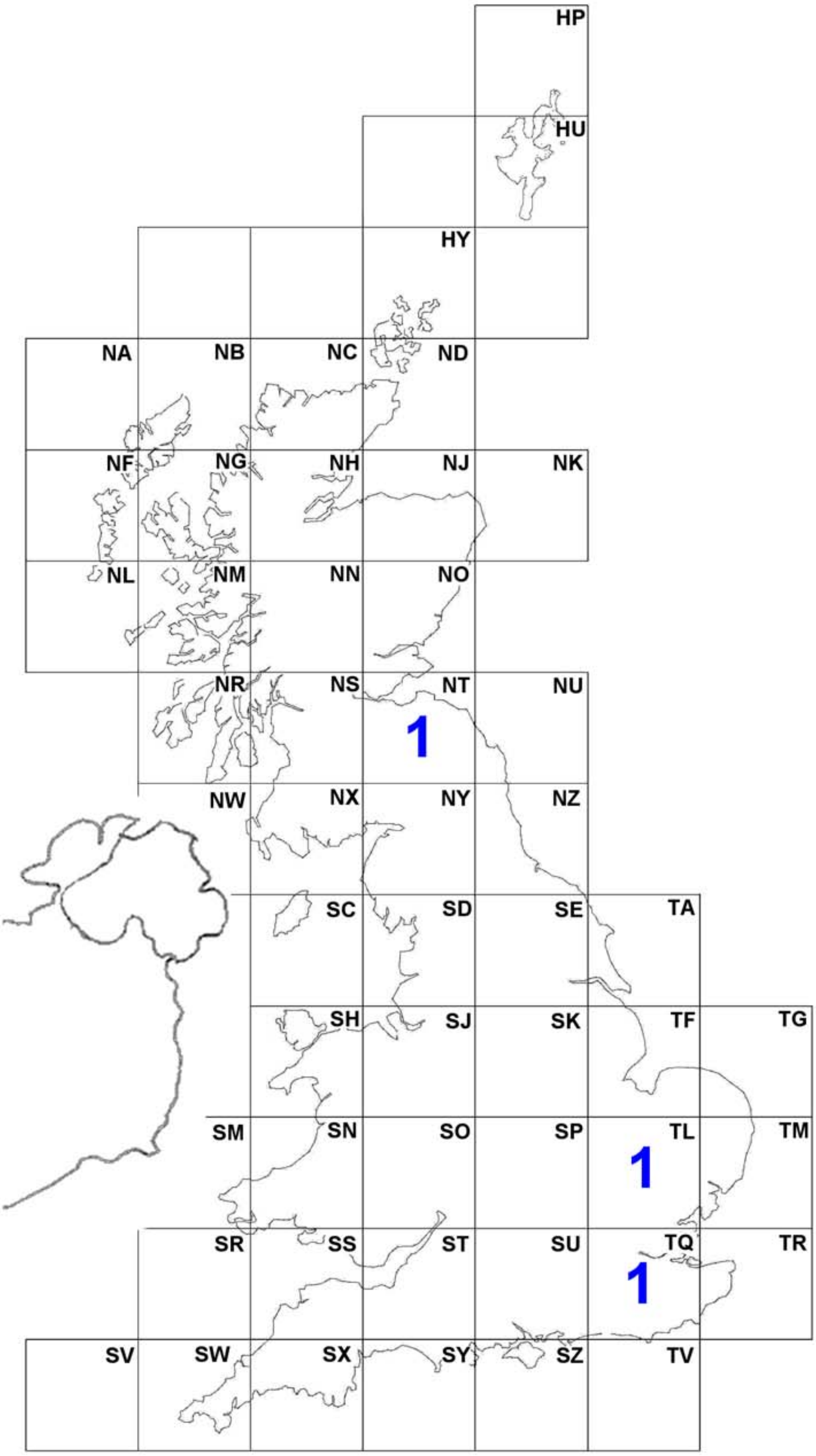
The numbers shown in the grid boxes identify the areas of VTS coverage (Figure 3.1.1-18 cross references the numbers to actual VTS coverage locations)

Areas shown in Red use S-Band radars.

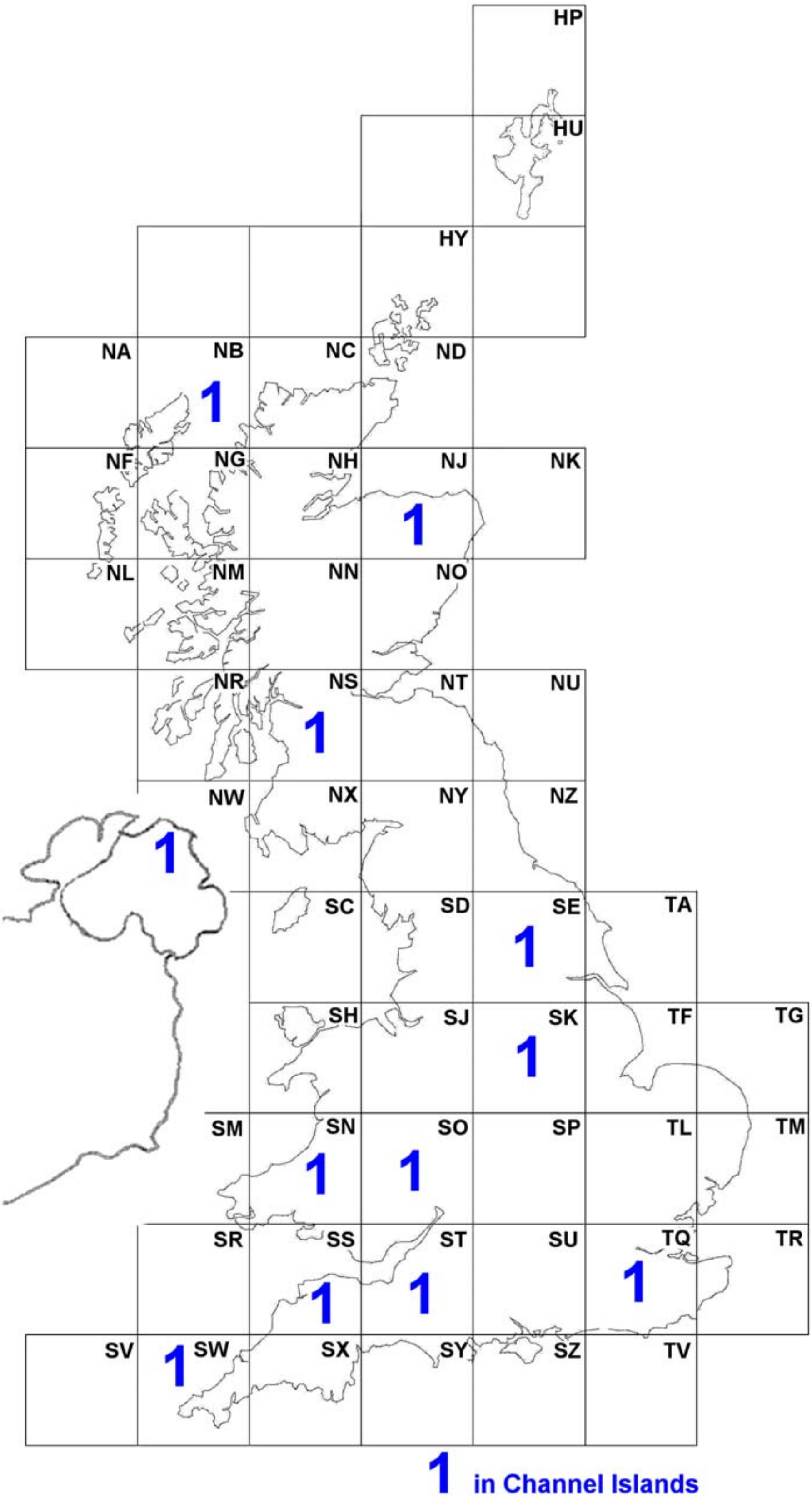
Areas shown in Blue use X-Band radars.

There is no information available regarding the radar band used in the other VTS areas shown in Green.

Map 3.1.1-6 Ku-Band ASDE Systems



Map 3.1.1-7 C-Band ground based Meteorological Radar Systems



Section 3.1.2

The Wanted Transmission Characteristics and Operational Parameters of Commercial Radars in use in the UK.

Contents:

Figures

Tables

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3.1.2 Wanted Transmission Characteristics and Operational Parameters of Commercial Radars in use in the UK.

3.1.2.1 Introduction

This section discusses the wanted transmission characteristics of Current & State of The Art Civil Radar Systems in the UK. The transmission characteristics of radar systems depend critically on the role or mission of the radar and the technology used. This section discusses how each parameter affects the transmitted spectrum and how the definition of these parameters is driven by the needs of the radar or the technology employed.

In order to detect a target at extended range the radar has to overcome a range loss proportional to $1/R^4$, thus very high powers are required. In the early days of Radar, the only transmitters available were broadcast transmitters operating in the HF band. These systems suffered from the need to use physically very large antennas to achieve the required antenna gains and beamwidths. Soon it became clear that microwave frequencies were the optimum for radar use particularly because of their ability to generate beams with the required gains from manageable antennas.

The invention of the magnetron (oscillator) valve enabled a sufficient amount of power to be produced at these frequencies. However the nature of the power was such that it was generated in short pulses at very high peak level. The magnetron when pulsed with a high voltage could produce very high powers; the pulses were short and the duty cycle was low. This type of waveform suited the early radars as it allowed them to distinguish two targets that were relatively close using very simple signal processing and by the end of the second world war magnetron radars were operating in the L, S & X-Bands.

Thus in a relative short period of time, radar operating frequencies had moved from the HF/VHF/UHF bands into the SHF band, well away from all other users of the spectrum. The use of magnetron pulses, however, was at the expense of the occupied bandwidth since the magnetron pulses occupied wide bandwidths; much larger than those required to theoretically transmit the pulse shape.

For many years the radar bands were left generally 'untouched' from a regulatory view point, as radars' capacity to interfere with other services and other services' capacity to interfere with radar was small. The interference was limited as there were no other services operating at frequencies close to those used by the radars and the use of waveguide feeds meant that interference generated below the radar frequency was minimal as the lower frequencies did not propagate along the waveguide.

What interference there was, was limited to 'radar to radar' interference. However, the amount of available spectrum and the nature of the systems meant that it was generally possible to manage the situation by co-ordinating operating frequencies and geographical separation.

Later, as other non-radar systems were developed, the microwave bands began to be used increasingly by point to point users such as satellite and microwave links. These systems were generally operated by professional users, were generally fixed geographically and had well controlled radiation characteristics making their potential for interference low.

Primary Radar is probably unique in that it effectively only communicates with itself, hence there has been no need to have a set of predetermined "signals in space". The radar designer has been free to vary the transmitted parameters of pulse width, bandwidth, pulse repetition rate (PRR) etc. to optimise the performance of the radar. The radar bands were thus never subject to specified forms of modulation or formally channellized like those bands used for communications and broadcasting.

From the 1950's onwards, other systems developed and the need for more and more spectrum forced other users to operate at higher and higher frequencies. The introduction of broadcasting and mobile systems in the UHF band meant that the use of this band by radar (in peacetime) became more and more difficult. UHF radars were used by the UK National Air Traffic Services (NATS) up until the 1980's as part of the UK Air Traffic Control

(ATC) system (Mediator). Most of these radars have been replaced by S-Band systems (S-Band is the preferred band for terminal area and airfield operations).

Currently there is only one civil UHF radar remaining on the UK mainland and one on the Channel Islands, both of these systems are limited to the use of TV Channel 36. The military stopped using UHF and VHF radars during this time with a few minor exceptions. The introduction of the RadioNavigation-Satellite Service (RNSS) led to a further reduction in the frequencies in L-Band available for radar usage.

Since then, more and more services have been developed that use frequencies close to the radar bands, many of these being mobile or domestic services; these services need spectrum and have been prepared to pay for usage. Radar no longer has its "privileged" position in terms of spectrum allocation. Military radar, since the collapse of the Warsaw Pact, is seen by some as no longer a "primary candidate" for spectrum allocation.

However radar technology has moved on and the need for better cancellation of clutter led to the development of the driven systems which replaced the old magnetron systems in some areas. Later the development of pulse compression based systems allowed for the use of longer pulses with better spectral control.[1] Recently the benefits of Solid State systems have resulted in a further lowering of peak power and the use of much longer uncompressed pulses.

In order to facilitate sharing and to improve spectral usage and reduce interference, the International Telecommunication Union (ITU) and the Conférence Européenne des Administrations des Postes et des Télécommunications (CEPT) have agreed new limits on unwanted emissions for all radio services. As from the start of 2003, all new equipment introduced into service will have to meet the new limits on Spurious Emissions (SE). Two categories of SE limits pertain to radar services Category A and Category B.

The ITU have proposed a set of unwanted emission limits for Category A radars which roll-off from the carrier frequency down to the SE level. This sets the regions over which the SE limits apply. CEPT working group SE 21 has agreed the unwanted emission limits for Primary radars that fall into the Category B[2] SE.

3.1.2.2 Radar Characteristics

3.1.2.2.1 System Requirements

3.1.2.2.1.1 Choice of Frequency Band

The frequency band chosen for radar is controlled by two factors, the technical characteristics of the radar and the frequency bands allocated for use by the type of radars being considered. Radars are allocated frequency bands depending on the role being carried out. The choice of which of the bands allocated for a particular use is used depends on the application parameters such as range, update rate, weather and physical size to name a few. Table 3.1.2-1 gives a précis of radar frequency allocations for civil systems.

The majority of civil radar systems come under the auspices of the following radio services:

- Aeronautical Radio Navigation
- Marine Radio Navigation
- Meteorological

[1] It should be noted however that until relatively recently some authorities, in particular the Federal Aviation Administration (FAA), disapproved of the use of pulse compression radars.

[2] All fixed radars excluding multifrequency, windsheer & active array radars. Administrations may also exempt Vessel Traffic System (VTS) systems to allow the use of Maritime surveillance radars in this role.

Table 3.1.2-1 Allocated Civil Frequency Bands in the UK[3]

Frequency Band GHz	Designation	Service	Use
Channel 36	UHF	ARNS	ATC
0.96 to 1.215	L	ARNS	DME
1.030 & 1.090	L	ARNS	SSR
1.215 to 1.365	L	ARNS	ATC
1.559 to 1.6265	L	ARNS	
2.7 to 2.9	S	ARNS/Met	ATC/WF
2.9 to 3.1	S	ARNS/MRNS	MSR
4.2 to 4.4	C	ARNS	
5.0 to 5.25	C	ARNS	MLS
5.35 to 5.46	C	ARNS	
5.46 to 5.47	C	ARNS/MRNS	
5.47 to 5.6	C	MRNS	MSR
5.6 to 5.65	C	MRNS/Met	
8.75 to 8.85	X	ARNS	
8.85 to 9.0	X	MRNS	MSR
9.0 to 9.2	X	ARNS	PAR
9.2to 9.3	X	MRNS	MSR
9.3 to 9.5[4]	X	MRNS	MSR/VTS
9.3 to 9.5	X	ARNS	ATC/ASDE/AW
13.25 to 13.4	Ku	ARNS	
13.7 to 14.3	Ku	ARNS/MRNS	
15.4 to 15.7	Ku	ARNS	ASDE

The choice of frequency is generally affected by two main issues, the range required of the radar and the maximum size of the antenna that can be accommodated. The detection range for a given target cross section (size) that can be achieved with a given Equivalent Isotropically Radiated Power (EIRP) generally falls as the frequency increases. This is particularly true above about 5 GHz where the effect of precipitation, particularly the production of rain clutter (backscatter), starts to have a disproportionate effect. To some extent this loss of performance can be compensated for by the ability to use electrically larger antennas for the same physical constraints (i.e. antennas with higher gains).

3.1.2.2.1.2 Frequency Accuracy

There are three issues related to the accuracy of the transmitted frequency:

- The fundamental frequency which the radar is initially set to;
- The short to long term frequency drift of the radar;
- The pulse to pulse frequency stability.

[3] Information supplied by the Radiocommunications Agency

[4] Existing harbour radars at Gravesend, Southampton and Crayfordness may operate up to 9530 MHz.

The accuracy to which the fundamental frequency is set does not in general have an impact on the operation of the radar, provided the system operates in its allocated band. What is important is that the radar receiver is set to the same frequency and for Moving Target Indicator (MTI) radars that all pulses in a burst have the same frequency.

From a regulatory, frequency planning and interference point of view however it is important.

Driven systems have the ability to set the final frequency to an accuracy much higher than the accuracy to which the radar is assigned a frequency. Magnetron radars are much more difficult to control as they rely on mechanical manufacture of the valve. For example X-Band Magnetrons are typically specified to an accuracy of ± 30 MHz, S-Band Magnetrons are specified to ±10 MHz.

3.1.2.2.1.3 Frequency Stability

The absolute frequency of the transmitted signal is not generally important as the receiver generally uses the same source to demodulate the returned signal. In MTI systems the pulse to pulse stability is however very important as it affects the ability of the radar to detect targets in clutter. The requirements for clutter cancellation are generally far tighter than those imposed by frequency planners or regulators.

The frequency stability achieved at the output of a radar depends on the type of transmitter being used. Oscillator radar types tend to have poor stability and, as has been stated, they depend on the mechanical size of the oscillating cavity to set the frequency. Oscillator systems are thus sensitive to temperature, taking some time to warm up and to achieve their final stable frequency. The time taken is dependent on the environmental ambient temperature which can vary greatly from the arctic to the tropics. They can also be affected by changes in the modulator voltage, pulse length, duty cycle and load impedance, so called "pushing and pulling". Magnetron radars generally require the use of an Automatic Frequency Control (AFC) loop to keep the receiver tuned to the transmitted frequencies.

Typical figures for an X Band magnetron would be:

Drift with temperature 0.25 MHz/°C say -50 to +120°C	= 42.5 MHz
Life effects	= 20 MHz
Pushing	= 20 MHz
Pulling	= 15 MHz
TOTAL	**= 97.5 MHz**
RSS (Typical Value)	≈ 50 MHz[5]

Driven systems use a low power driver stage to generate the modulated signal, which is amplified up to the final transmitted power. The driver can be a crystal oscillator or a synthesised source. The frequency of the crystal source can be specified to 1 Hz, however they have a fundamental accuracy set for the final frequency and long term frequency drift. This results in a total frequency tolerance at S-Band of approximately 25 kHz.

[5] This is very rough estimate as the parameters are not random and have subtle interactions. The stability depends heavily on the ambient temperature, how good the equipment design is and how often the valve is replaced.

UK NATS specify[6] the following frequency stability numbers for primary ATC radars:

Frequency band:	500 to 1365 MHz	500	ppm
	2700 to 9500 MHz	1250	ppm
	15.4 to 35.5 GHz	5000	ppm

When considering stability it is very important to consider the operational environment. Most large ATC radar transmitters operate in a temperature controlled environment and run continuously, this ensures that they can reach a stable temperature. Ovens can be used to control the temperature of crystals to keep the frequency as stable as possible. Mobile systems in ships or aircraft seldom have the luxury of conditioned environments, particularly if they are mast mounted, and have to cope with large changes in temperature; -50 to 120 °C is not unknown as the specification on the operating temperature of a magnetron system.

3.1.2.2.1.4 Peak Power

The ability to detect a target at a given range is affected by the energy in the pulse, this is a combination of the peak power and the pulse length. In theory radar designers like to keep the pulses as short as possible subject to the available transmitter peak power. The peak power of the pulse does not affect the spectrum except that higher peak powers tend to be associated with narrower pulses due to the nature of transmitters.

3.1.2.2.1.5 Pulse Repetition Rate (PRR)

In order to detect a target with a high probability particularly if the target is fluctuating, the radar needs to illuminate more than once per scan; the more "hits per beamwidth" the higher the probability of detection. The PRR is thus a function of the number of hits per beam dwell that are required and the dwell time. The limiting factor to the PRR is the target range. To get an unambiguous reply, the PRR needs to be such that a new pulse is not sent out before the previous one is received even for a target at maximum range.

The PRR changes the spacing of the lines in the spectrum but does not affect the overall envelope of the spectrum.

3.1.2.2.1.6 Pulse Length

The pulse length is generally set as short as possible commensurate with providing sufficient energy to the target. If the pulses are too long then this limits both the range resolution and the minimum range of the radar. If long pulses are required to provide sufficient energy on a target with a specified peak power then it is possible to use pulse compression techniques to overcome the target resolution issues. The shorter the transmitted pulse the wider the spectrum.

3.1.2.2.1.7 Mean Power

The mean power of the radar is a consequence of the pulse length, PRR and peak power. The mean power has no effect on the transmitted spectrum.

3.1.2.2.1.8 Rise Time

In a pulse radar, in order to effectively deliver energy onto a target, the radar pulse needs to be constrained in time, this limits the maximum rise time that can be tolerated by the radar system. In many cases however the rise time is defined by the characteristics of the transmitting device. In order to achieve an efficient generation of RF power, class C amplifiers are traditionally used and this means running tubes into saturation. If pulse to pulse stability is to be achieved and the tube is not to produce excess noise or oscillate in spurious modes then the tube needs to be turned on very fast.

Modern solid state lumped transmitters do give more control over the rise time of the pulse. The faster the rise time the wider the spectrum that is produced.

[6] CAP 670 RAD 02 para 8

3.1.2.2.1.9 Pulse Compression Coding

The application of chirp (FM modulation) is used to expand the transmitted pulse so that on reception it can be compressed. To a first approximation the amount of chirp applied is unevenly proportional to the compressed pulse length. The larger the chirp used, the wider the spectrum produced. However the use of long pulses does give the opportunity to control the pulse rise-time[7] and the use of a weighted FM modulation can also help reduce the extent of the spectrum.

An alternative method of pulse compression is phase coding. Here instead of an extended pulse with FM modulation, a series of sub-pulses is produced, each sub-pulse being one range cell long and phased coded (binary 0 & 1). The receiver correlates the reply with the known transmitted code, and this results in effectively (neglecting range side-lobes) a single large return at the range cell of the target. In this case the spectrum of the transmission is the spectrum produced by a single sub-pulse. However, because the sub-pulses are contiguous with range cells, there is less flexibility to control the transmitted spectrum.

3.1.2.2.2 Antenna Characteristics

To a first approximation the antenna characteristics do not affect the transmitted spectrum however they can affect the spatial or temporal distribution of the emission which, from a fixed viewpoint, could appear as a change in the spectrum. Antennas with narrow bandwidth or with a fill time[8] which is a significant proportion of the pulse length, could also modify the transmitted spectrum.

3.1.2.2.2.1 Rotation Rate

A limit is reached where the antenna beamwidth is too narrow to accommodate the required number of hits (pulses) to detect the target with a high probability. Once this limit is reached the only solution is to increase the dwell time by slowing the rotation. Slowing the rotation affects the update rate of which there is a minimum requirement set by the operation of the radar. For example Airport radars generally do not operate below 15 rpm. This update rate gives the controllers time to react and correct potential conflicts.

In general for civil systems the following applies:

- Long range systems (>300 nm) have large antennas with slow rotation rates (5 to 10 rpm) and use L-Band.
- Medium range systems (50 to 100 nm) use S-Band with medium sized antennas rotating at 12 to 15 rpm.
- Short range systems (< 20 nm) use X or Ku-Band and tend to have much smaller antennas and faster rotation (20 to 60 rpm) rates.

In electronically scanned antennas the rotation rate is replaced by the dwell time.

3.1.2.2.2.2 Azimuth (Horizontal) Beamwidth

The azimuth beamwidth of the antenna is a compromise between the azimuth accuracy and the number of hits required for detecting a target.

3.1.2.2.2.3 Elevation (Vertical) Pattern

The elevation pattern of the antenna is defined by the coverage requirements of the radar. This can be achieved in several ways. In a 2D radar the elevation pattern is either a simple fan beam or is shaped to direct energy into specific regions. In 3D radars the coverage is obtained by the use of, either a scanning pencil beam, or a series of stacked pencil beams.

[7] Transmitter technology permitting.

[8] Defined as the time required to establish a fully formed flat phase front.

3.1.2.2.2.4 Antenna Gain

The gain of the antenna needs to be sufficient to produce the required EIRP. The gain however is related to the azimuth beamwidth and the elevation pattern. The only control the antenna designer has is the efficiency of the antenna design. Increasing the efficiency is achieved by reducing the energy radiated into unwanted angular regions and the losses (ohmic & spill-over). For a pencil beam antenna the gain *G* in dBi is given approximately by:

$$G \approx 10 \times \log\left(E_{ff} \times \frac{41000}{\theta \times \phi} \right)$$ Equation 3.1.2-1

where:

E_{ff} is the efficiency of the antenna

ϕ and θ are the horizontal and vertical beamwidths in degrees.

3.1.2.2.2.5 Side-lobes

The side-lobes of the antenna need to as low as possible to prevent the radar detecting large targets that are outside the main beam. There is a balance between the achievement of low side-lobes and antenna gain for a given size of antenna.

3.1.2.2.2.6 Polarisation

The polarisation selected depends on the nature of the targets required to be detected and to some extent the clutter environment. For example, small round targets are not detected by Circular Polarisation (CP) hence defence systems looking for approaching missiles would not use CP. They would use linear polarisation. ATC radars use circular polarisation to suppress clutter from rain (small round targets). Naval radars tend to use horizontal polarisation as its produces less sea clutter. Weather radars can use both polarisations to allow classification of types of precipitation.

3.1.2.3 Wanted Transmission Characteristics of Civil Radars

3.1.2.3.1 Introduction

The following tables give the wanted transmission of representative radar systems. Where measured spectra are available they are presented. Representative antenna patterns and calculated emission masks are also provided. The selection of the systems presented in this section is based on one of two criteria. For fixed systems the selection is based on the most numerous systems in use in the UK. For mobile systems where the exact mix of systems in use in the UK is not known, then the selection has been made on the basis of the choice of two extremes i.e. "high" and "low" spec system.

Notes on the data in the tables:

- The data is obtained from published sources, measurements of in service radars, or calculated from these two sources.
- Where data has been estimated from other sources this is indicated by a footnote.
- The incidence of a ≈ before a value indicates that this is a typical value obtained by experience from similar systems.
- NA means that the data is not applicable to this type of radar.
- NDA means no data is available on this parameter in the public domain.
- The range of frequencies over which the radar is designed to operate is given. Where the actual frequency of operation is available in the public domain then this is listed. Where this information is not available in the public domain, then the number of operational frequencies is listed.

3.1.2.3.2 Aeronautical Radio Navigation Radars Ground Based (L-Band)

The typical parameters of this class of radars in use in the UK are presented in Table 3.1.2-2. Two of the systems listed are Travelling Wave Tube (TWT) driven systems and one is a Magnetron based system. The TWT Type1 system also has a special short range variant used at one site only in the UK.

Table 3.1.2-2 Aeronautical Radio Navigation Radars Ground Based (L-Band)

CHARACTERISTICS	TWT Type 1 Long Range	TWT Type 1 Short Range	TWT Type 2	Magnetron Type
Tuning range (GHz)	1.260 to 1.300	1.260 to 1.300	1.250 to 1.300	1.200 to 1.300
Operational Frequencies Used	2 or 4	2 or 4	2 or 4	2
Frequency Accuracy	≈25 kHz	≈25 kHz	25 kHz	≈10 MHz[9]
Frequency Stability	≈12.5 kHz	≈12.5 kHz	12.5 kHz	≈20 MHz[10]
Modulation	Non-Linear FM	Non-Linear FM, P0N	Non-Linear FM, P0N	P0N
Transmitter Power into Antenna (kW)	160	75	150	1800
Pulse width (μs)	66 & 3	33 & 1	50 & 0.8	3.6
Pulse rise/Fall time (μs)	0.03	0.03	0.02	≈ 0.06
Pulse repetition rate (Hz)	420 & 830	800 &1600	680	380
Duty cycle (%)	2.8	2.6	3.4	0.14
Chirp bandwidth (MHz)	2.5	1	1.25 & 1.7	0
Compression ratio	100:1 & 5:1	33:1	62.5:1	NA
RF emission bandwidth (-3 dB) MHz	≈2.5 & 2.5	1.1 & 0.7	1.7 & 1.25	0.3
RF emission bandwidth (-20 dB) MHz	≈ 5.6 & 8	2.9 & 3	8.5 & 9.2	1.5
RF emission bandwidth (-40 dB) MHz	≈10.8 & 26.8	8.1 & 7.8	≈10 & 7	≈15
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Composite	Composite	Composite	$Cosec^2$ to 40°

[9] Some systems use tuneable magnetrons, which can reduce this figure to zero.

[10] Good environmental control, equipment design and performance monitoring can improve this figure.

CHARACTERISTICS	TWT Type 1 Long Range	TWT Type 1 Short Range	TWT Type 2	Magnetron Type
Antenna type (reflector, phased array, slotted array, etc.)	Reflector	Reflector	Reflector	Reflector
Antenna Horizontal beamwidth -3dB (degrees)	1.03	1.03	1.03	1.1
Antenna polarisation	Circular	Circular	Circular	Variable Linear-circular
Antenna mainbeam gain (dBi)	35.3	35.3	35.3	35
Antenna Vertical beamwidth -3dB (degrees)	3	3	3	4.5
Antenna horizontal scan rate (degrees/sec)	45[11]	90	60	42
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	360 degrees, Continuous	360 degrees, Continuous	360 degrees, Continuous	360 degrees, Continuous
Antenna vertical scan rate (degrees/sec)	NA	NA	NA	NA
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA	NA	NA	NA
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	-22 & -34	-22 & -34	-22 & -34	-25 & -30
Antenna height above ground (m)	35	35	35	15

The calculated masks for these three types of radar are given in Figures 3.1.2-1, 2 and 3. Details of the derivation of the emission masks can be found in ITU-R Recommendation SM.1541 "Unwanted emissions in the out of band domain" see section 3.1.2.5 of this report.

[11] Some systems work at 7 rpm (42 degrees/sec) with PRR of 670 Hz

Figure 3.1.2-1 Emission Mask TWT Type 1 Short range L-Band 33µs Long Pulse

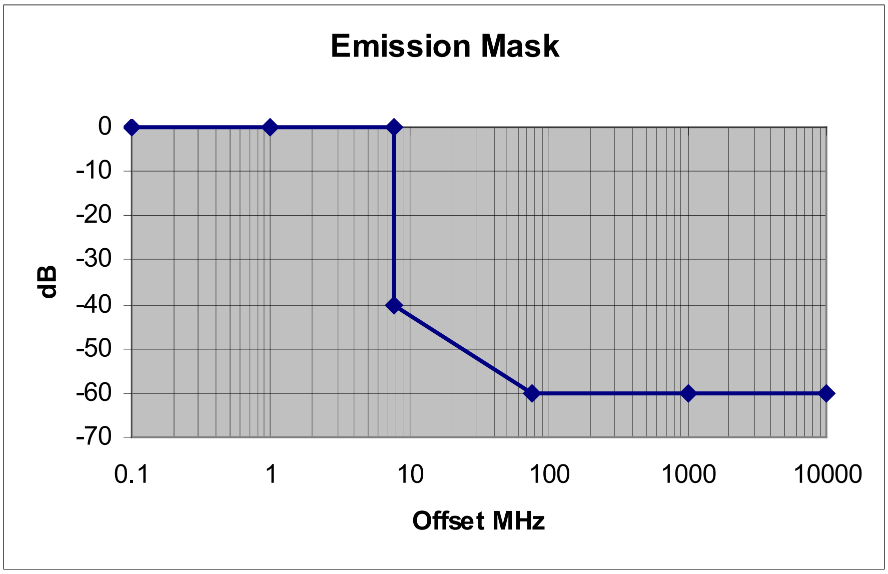


Figure 3.1.2-2 Emission Mask TWT Type 2 L-Band 50 µs Pulse

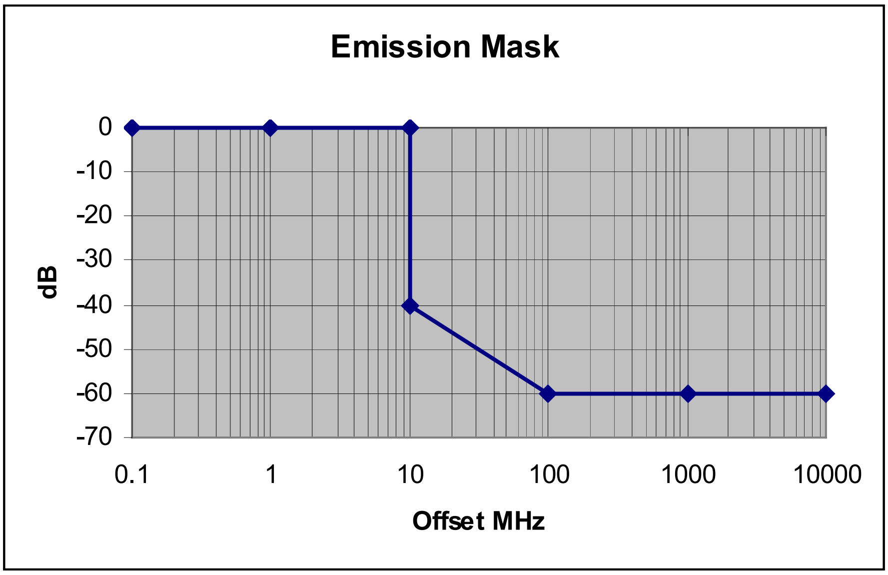
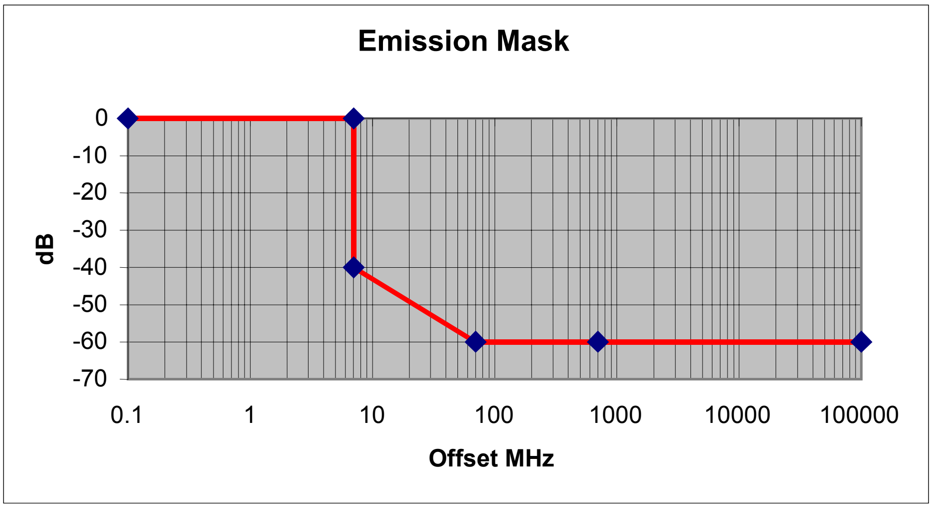


Figure 3.1.2-3 Calculated Emission Mask Magnetron L-Band



3.1.2.3.3 Aeronautical Radio Navigation Radars Ground Based (S-Band)

The UK has several types of this class of radar in service, they are the most numerous of the classes of ground based radars in the UK.

Of the types selected the Solid State is the latest design to go into service, the Magnetron represents the oldest types still in service whilst the TWT type represents the most numerous type in service at this current time.

Table 3.1.2-3 Aeronautical Radio Navigation Radars Ground Based (S-Band)

CHARACTERISTICS	Solid State	TWT	Magnetron
Tuning range (GHz)	2.7 to 2.9	2.7 to 3.1	2.7 to 2.9
Operational Frequencies Used	4	2 or 4	1 or 2
Frequency Accuracy	≈50 kHz	50 kHZ	10 MHz[9]
Frequency Stability	≈25 kHz	25 kHz	20 MHz[10,12]
Modulation	P0N/Non-linear FM	P0N/Non-linear FM	P0N
Transmitter Power into Antenna (kW)	15 or 30	75	625
Pulse width (μs)	1 & 100	0.4 & 20	1
Pulse rise/Fall time (μs)	0.169	0.08	0.06
Pulse repetition rate (Hz)	825	1100	700
Duty cycle (%)	8.25	2.75	0.7
Chirp bandwidth MHz	1	0 & 2.5	0
Compression ratio	100:1	50:1	NA
RF emission bandwidth (-3 dB) MHz	0.8 & 0.8	2.5 & 2.5	1
RF emission bandwidth (-20 dB) MHz	2 & 1.4	16.8 & 3.6	6.0

[12] SE34(99)29 - S-Band radar magnetron frequency stability and spectrum characteristics

CHARACTERISTICS	Solid State	TWT	Magnetron
RF emission bandwidth (-40 dB) MHz	4 & 2	45 & 10	45
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	$Cosec^2$	$Cosec^2$	$Cosec^2$
Antenna type (reflector, phased array, slotted array, etc.)	Reflector	Reflector	Reflector
Antenna Horizontal beamwidth -3dB (degrees)	1.4	1.5	1.4
Antenna polarisation	Linear/Circular	Circular	Linear /Circular
Antenna mainbeam gain (dBi)	35	33	32
Antenna Vertical beamwidth -3dB (degrees)	4.5	5	5
Antenna horizontal scan rate (degrees/sec)	90	90	90
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	360 degrees, Continuous	360 degrees, Continuous	360 degrees, Continuous
Antenna vertical scan rate (degrees/sec)	NA	NA	NA
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA	NA	NA
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	≈ - 26/ -40	-26 / -35	-21 / -33
Antenna height (m) above ground	8 to 15	8 to15	12

It may be worthwhile at this point to consider the theoretical and practical differences in the spectra of these three systems that are carrying out essentially the same role.

Initially consider the Magnetron radars. Figures 3.1.2-4 and 5 show measured spectrum of a naval Magnetron radar. This radar, with the exception of the pulse length used, is the same as that used in an ATC role.

As can be seen in these figures, the spectra of the Magnetron radars show the characteristic porch on the lower frequency side of the spectrum. This is caused by Magnetron Pulling this being more pronounced on the short pulse spectra which is shown plotted on a wider frequency scale.

Figure 3.1.2-4[13] Spectrum of Naval S-Band Magnetron Radar 0.4μs -Vertical Scale 10 dB/div

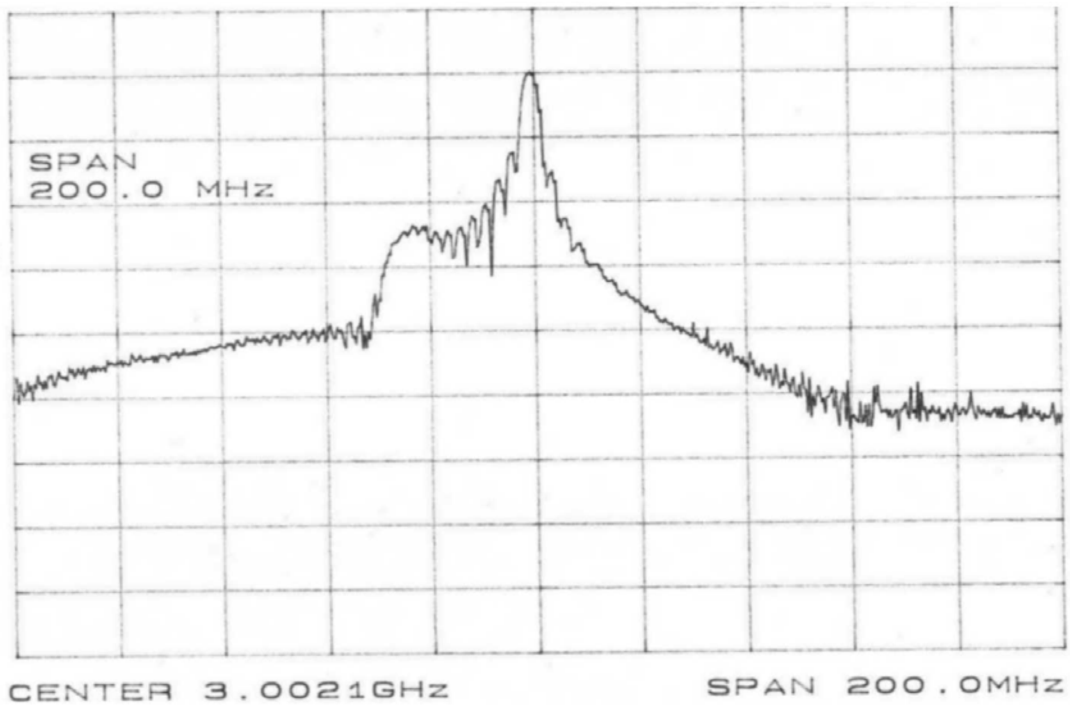
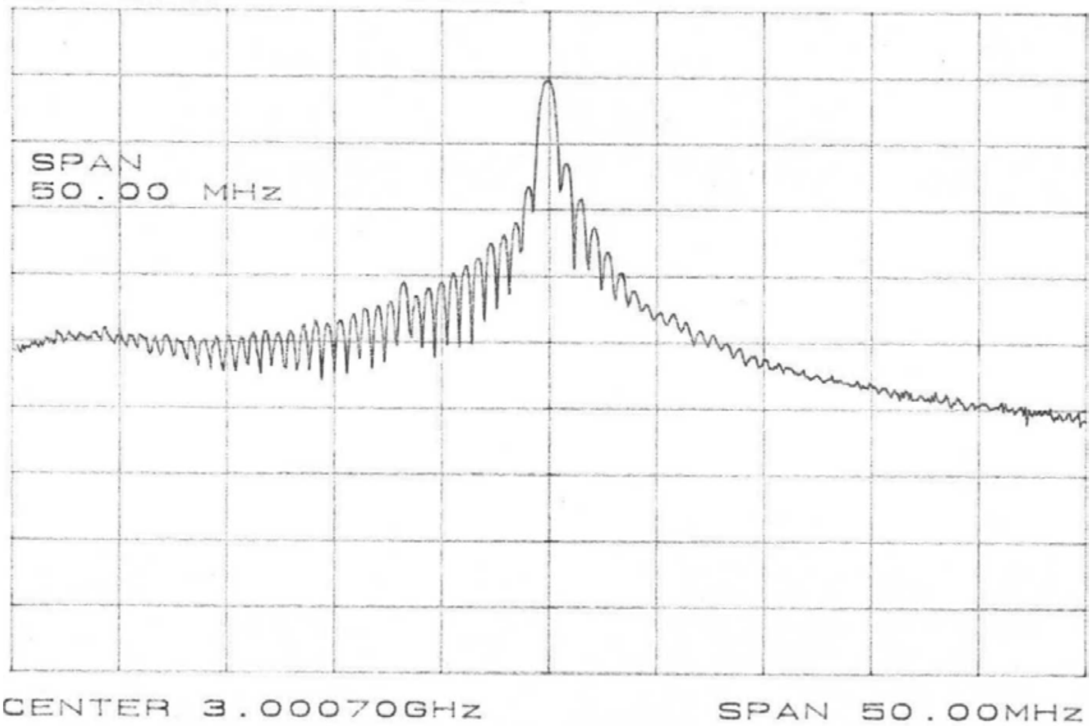


Figure 3.1.2-5[13] Spectrum of Naval S-Band Magnetron Radar 1.7 μs - Vertical Scale 10 dB/div



It should be noted however that these spectrum measurements are made at the output of the transmitter. The antennas used on these types of systems are broadband and squint-

[13] Source AMS Cowes

less and hence will produce no antenna modulation. The measurements were made with a Spectrum Analyser and have a limited dynamic range.

Table 3.1.2-4 shows a comparison of the measured bandwidths for the two Magnetron spectra presented above, to those calculated using the ITU recommendations[14] see also Section 3.1.2-5.

Table 3.1.2-4 Comparison of measured to calculated bandwidths naval Magnetron

	Measured MHz			**Calculated[15] MHz**		
	3 dB BW	20 dB BW	40 dB BW	3 dB BW	20 dB BW	40 dB BW
Long Pulse	0.6	3.26	32.2	0.6	5.6	19.4
Short Pulse	2.74	15	59.2	2.78	12.2	42.2

Table 3.1.2-4 shows that for the 3dB and 20 dB bandwidths the measured results are similar or less than the calculated results. At the 40 dB point the calculated masks are much less than the measured values. This is due to the presence of the "porch" on the magnetron spectra. The pulse length used in the ATC version is 1µs, which falls between the two pulse lengths in the naval version. Hence it can be assumed that the spectrum produced will be close to the calculated masks at the 3dB & 20 dB widths and around 45 MHz at 40 dB level.

If we now consider the TWT systems, Figures 3.1.2-6 and 7 show measured spectrum of a TWT based ATC radar. Tables 3.1.2-5 and 6 give the comparison between measured and calculated values for these systems. It should be noted that this radar is a longer-range version than that specified in Table 3.1.2-3 and operates with pulse lengths of 0.5 & 26.5 µs.

[14] ITU-R Recommendation SM.1541 Unwanted emissions in the out-of-band domain

[15] See Section 3.1.2.5

Figure 3.1.2-6[16] S-Band ATC TWT Radar 26.5 µs pulse 2.5 MHz Chirp[17] - Vertical Scale 10dB/div

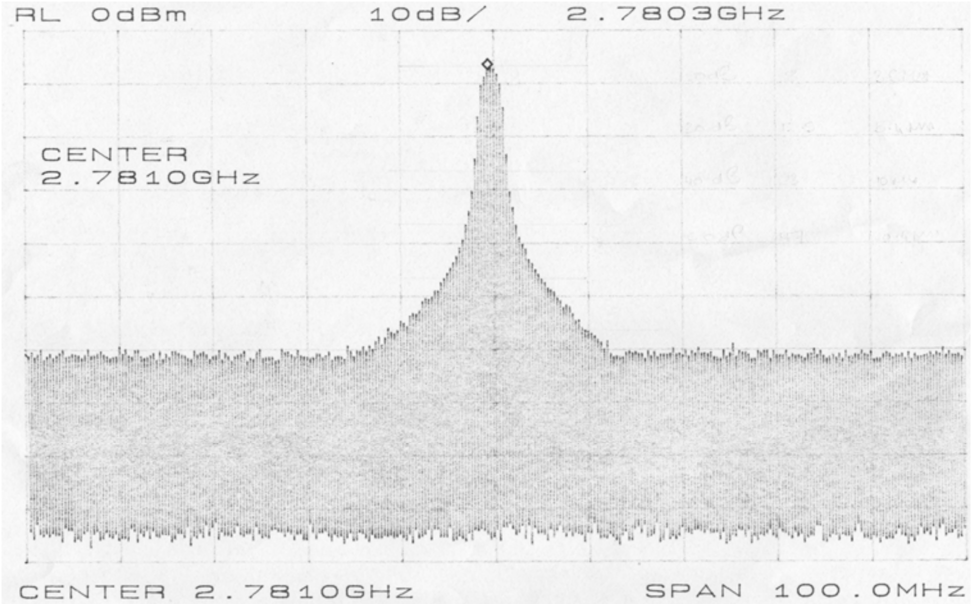
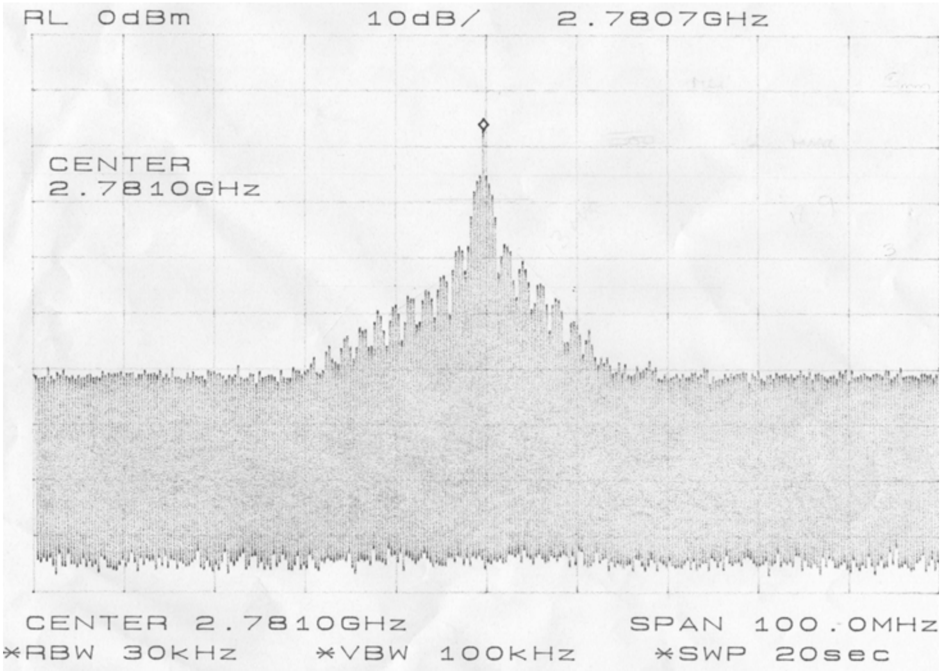


Figure 3.1.2-7[18] S-Band ATC TWT Radar 0.5µs CW short pulse[19] - Vertical Scale 10dB/div



[16] Source AMS Cowes

[17] This measurement was made at the output of the transmitter. The antennas used on these types of systems are broadband and squint-less and hence will add no antenna modulation.

[18] Source AMS Cowes

[19] This measurement was made at the output of the transmitter. The antennas used on these types of systems are broadband and squint-less and hence will add no antenna modulation.

Table 3.1.2-5 Comparison of measured and calculated results[20] TWT system 26. µs pulse with 2.5MHz chirp

Measured MHz			**Calculated [15] MHz**		
3 dB BW	20 dB BW	40 dB BW	3 dB BW	20 dB BW	40 dB BW
2.5	3.6	10	2.5	7.8	25.7

Table 3.1.2-6 Comparison of measured and calculated results TWT system 0.5 µs CW short pulse

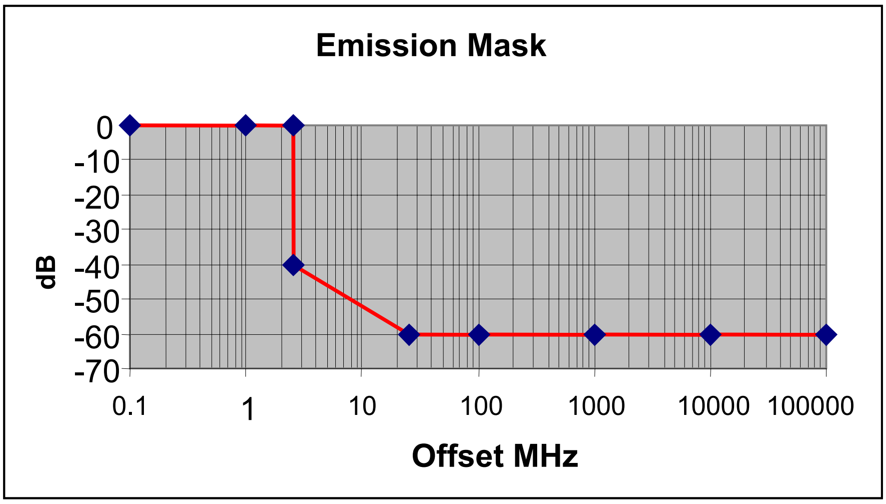
Measured MHz			**Calculated[15] MHz**		
3 dB BW	20 dB BW	40 dB BW	3 dB BW	20 dB BW	40 dB BW
2.2	13.5	45	2.0	12.7	87.7

Considering the TWT system, for the short pulse the measured 3 & 20 dB bandwidths are close to those calculated, whereas at the 40dB points, the measured bandwidth is less than calculated. For the long pulse the measured 20 and 40 dB bandwidths are less than those calculated using the emission masks. The masks however do provide a worst case guide to the final extent of the spectrum.

If we wish to compare the three types of radars in Table 3.1.2-3 then it is possible to use the calculated worst case emission masks for the comparison.

Using the parameters given in Table 3.1.2-3 the emission masks can be calculated for three types given. These are given in Figures 3.1.2-8, 9 and 10. The long pulses will be considered for the TWT and the Solid State radar and compared to the Magnetron radar.

Figure 3.1.2-8 Emission Mask Solid State S-Band 100µs Pulse 1 MHz Chirp



[20] This transmitter had a measured rise-time of 15 ns unlike the typical example of 18 ns given in Table 3.1.2-3.

Figure 3.1.2-9 Emission Mask TWT S-Band 20µs Pulse 2.5 MHz Chirp

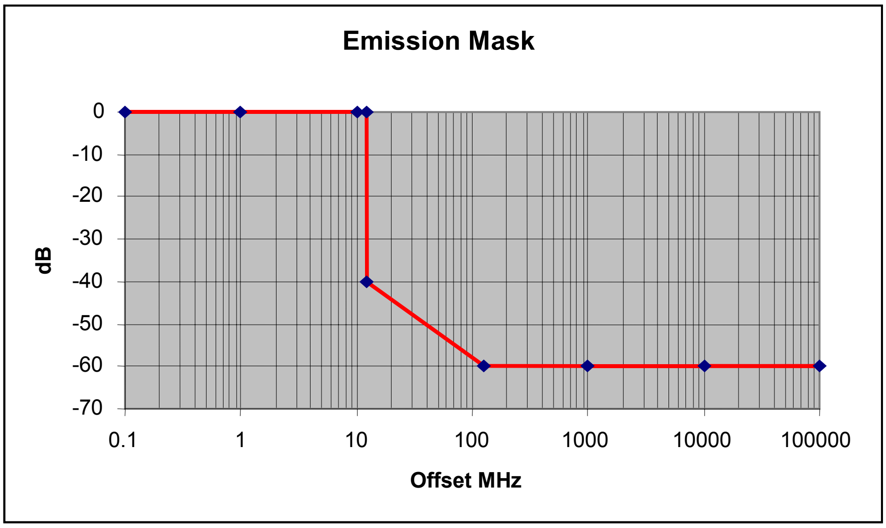
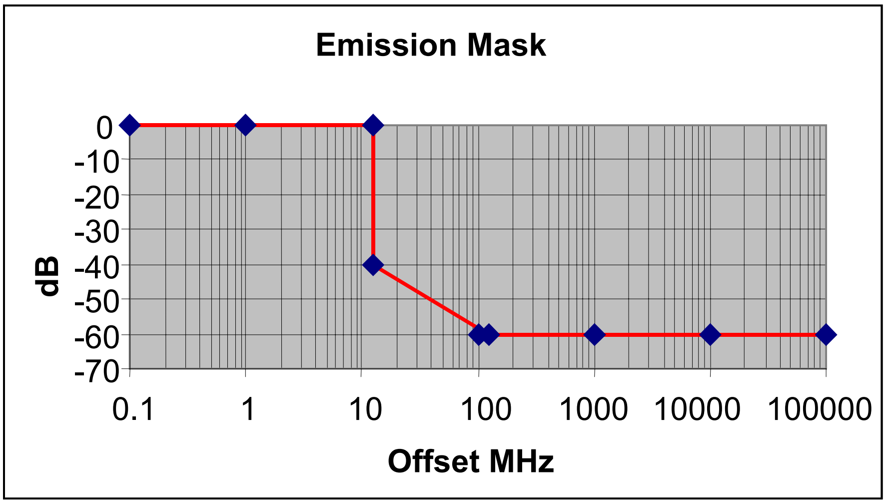


Figure 3.1.2-10 Emission Mask ATC Magnetron S-Band 1µs Pulse



For comparison the three masks based on Table 3.1.2-3 are plotted on the same Figure 3.1.2-11.

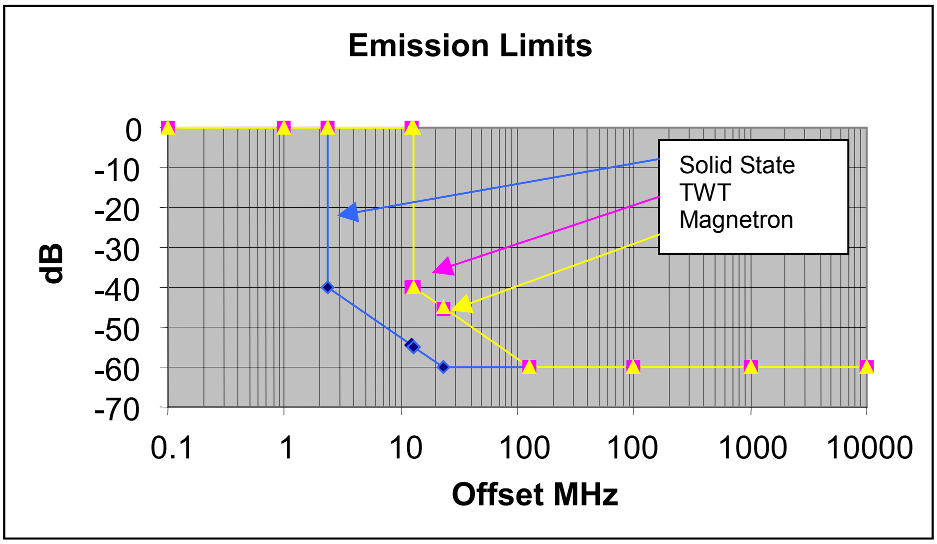
When comparing these three radars that have "essentially" the same role it can be seen that there are large differences in the calculated $Bw_{-40\ dB}$ bandwidths ranging from 25.3 MHz for the Magnetron based system through 24.9 MHz for the TWT to 5.1 MHz for the Solid State system.

The measured results show that the TWT system in practice has a narrower 40 dB bandwidth than predicted, the measured results being 4 MHz for the Solid state radar, 10 MHz for the TWT and 45 MHz for the Magnetron.

The Spectra of the driven systems (i.e. TWT and Solid State) are much more symmetrical than Magnetron systems. In these driven systems, the shape of the spectrum is controlled by the drive system not by the valve. The top of the spectrum shows the characteristic shape caused by non-linear FM chirp.

This comparison shows that the choice of the radar implementation can make up to a 10:1 difference at the 40dB level, but has less of an effect at the 3dB level. The 3dB bandwidth is a product of the range resolution required and is not dependent upon the transmitter design.

Figure 3.1.2-11 Emission Mask ATC Radar Types



A further point to consider, as well as the bandwidth occupied by the spectrum, is that to achieve the frequency diversity performance required, these ATC systems also operate on at least two frequencies. The Solid State system operates on four frequencies continuously[21], while the TWT Systems only use four frequencies in dual diversity mode, that is, it only uses two of the four at any given time switching over to the other pair if a fault develops in the first channel.

However when making these type of comparisons it must be recognised that whilst the systems are being used in essentially the same role, the systems were designed for different basic requirements.

The TWT based system operates with a range cell of 0.5 μs, a requirement driven not by resolution but by the detailed clutter specification placed on the system. The use of more and smaller range cells gave more ability to control the clutter. The other two systems operate with range cells of 1.0 μs, which is the maximum acceptable for basic ATC designs. If the TWT were to operate with a compressed pulse length of 1 μs then the calculated 40 dB bandwidth would fall from 24.9 to 22 MHz.

The TWT system also has a tuning bandwidth of 300 MHz, where the wider bandwidth provides extended Electronic Counter Measures (ECM) performance. This feature is used when the system is supplied in other configurations apart from strictly Civil ATC. Until recently it has not proved possible to design Solid State systems of this type to have the wider bandwidth needed to provide the ECM performance required. Recent advances in transistor design now mean that system operating bandwidths of 400 MHz are becoming feasible.

Both the driven systems have lower emission bandwidths than the Magnetron based system and, having crystal locked drives, do not suffer the problems associated with Magnetron drift with temperature, pushing, pulling or ageing.

The difference in transmitted bandwidth between the two driven systems and in particular the reason for the difference in the -40 dB bandwidth, is due to two features:

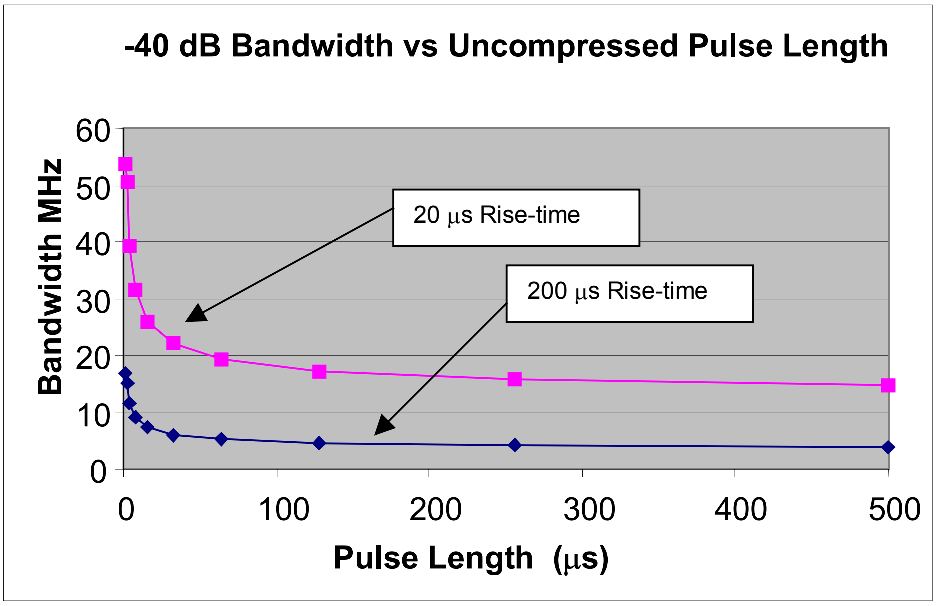
- The rise time in the transmitted pulse of the Solid State is some 10 times longer than that in the TWT system. In a centralised solid state transmitter made up of individual modules, it is possible to control or "shape" the rising and falling edge of the pulse, this is not possible in a TWT based system. By having a slow rising pulse the bandwidth is minimised.

[21] Some solid state systems can operate with two frequencies only

- The second feature of the Solid State system is its need to use long pulses. Long pulses are required in a solid state system as a consequence of its low peak power. In order to achieve the required energy in the pulse to successfully detect the target, the pulse length must be increased.

The combination of long pulses and slow rise-times leads to lower emission bandwidths. The system also uses pulse compression to achieve the required range cell size. The combination of chirp together with the long pulses also reduces the bandwidth occupied compared to an equivalent magnetron radar. Figure 3.1.2-12 below shows the calculated -40 dB bandwidth as a function of pulse length for a constant compressed pulse length of 1 µs. This is shown for two sample rise times of 20 µs and 200 µs.

Figure 3.1.2-12 Variation of -40 dB Bandwidth with Uncompressed Pulse Length for fixed Compressed Pulse Length of 1 µs



However it must be remembered that the long pulse radars (e.g. Solid State etc.) must also make use of a short pulse for short range targets that are eclipsed by the long pulse and for this pulse, the only control mechanism available is the rise-time.

The TWT system defined in Table 3.1.2-3 swaps the long and short pulse frequencies, on alternate bursts. The time-averaged spectrum measured will thus be a composite spectrum of the long and the short pulse.

The spectrum masks for the two pulse lengths are based on levels relative to the maximum of the spectral power density so it is necessary to calculate the difference in the two spectral power densities.

The maximum spectral power density P_t is normally defined in dBm/kHz and is calculated from the following formula[22]:

$$P_t = P_p + 20\log(t) + 10\log(PRR) - PG - 90$$ Equation 3.1.2-3

where :

P_p = *Peak power in dBm*

t = *Pulse Length in µs*

[22] NTIA Document Radio Spectrum Engineering Criteria Chapter 5 Section 4.1

PG = *10log(d) where d is compression ratio*

PRR = *Pulse Repetition Rate in Hz*

For the TWT system defined in Table 3.1.2-3 this results in the following values of P_t.

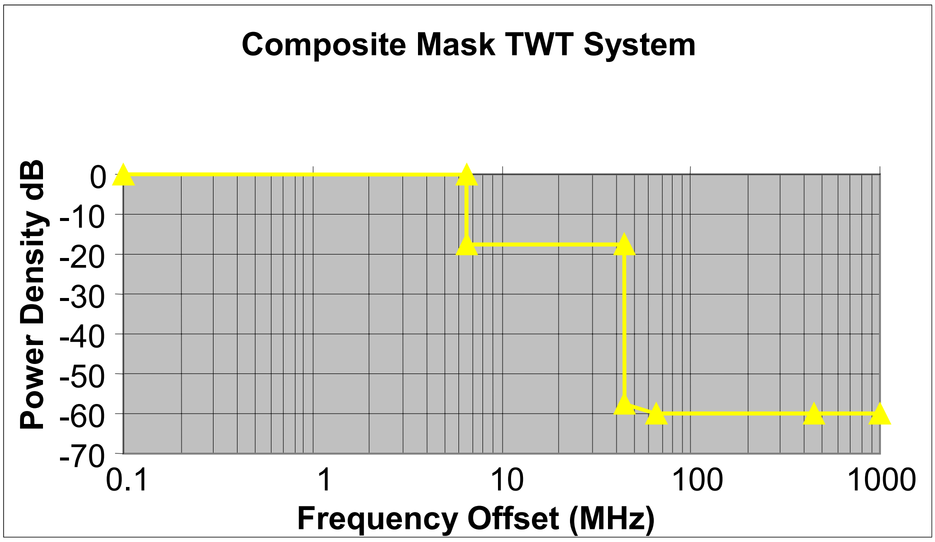
Long Pulse P_t = 28.3 dBm/kHz

Short Pulse P_t = 10.9 dBm/kHz

This gives a difference in P_t = 17.4 dBm/kHz.

Figure 3.1.2-13 below shows the composite mask produced by adding the maximum values of the two masks with an offset of 17.4 dB.

Figure 3.1.2-13 Composite Mask TWT System[23]



3.1.2.3.4 Aeronautical Radio Navigation Radars Ground Based (X-Band)

These types of radar are used for shorter range applications than the S-Band systems previously described. The Airfield Control Radar (ACR) is used for local surveillance and Surveillance Radar Approach (SRA) applications. The Precision Approach Radar (PAR) is used for precision approach landings and the Airport Surface Movement Detection Equipment (ASDE) for controlling aircraft on the ground. Until recently all these systems were Magnetron based and with the exception of any spatial modulation of filtering produced by the antenna, would have had very similar characteristics. However recently solid state systems have started to become available for the PAR and ASDE applications.

Table 3.1.2-7 Aeronautical Radio Navigation Radars Ground Based (X-Band)

CHARACTERISTICS	Airfield Control Radar	PAR	ASDE
Tuning range (GHz)	9.3 to 9.5	9.0 to 9.2	9.3 to 9.5
Operational Frequencies Used	2 (9320 & 9460 MHz)	1	1[24]

[23] This mask is not directly measurable

CHARACTERISTICS	Airfield Control Radar	PAR	ASDE
Frequency Accuracy	20 MHz	150 kHz	30 MHz
Frequency Stability	≈50 MHz	75 kHz	≈50 MHz
Modulation	P0N	NDA	P0N
Transmitter Power into Antenna (kW)	50	0.5	10
Pulse width (μs)	0.1 & 0.5	Variable, 0.05 min	0.04
Pulse rise/Fall time (μs)	0.015[25]	≈0.02	0.015
Pulse repetition rate (Hz)	2000 & 1000	Variable	4000
Duty cycle (%)	0.05 max	20	0.016
Chirp bandwidth MHz	0	NDA	0
Compression ratio	NA	NDA	NA
RF emission bandwidth (-3 dB) MHz	5 & 2	NDA	25
RF emission bandwidth (-20 dB) MHz	32.7 & 20.7[26]	NDA	≈73
RF emission bandwidth (-40 dB) MHz[27]	50 to 150 [28]	NDA	≈150
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil & Cosec^2	Pencil/Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	Reflector	Phased Array	Open Array 18 foot
Antenna Horizontal beamwidth -3dB (degrees)	0.65	NDA	0.4[28]
Antenna polarisation	Circular	NDA	Horizontal
Antenna mainbeam gain (dBi)	37 & 41.5	NDA	36

[24] One UK system operates in dual frequency diversity, the second frequency is in the range 9.1 to 9.3 GHz

[25] Estimated from similar systems

[26] Estimated from pulse parameters

[27] Most Magnetrons exhibit distorted spectra around the operating frequency due to low current twinning and frequency pushing effects. This means that every pulse starts at a low frequency before stabilising at its operating frequency. This expands the –60 dB bandwidth (and consequently the -40 dB bandwidth) by some 20 MHz in the case of the ATC magnetrons at a relatively long pulse of 1 μs. This can be significantly more at short pulse and other frequency bands. The -40 dB is thus very system and device dependent. For X Band devices, depending on the pulse length, the -40dBc bandwidth is estimated to lie within the region of 50 to 150 MHz.

[28] Estimated from antenna size

CHARACTERISTICS	Airfield Control Radar	PAR	ASDE
Antenna Vertical beamwidth -3dB (degrees)	2.5	NDA	≈20
Antenna horizontal scan rate (degrees/sec)	120 & 60	1 sec[29]	360
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	360 degrees, Continuous	Sector ± 15°[30]	360 degrees, Continuous
Antenna vertical scan rate (degrees/sec)	NA	1 sec[31]	NA
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA	Sector -1 to +7	NA
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	-20 / -30	NDA	≈ -23 / -30
Antenna height above ground (m)	1	2 & 3	Site Dependent

In the UK the next generation of PARs currently being installed will use a solid state active array antenna in place of the traditional mechanically scanned antenna used with a Magnetron transmitter. Table 3.1.2-7 gives the characteristics of three systems. The data given for the ACR is the more modern of the two X-Band ACR types listed in the UK, the PAR is the new type and the ASDE parameters are based on the most numerous type in use.

The ASDE systems described use slotted waveguide antennas 18 foot wide with a fan beam of approx. 20° elevation beamwidth, however some other systems in use in the UK have bespoke reflector antennas with shaped coverage.

The ACR antennas are traditional shaped reflectors, the one listed has a two-beam antenna system, a Surveillance and a Control beam.

The PAR system uses two fan beam antennas one scanning in azimuth and one in elevation.

Figures 3.1.2-14, 15 and 16 give the calculated emission masks for these three systems.

[29] Antenna scans left & right at a 1s update rate.

[30] The antenna can be mechanically slewed to any required azimuth

[31] Antenna scans up & down at a 1s update rate

Figure 3.1.2-14 Airfield Control Radar X-Band 0.1 µs Pulse

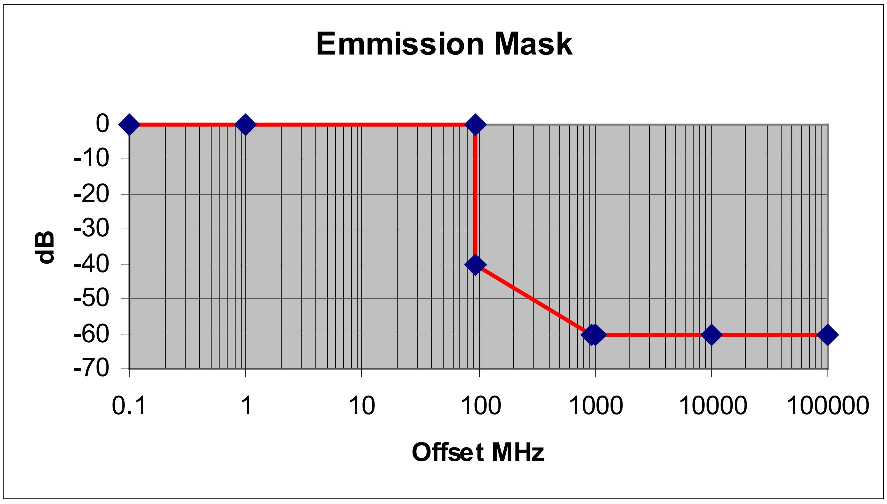


Figure 3.1.2-15 X-Band Precision Approach Radar 50 ns pulse length

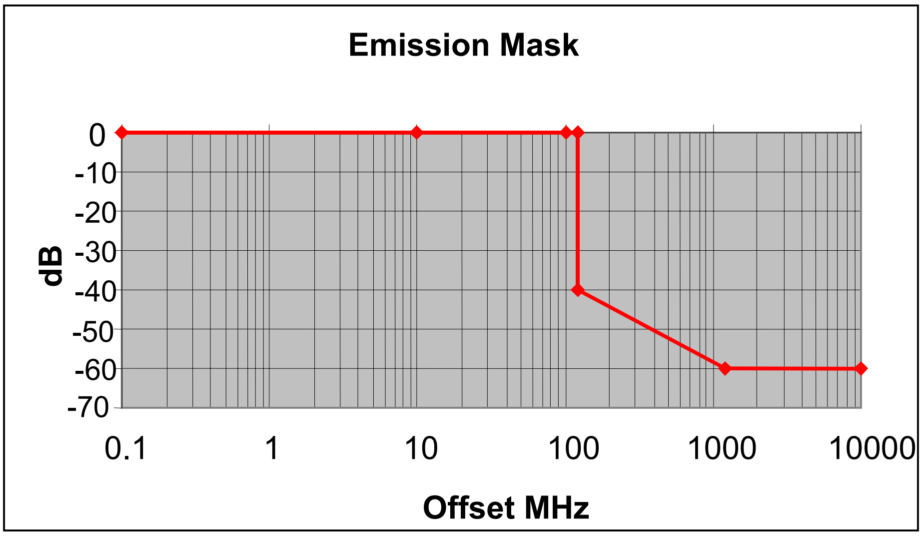
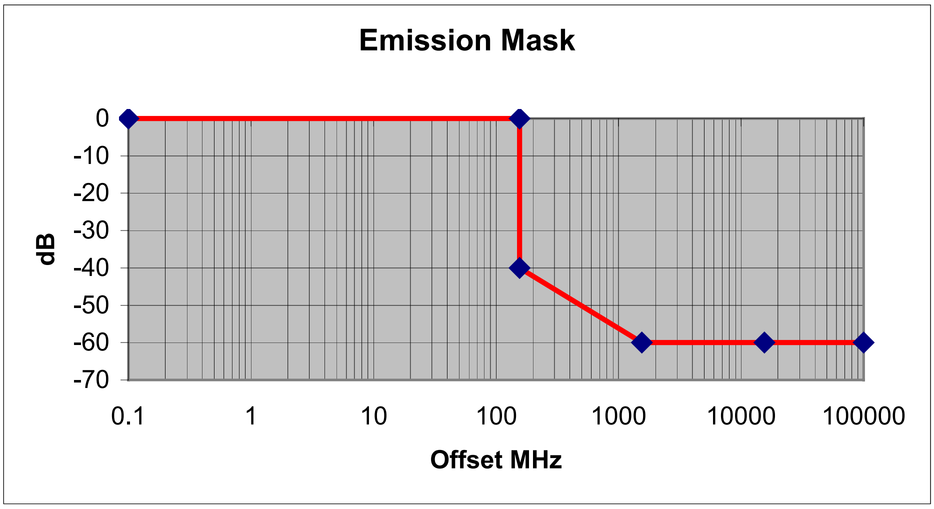


Figure 3.1.2-16 ASDE X-Band



Of the three systems listed, the two that are Magnetron based have very similar characteristics. The third system, the PAR, is a solid state system operating at much lower peak power.

3.1.2.3.5 Aeronautical Radio Navigation Radars Ground Based (Ku-Band)

Traditionally Ku-Band has been used for high performance ground movement use, as this frequency was seen as a good compromise between angular resolution and antenna size. In the USA, the Federal Aviation Administration (FAA) funded the development of and procurement of the ASDE-3 radar. This radar utilised a TWT transmitter and operated on multiple frequencies (upto 14) to minimise the effect of rain clutter that starts to become considerable at Ku-Band. This approach gave very good RF performance but at very high cost of ownership. In the USA the ASDE-X (X = Experimental) research programme was started in order to develop a replacement for the ASDE-3. From this programme has developed the ASDE-X (X = X-Band). However the FAA required the system to operate in the 9.0 to 9.2 GHz region of the X-Band to avoid any conflict with Maritime Navigation systems. In the UK the Ku-Band ASDEs are Magnetron based systems and operate on up to three frequencies. They all use reflector antennas (squintless) and have inverse Cosec$^{1.4}$ shaping to give constant detection probability with range to targets moving on the ground.

Table 3.1.2-8 Aeronautical Radio Navigation Radars Ground Based (Ku-Band)

CHARACTERISTICS	ASDE
Tuning range (GHz)	15.4 to 16.4
Operational Frequencies Used	2 or 3
Frequency Accuracy	≈ 40 MHz
Frequency Stability	≈80 MHz
Modulation	P0N
Transmitter Power into Antenna (kW)	20
Pulse width (µs)	0.04
Pulse rise/Fall time (µs)	0.016[32]
Pulse repetition rate (Hz)	8192
Duty cycle (%)	0.033
Chirp bandwidth MHz	0
Compression ratio	0
RF emission bandwidth (-3 dB) MHz	14.3[32]
RF emission bandwidth (-20 dB) MHz	50[32]
RF emission bandwidth (-40 dB) MHz	119[32]
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Inverse Cosec$^{1.4}$
Antenna type (reflector, phased array, slotted array, etc.)	Shaped Reflector
Antenna Horizontal beamwidth -3dB (degrees)	0.33
Antenna polarisation	Circular
Antenna mainbeam gain (dBi)	41

[32] Measured

CHARACTERISTICS	ASDE
Antenna Vertical beamwidth -3dB (degrees)	3
Antenna horizontal scan rate (degrees/sec)	360
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	360 degrees, Continuous
Antenna vertical scan rate (degrees/sec)	NA
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	≈ -26 / -35
Antenna height (m) above ground	Site Dependent

Figure 3.1.2-17 Calculated Emission Mask ASDE Ku-Band

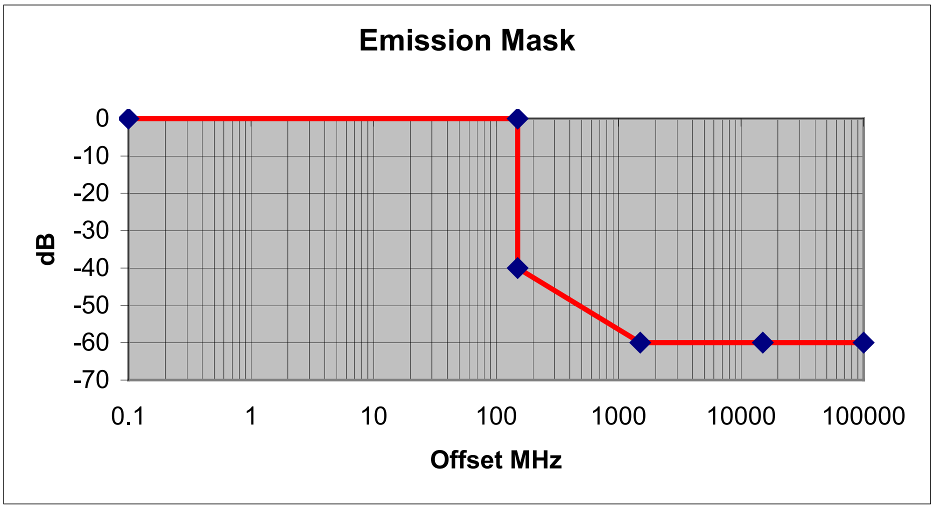
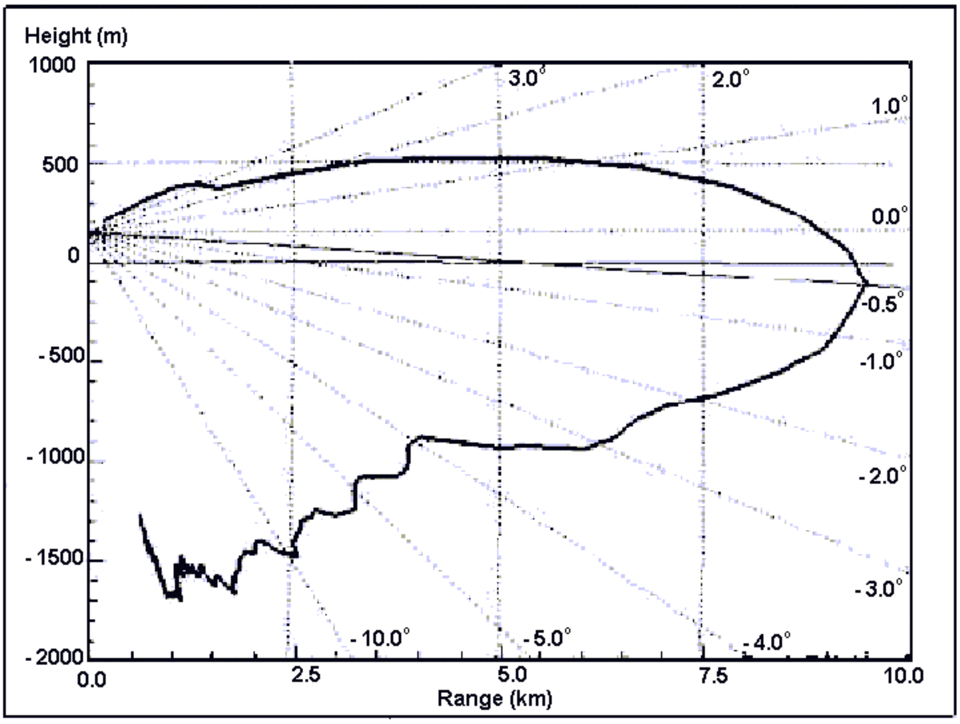


Figure 3.1.2-18 Typical Inverse "Cosec^2" Coverage used by an ASDE



The coverage diagram shows the detection contour of the radar for a given Probability of Detection (Pd) and Probability of False Alarms (P_{fa}). To a first approximation, the shape of the coverage diagram is related to the vertical beam pattern of the antenna. This shows that the antenna is designed to preferentially radiate below -4° to provide constant detection for targets approaching on the ground. Such an antenna will produce more ground-wards interference than a traditional air surveillance radar that is designed to radiate up-wards.

Table 3.1.2-9 Comparison of measured to calculated bandwidths - Ku-Band ASDE

Measured MHz			Calculated[33] MHz		
3 dB BW	**20 dB BW**	**40 dB BW**	**3 dB BW**	**20 dB BW**	**40 dB BW**
14.3	50	119	25	70.75	300.4

Table 3.1.2-9 above gives a comparison of the calculated and measured, Figure 19 shows the measured results for a Ku-Band ASDE.

[33] See Section 3.1.2.5

Figure 3.1.2-19[34] Measured Spectrum Ku-Band ASDE

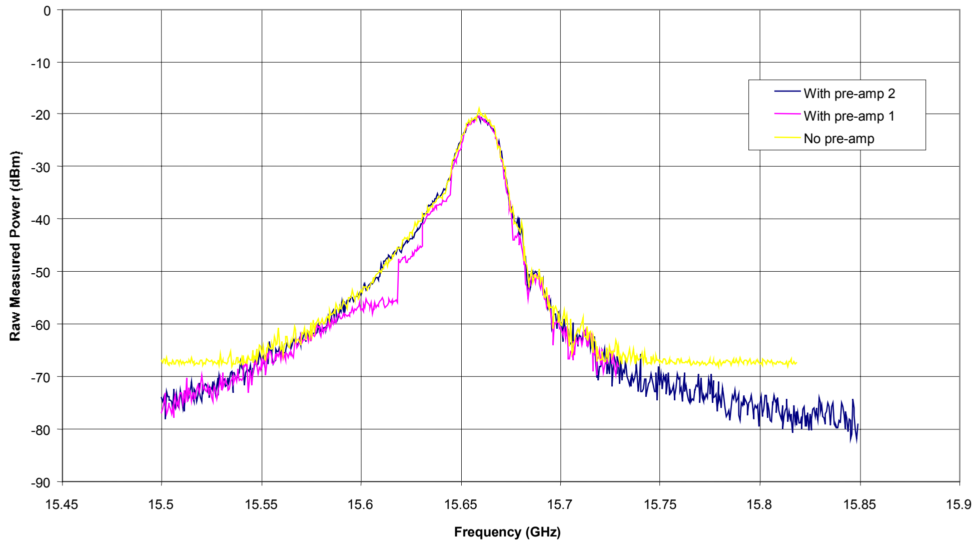


Table 3.1.2-9 shows that the measured band-widths are considerably below those calculated using the formula in Section 3.1.2.5.

3.1.2.3.6 Meteorological Radars Ground Based (C-Band)

The UK Met-Office, Met Eireann and the Jersey State operate a network of met radars to measure precipitation over the British Isles. These systems are Magnetron based systems and use pencil beam parabolic reflector antennas. All the UK systems operate on a single frequency of 5.625 GHz.

Table 3.1.2-10 Meteorological Radars Ground Based (C-Band)

CHARACTERISTICS	MET
Tuning range (GHz)	5.4 to 5.9
Operational Frequencies Used	1 (5.625 GHz)
Frequency Accuracy	20 MHz
Frequency Stability	1 MHz
Modulation	P0N
Transmitter Power into Antenna (kW)	250
Pulse width (µs)	2 or 0.5[35]
Pulse rise/Fall time (µs)	0.050
Pulse repetition rate (Hz)	300 or 1200
Duty cycle (%)	0.06
Chirp bandwidth MHz	0
Compression ratio	NA

[34] Source - measurement made under this contract - see section 3.1.3

[35] The 0.5 µs Pulse is only used on two systems fitted with Doppler processing

CHARACTERISTICS	MET
RF emission bandwidth (-3 dB) MHz	0.5
RF emission bandwidth (-20 dB) MHz	3.0
RF emission bandwidth (-40 dB) MHz	15
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil
Antenna type (reflector, phased array, slotted array, etc.)	Reflector
Antenna Horizontal beamwidth -3dB (degrees)	1
Antenna polarisation	Linear
Antenna mainbeam gain (dBi)	43
Antenna Vertical beamwidth -3dB (degrees)	1
Antenna horizontal scan rate (degrees/sec)	0 or 0.6 to 36
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Variable from fixed to continuous
Antenna vertical scan rate (degrees/sec)	10
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	Helix
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	-25 / -30
Antenna height above ground (m)	Various

Figure 3.1.2-20[36] Measured Spectrum Weather Radar Long Pulse

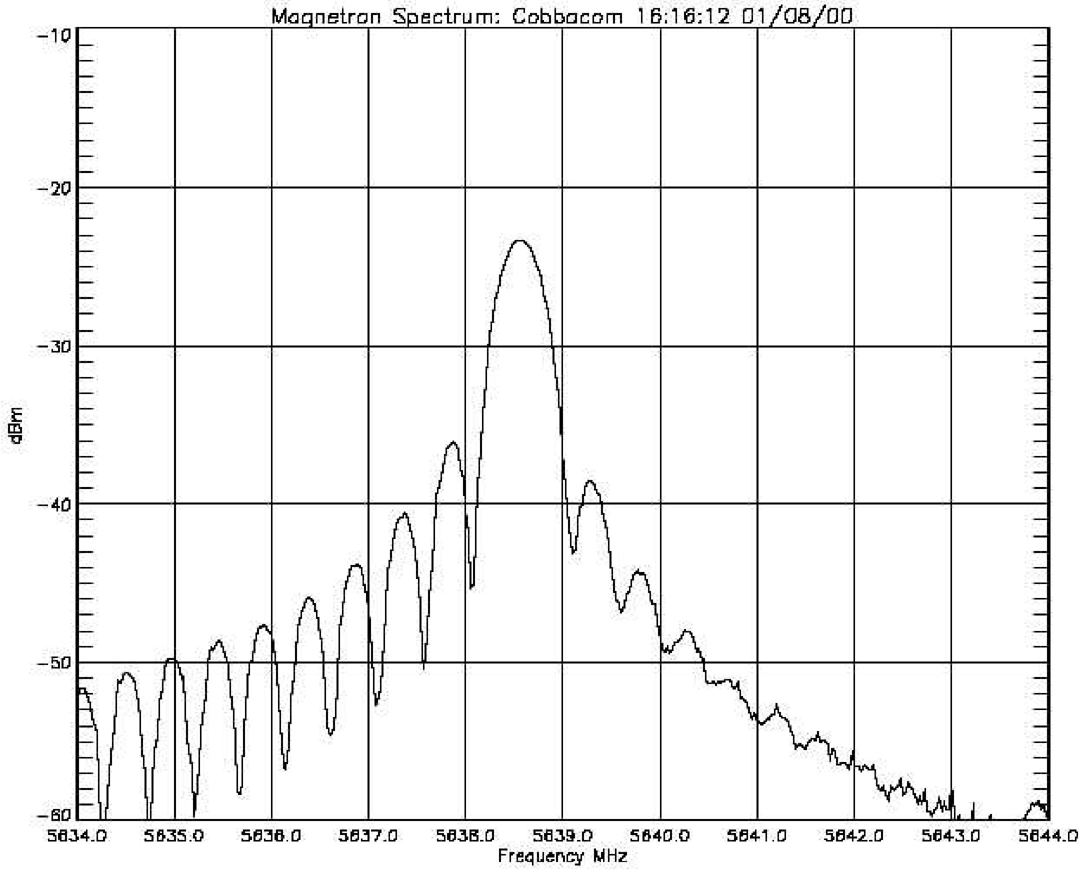


Table 3.1.2-11 Comparison of results Weather Radar Long Pulse

Measured MHz			Calculated[33] MHz		
3 dB BW	20 dB BW	40 dB BW	3 dB BW	20 dB BW	40 dB BW
0.5	2.7	≈15	0.5	3.18	19.6

[36] Source American Meteorological Society Web http://cdserver.ametsoc.org/cd/010430_1/html/radcal-08-clarke-transmitter-presentation/FMU.html

Figure 3.1.2-21 Emission Mask Weather Radar Long Pulse 2µs

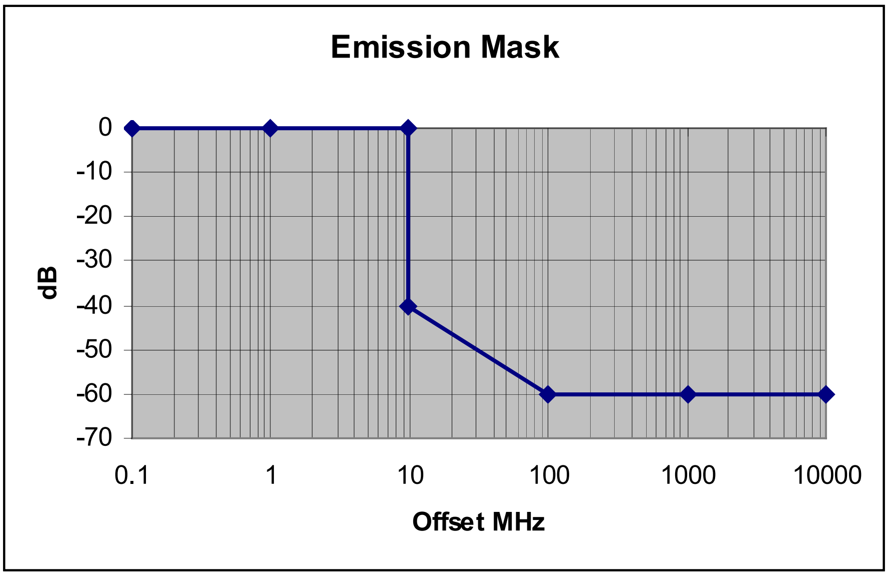
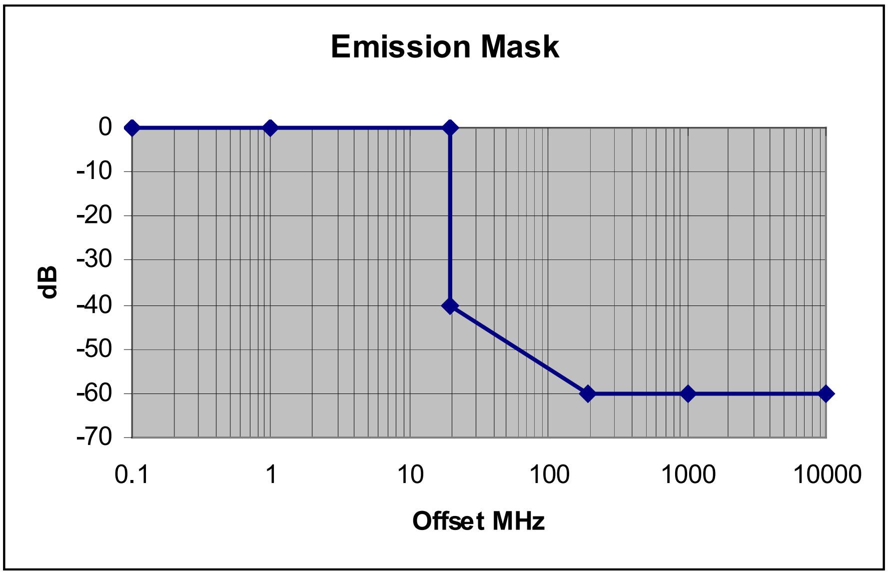


Figure 3.1.2-22 Emission Mask Weather Radar Short Pulse 0.5µs

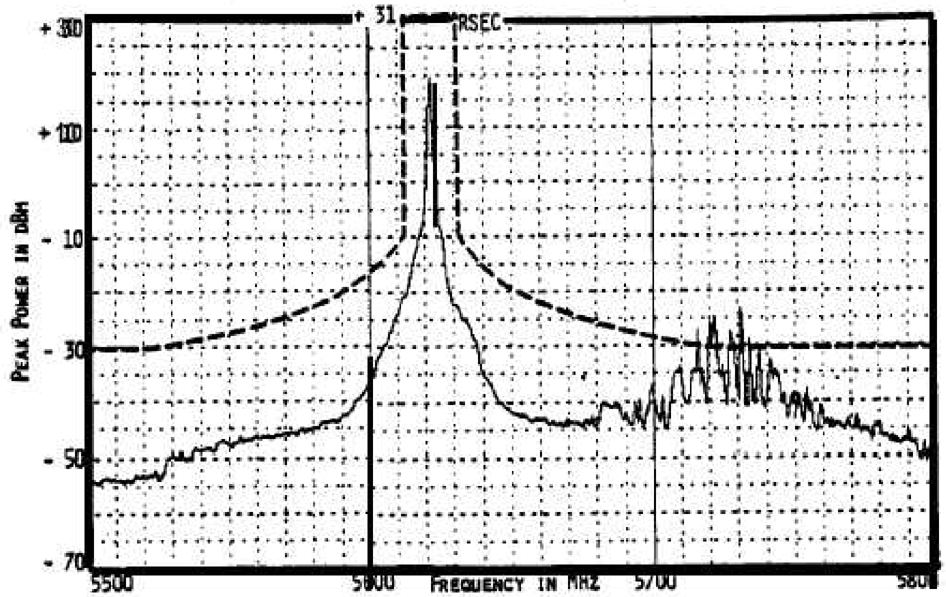


These systems use Coaxial Magnetrons which are not as susceptible to frequency pulling as a standard Magnetron so they have a much cleaner spectrum on the lower frequency side. They do however exhibit extra radiation on the high frequency side of the spectrum.

A survey of the use of Coaxial Magnetrons was carried out by the National Telecommunications and Information Administration (NTIA) in the USA[37] and concluded:

[37] Output Tube Emission Characteristics of Operational Radars NTIA Report Number 82-92

Figure 3.1.2-23[38] US Weather Radar Spectrum Coaxial Magnetron[39]



"The coaxial magnetron produces a cleaner spectrum (near centre frequency) than the conventional magnetron, completely eliminating the "porch" which is present with conventional magnetrons. Further away in frequency, however, the improvement is not particularly noticeable. A "hump" about 100 MHz above the fundamental frequency is present in many coaxial magnetron spectra. Whether the {1, 2, 1} mode "hump" of a coaxial magnetron spectrum is more objectionable than the frequency pulling "porch" (produced by conventional magnetrons) is a matter of question".

The UK radars were initially fitted with standard Magnetrons but modified to take the coaxial types. This was carried out not to improve the spectrum but to reduce the effect of ageing and to improve the "life" of the tube[40].

Measurements on the UK weather radars (see section 3.1.3.5.7) show a similar "hump" at approximately 100 MHz above the fundamental frequency. This is not surprising as with the limited availability of C-Band Coaxial Magnetrons it is likely that the UK Magnetrons are the same or a development of the US type.

3.1.2.3.7 Meteorological Radars Airborne (X-Band)

These types of radars are used in commercial and general aviation to detect weather phenomena such as storms and wind-sheer. Some systems are also capable of interrogating Search And Rescue Transponders (SARTs) and RAdar beaCONs (RACONs). General aviation pilots also use these systems for ground mapping to aid navigation.

The majority of installed systems are Magnetron based however solid state systems are now coming into service. Of the Magnetron systems there are many system variants generally based on antenna size.

[38] Source NTIA report 82-92

[39] The Radio Spectrum Engineering Criteria (RSEC) limit is not referenced to the peak of the spectrum due to the use of a wide measurement bandwidth.

[40] AMS 61ST Annual Meeting: Workshop on Radar Calibration "Operational Transmitter Issues in the UK Met Office"

Table 3.1.2-12 Meteorological Radars Airborne (X-Band)

CHARACTERISTICS	Solid State	Magnetron
Tuning range (GHz)	9.3 to 9.5	9.3 to 9.5
Operational Frequencies Used	1 (9.345 MHz)	1 (9.345 MHz)
Frequency Accuracy	≈ 150 kHz	30 MHz
Frequency Stability	≈ 75 kHz	≈ 50 MHz
Modulation	NDA	P0N
Transmitter Power into Antenna (kW)	0.125	10
Pulse width (µs)	1. 25, 6, 18	0.1, 0.5, 2.35
Pulse rise/Fall time (µs)	≈0.02	≈0.015
Pulse repetition rate (Hz)	6000,1600,380	1600, 800, 200
Duty cycle (%)	1 max	0.05 max
Chirp bandwidth MHz	0	0
Compression ratio	NA	NA
RF emission bandwidth (-3 dB) MHz	0.8, 0.17, 0.06	10, 2, 0.5
RF emission bandwidth (-20 dB) MHz	5.1, 1.1, 0.4[41]	≈40, 8, 4
RF emission bandwidth (-40 dB) MHz	51.2, 10.7, 3.6[41]	50 to 150[25]
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil	Pencil
Antenna type (reflector, phased array, slotted array, etc.)	Flat Plate	Flat Plate
Antenna Horizontal beamwidth -3dB (degrees)	2.9 or 3.6	3.6 or 4.8 or 7.3
Antenna polarisation	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	35 or 33	33 or 31 or 27
Antenna Vertical beamwidth -3dB (degrees)	2.9 or 3.6	3.6 or 4.8 or 7.3
Antenna horizontal scan rate (degrees/sec)	45 or 38	45 or 38
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Sector 60°	Sector 60°
Antenna vertical scan rate (degrees/sec)	Tilt	Tilt
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	Sector	±15°
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	NDA	NDA

[41] Estimated from rectangular pulse.

Figure 3.1.2-24 Calculated Emission Mask Airborne Weather Radar 2.0μs

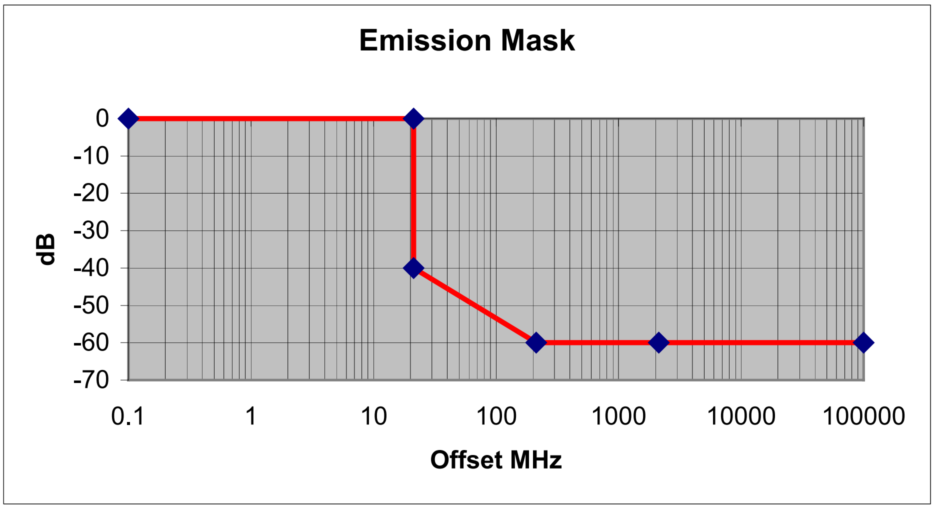
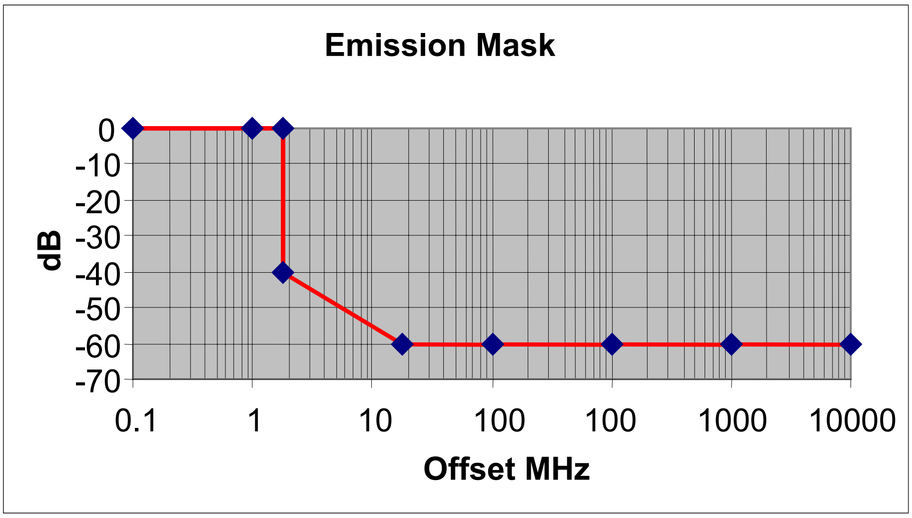


Figure 3.1.2-25 Calculated Emission Mask Airborne Weather Radar Solid State 18 μs pulse



3.1.2.3.8 Marine Radio Navigation Radars (X-Band)

There are many radar types that come into this category of radar with literally hundreds of variants. However they are, with a few very specialised exceptions, nearly all magnetron based systems. The main difference in the transmitted spectrum will be spatial differences caused by antenna modulation. However the emission masks are applied to a test result which is designed to remove the effect of antenna modulation.

Table 3.1.2-13 gives the characteristics for the two most "professional" types of marine radar that are used on SOLAS vessels and on bespoke Vessel Traffic System (VTS) systems. The main differences between the systems is the size of scanner used, those on ships range from 6 foot to 12 foot whereas the VTS systems use 8 foot to 22 foot open arrays or large, up to 7.5 metre reflector antennas.

Table 3.1.2-13 Marine Radio Navigation Radars (X-Band)

CHARACTERISTICS	Ship Based SOLAS	Shore Based VTS
Tuning range (GHz)	9.3 to 9.5	9.3 to 9.5
Operational Frequencies Used	1 (9410 MHz)	1 (9373 MHz[42])
Frequency Accuracy	30 MHz	30 MHz
Frequency Stability	≈ 50 MHz	≈ 50 MHz
Modulation	NA	NA
Transmitter Power into Antenna (kW)	50	25
Pulse width (μs)	0.08 to 1.2	0.04 to 1
Pulse rise/Fall time (μs)	0.015	0.02
Pulse repetition rate (Hz)	500 to 2200	400 to 8000
Duty cycle (%)	0.018 & 0.06	0.032 to 0.04
Chirp bandwidth MHz	0	0
Compression ratio	0	0
RF emission bandwidth (-3 dB) MHz	0.8 to 12.5	1 to 25
RF emission bandwidth (-20 dB) MHz	13.3 to 51.7	12.6 to 63.3
RF emission bandwidth (-40 dB) MHz	50 to 150 [25]	50 to 150 [25]
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan/Inverse $Cosec^2$
Antenna type (reflector, phased array, slotted array, etc.)	Slotted Waveguide	Slotted Waveguide /Reflector
Antenna Horizontal beamwidth -3dB (degrees)	0.75 or 0.95 or 1.23	0.6 or 0.3
Antenna polarization	Linear	Linear/Circular
Antenna mainbeam gain (dBi)	24 to 28	31 to 39[43]
Antenna Vertical beamwidth -3dB (degrees)	20 or 25	25
Antenna horizontal scan rate (degrees/sec)	120	120
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	360 degrees, Continuous	360 degrees, Continuous
Antenna vertical scan rate (degrees/sec)	NA	NA
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA	NA
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	-24 to -26 / -30 to -32	-26 / -32

[42] There are some proposals to use a frequency diversity system

[43] Reflector systems have considerably more gain for the same azimuth beamwidth than an open array scanner

CHARACTERISTICS	Ship Based SOLAS	Shore Based VTS
Height Above Ground (m)	NA	20

Figures 3.1.2-26 and 27 show the calculated emission masks for two selected pulse lengths for these types of radars.

Figure 3.1.2-26 Calculated Emission Mask SOLAS Marine Navigation Radar 80 ns Pulse

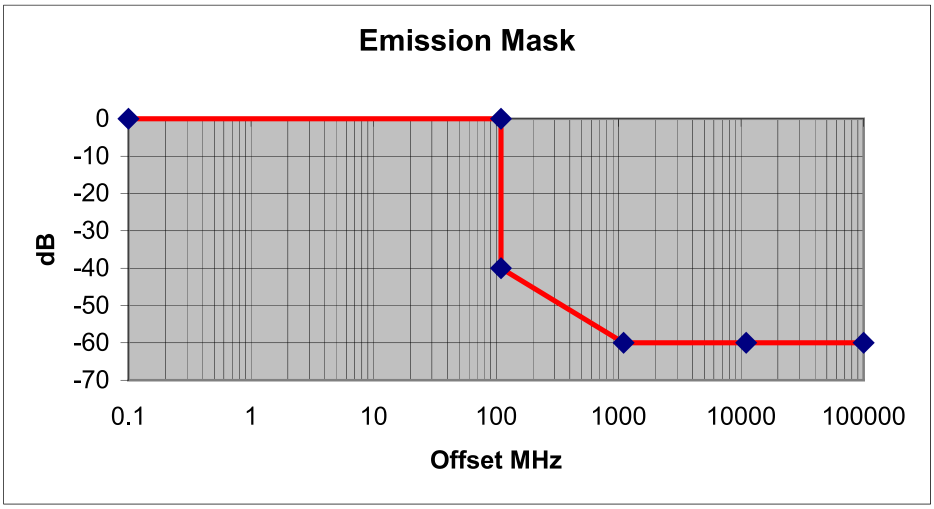


Figure 3.1.2-27 Calculated Emission Mask VTS Marine Navigation Radar 1µs Pulse

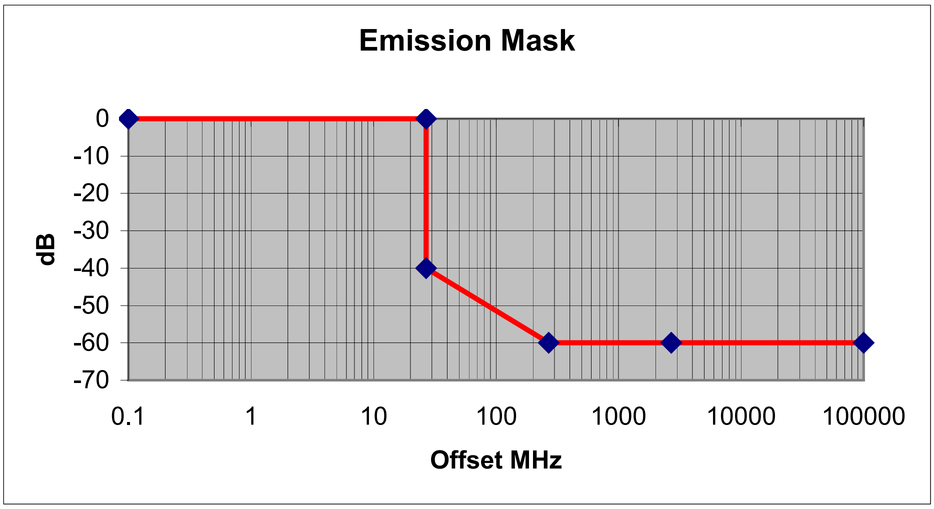


Table 3.1.2-14 below details two other radars of this type from the lower end of the specification range. These are the types of radar that would be fitted to a large pleasure craft, a small commercial vessel, a fishing craft or a small pleasure craft. They differ from those in Table 3.1.2-13 mainly in the power which can be as low as 1.5 kW and the antenna size which can be as small as a 10 inch radome scanner.

Table 3.1.2-14 Marine Radio Navigation Radars (X-Band)

CHARACTERISTICS	Ship Based Pleasure	Ship Based Fishing
Tuning range (GHz)	9.3 to 9.5	9.3 to 9.5
Operational Frequencies Used	1 (9410 GHz)	1 (9410 GHz)
Frequency Accuracy	30 MHz	30 MHz
Frequency Stability	≈ 50 MHz	≈ 50 MHz
Modulation	NA	NA
Transmitter Power into Antenna (kW)	4	12
Pulse width (μs)	0.08, 0.3, 0.8	0.08, 0.3, 0.8
Pulse rise/Fall time (μs)	0.015	0.015
Pulse repetition rate (Hz)	600, 1200, 2100	600, 1200, 2100
Duty cycle (%)	0.017, 0.036, 0.048	0.017, 0.036, 0.048
Chirp bandwidth	0	0
Compression ratio	0	0
RF emission bandwidth (-3 dB) MHz	12.5, 3.3, 1.25	12.5, 3.3, 1.25
RF emission bandwidth (-20 dB) MHz	≈ 63, 17, 6	≈ 63, 17, 6
RF emission bandwidth (-40 dB) MHz	50 to 150 [28]	50 to 150 [28]
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	22 inch Radome	4 foot or 6 foot Open Array
Antenna Horizontal beamwidth -3dB (degrees)	3.9	1.9 or 1.2
Antenna polarisation	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	≈ 25	28 , 30[44]
Antenna Vertical beamwidth -3dB (degrees)	20	22
Antenna horizontal scan rate (degrees/sec)	144	144
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	360 degrees, Continuous	360 degrees, Continuous
Antenna vertical scan rate (degrees/sec)	NA	NA
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA	NA
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	-22	-22 / -25

[44] Estimated from antenna size

CHARACTERISTICS	Ship Based Pleasure	Ship Based Fishing
Height Above Ground (m)	NA	20

Figures 3.1.2-28 and 29 show two calculated masks for these types of radars.

Figure 3.1.2-28 Calculated Emission Mask Marine Navigation Radar 0.3 µs Pulse

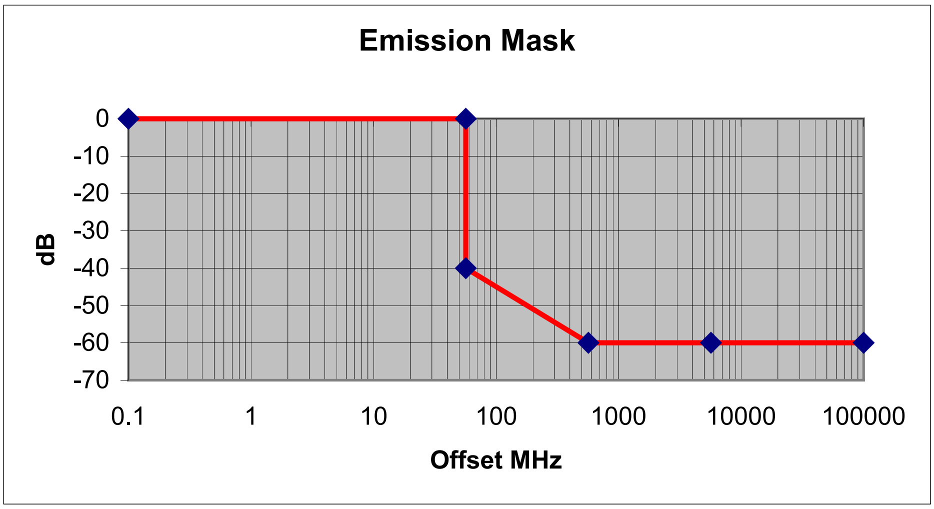


Figure 3.1.2-29 Calculated Emission Mask Marine Navigation Radar 0.8 µs Pulse

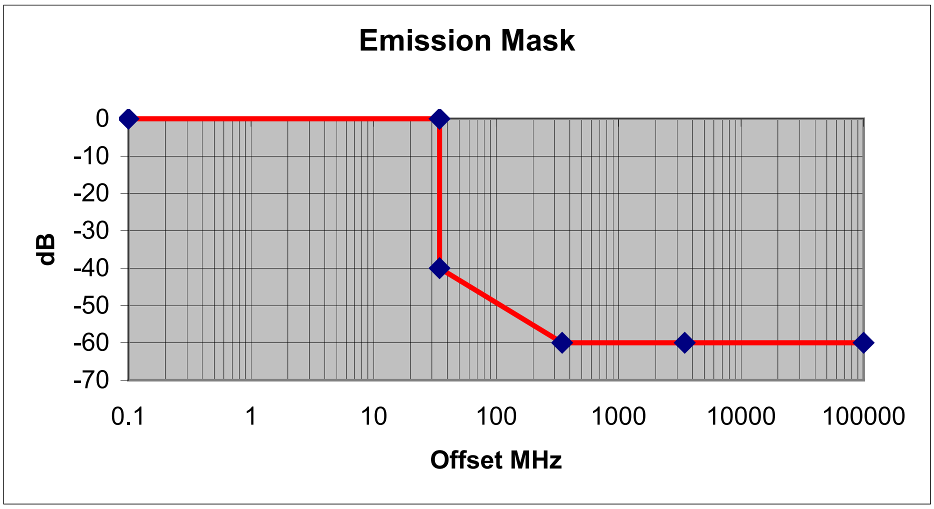
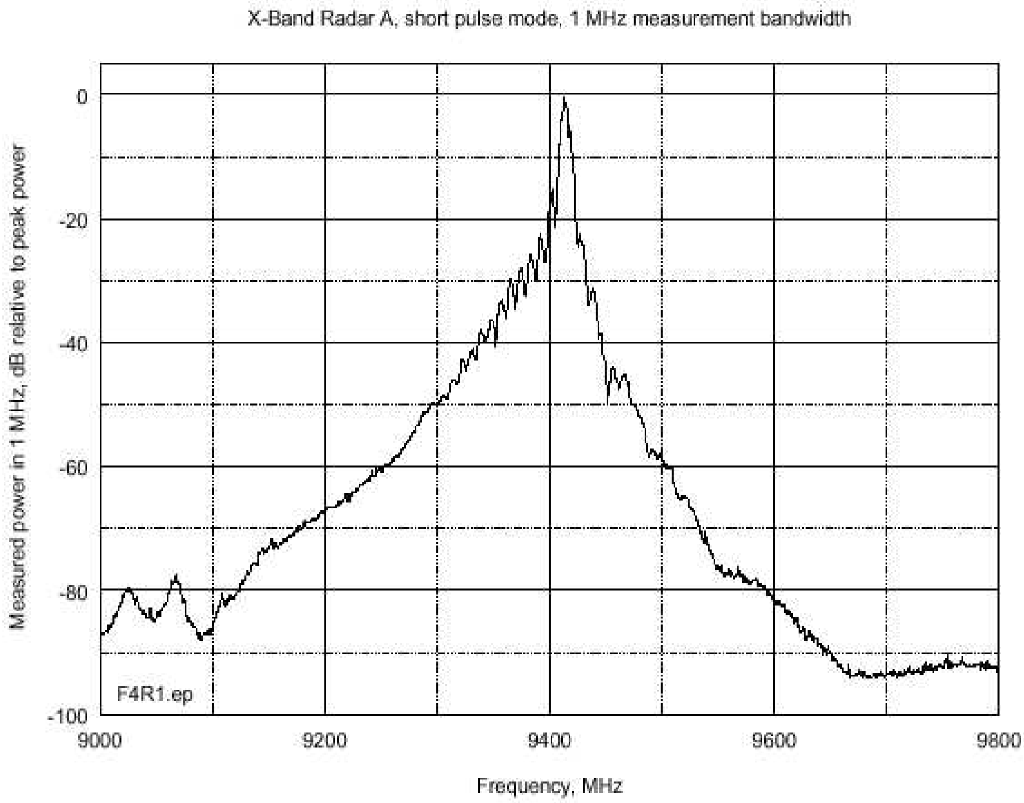


Figure 3.1.2-30 shows a measured spectrum of a Marine Navigation Radar. The radar tested was designed for professional commercial use. In order to speed up the measurements, the measurement was taken with the antenna fixed. The antenna used is an open array and thus will squint with frequency. The spectrum is thus subject to antenna modulation. However the spectrum close to the main-lobe down to approximately the 20dB level will be representative of this type of radar. Again this shows the classic Magnetron shape. If the antenna modulation is removed then the spectrum will widen significantly in the region of the -40 dB level.

Figure 3.1.2-30 Measured Spectrum Magnetron Short Pulse[45]



3.1.2.3.9 Marine Radio Navigation Radars (S-Band)

Larger vessels, particularly SOLAS vessels, carry S-Band radars as well as X-Band. In the future all SOLAS ships will be required to carry one of each type. These radars are very similar to the X-Band version, the main difference being that the antennas are electrically smaller giving rise to wider beam-widths.

Table 3.1.2-15 Marine Radio Navigation Radars (S-Band)

CHARACTERISTICS	Shore Based VTS	Ship Based SOLAS
Tuning range (GHz)	2.9 to 3.1	2.9 to 3.1
Operational Frequencies Used	1 (3050 MHz)	1 (3050 MHz)
Frequency Accuracy	10 MHz	10 MHz
Frequency Stability	≈10 MHz	≈10 MHz
Modulation	P0N	P0N
Transmitter Power into Antenna (kW)	25	30 or 60
Pulse width (μs)	0.05 to 1	0.08 to 1.2
Pulse rise/Fall time (μs)	0.02	0.015

[45] ITU Working Party 8B Radar Correspondence Group

CHARACTERISTICS	Shore Based VTS	Ship Based SOLAS
Pulse repetition rate (Hz)	800 to 8000	600 to 2200
Duty cycle (%)	0.08, 0.04	0.018 to 0.072
Chirp bandwidth MHz	0	0
Compression ratio	NA	NA
RF emission bandwidth (-3 dB) MHz	20 to 1	12.5 to 0.83
RF emission bandwidth (-20 dB) MHz	65.4 to 14.6	51.7 to 13.3
RF emission bandwidth (-40 dB) MHz	≈ 50 to 150	≈ 50 to 150
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	Open Array 13 foot or 22 foot	Open Array 12 foot
Antenna Horizontal beamwidth -3dB (degrees)	1.3 or 0.8	1.9
Antenna polarisation	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	28 or 30	28
Antenna Vertical beamwidth -3dB (degrees)	25	25
Antenna horizontal scan rate degrees/sec	120	120 or 156
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	360 degrees, Continuous	360 degrees, Continuous
Antenna vertical scan rate (degrees/sec)	NA	NA
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA	NA
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	-25 / -30	-25 / -30
Height Above Ground (m)	Variable	NA

Figure 3.1.2-31 Calculated Emission Mask S-Band VTS Marine Navigation Radar 50 ns Pulse

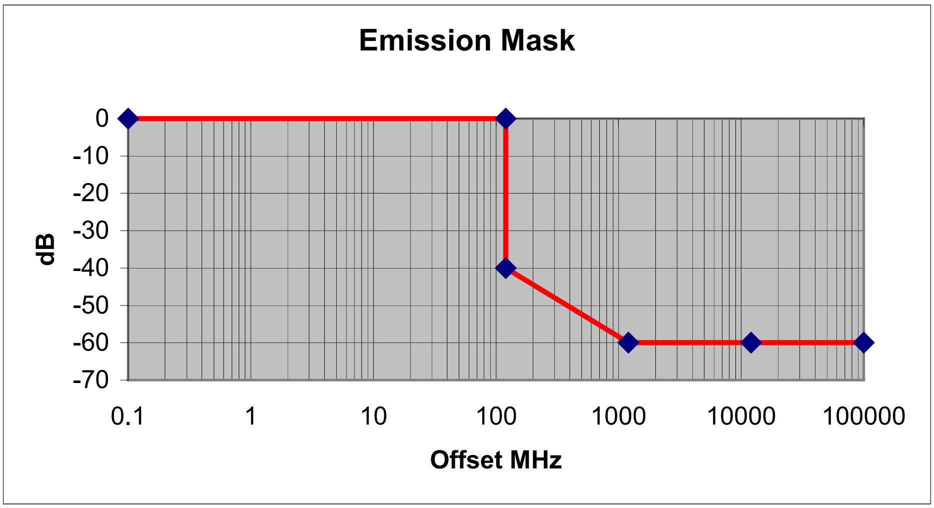


Figure 3.1.2-32 Calculated Emission Mask S-Band Marine Navigation Radar 1.2 μs Pulse

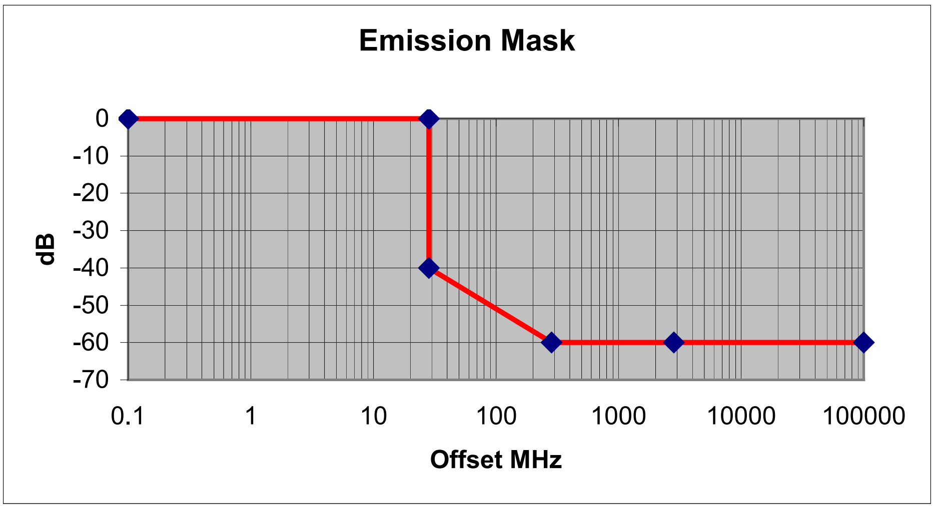
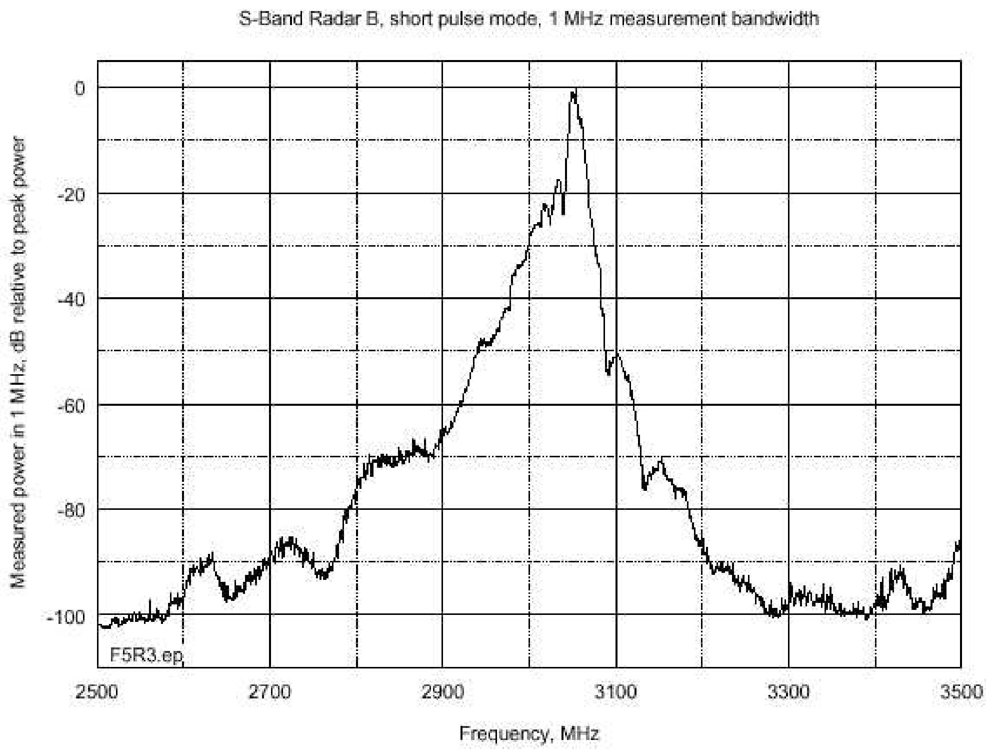


Figure 3.1.2-33 shows the measured spectrum of an S-Band Marine Navigation Radar, the radar tested was designed for professional commercial use. In order to speed up the measurements, these were made with the antenna fixed rather than rotating. The antenna used is an open array and thus will squint with frequency. The spectrum is thus subject to antenna modulation. However the spectrum close to the main-lobe down to approximately the 20dB level will be representative of this type of radar. Again this shows the classic Magnetron shape. If the antenna modulation is removed then the spectrum will widen significantly in the region of the -40 dB level.

Figure 3.1.2-33 S-Band Marine Navigational Radar Short Pulse[46]



3.1.2.3.10 Low Probability of Intercept Radars (LPI)

There are so called Low Probability of Intercept (LPI) marine navigational radars available. These work at X-Band and it may be worth considering their emission properties compared to a more standard design. Being classed as LPI they may be considered as producing less interference.

An LPI radar would have the following properties:

1W mean power 54 MHz Chirp at 9.35 GHz.

The spectral mask for such a radar is given below. Bw_{-40dB} is calculated using:

$$B_{-40} = 0.0003F_0 + 2B_d$$ Equation 3.1.2-3

where:

F_0 = 9350 MHz

B_d = 54 MHz

B_{-40} = 111 MHz

[46] Source ITU Working Party 8B Radar Correspondence Group

Figure 3.1.2-34 Showing the calculated mask for an LPI radar

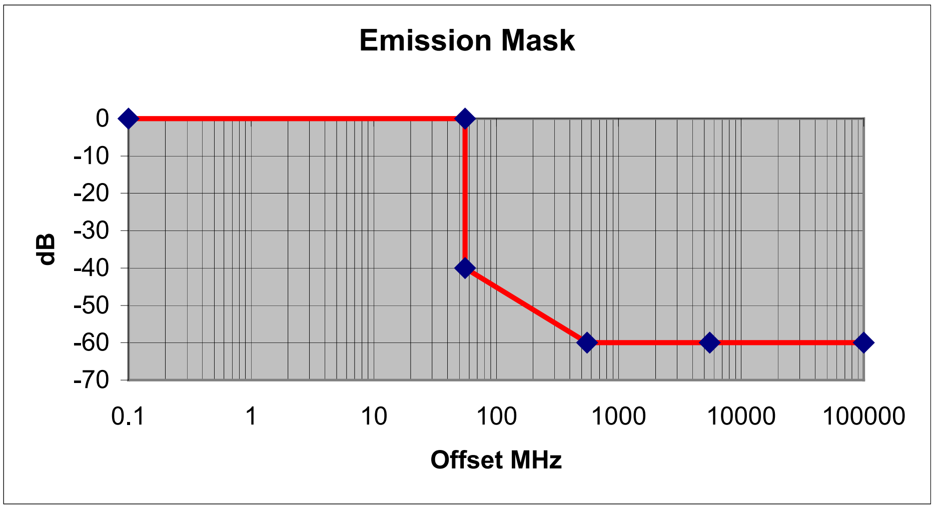


Figure 3.1.2-34 shows the calculated mask for such an LPI system. If we compare this with a pulse radar giving the same mean power, say 1µs pulse 1000 Hz at 0.1% duty cycle (i.e.1 W mean), then the emission mask for this radar is shown in Figure 3.1.2-35. In order to compare these masks, the peak spectral power density needs to be calculated. This is traditionally expressed in dBm/kHz.

For the LPI radar the peak of the spectral power density P_d is:

$$P_d = 10 \times \log\left(\frac{1000}{54000}\right) = -17.3dBm/kHz$$ Equation 3.1.2-4

For the Pulsed Radar this gives:

$$P_d = 10 \times \log\left(\frac{1000}{1000}\right) = 0dBm/kHz$$ Equation 3.1.2-5

Figure 3.1.2-35 Showing the calculated mask for a 1µs Pulsed Radar

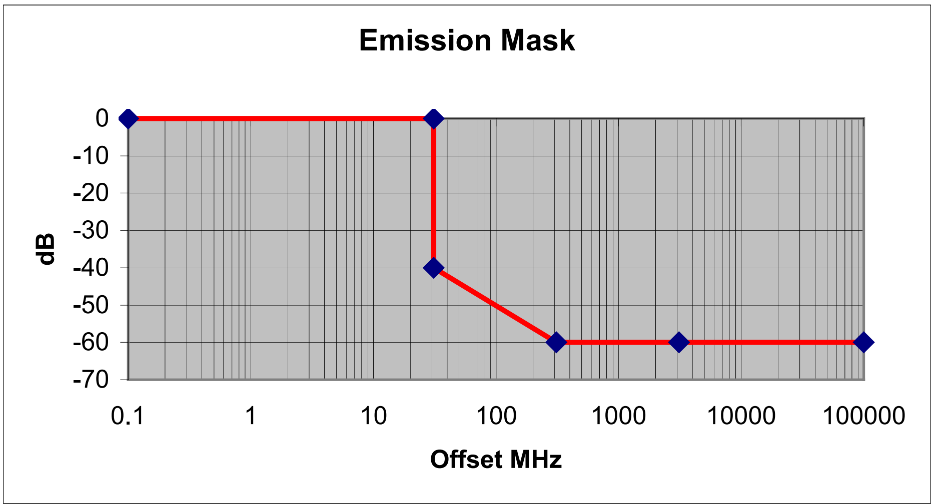


Figure 3.1.2-36 Comparison of a 1W, 1µs Pulsed and an LPI Radar

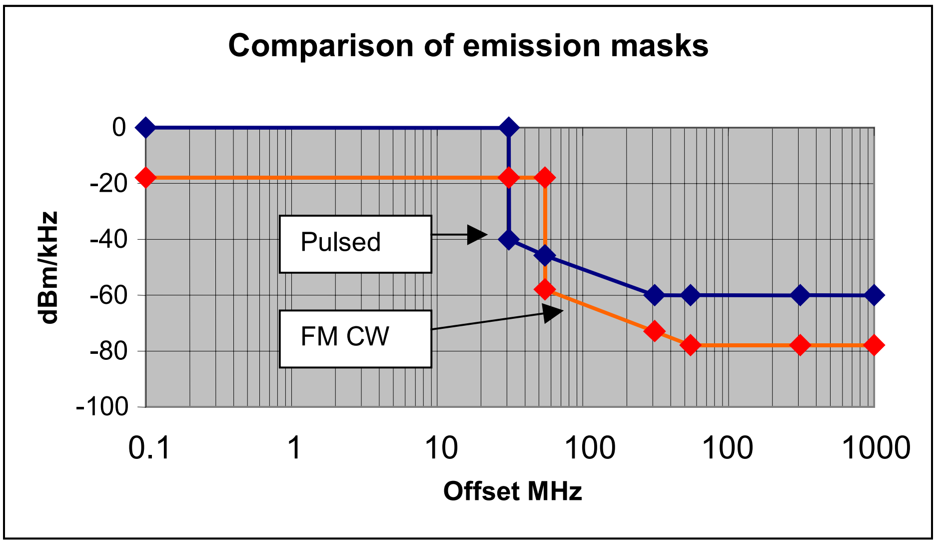
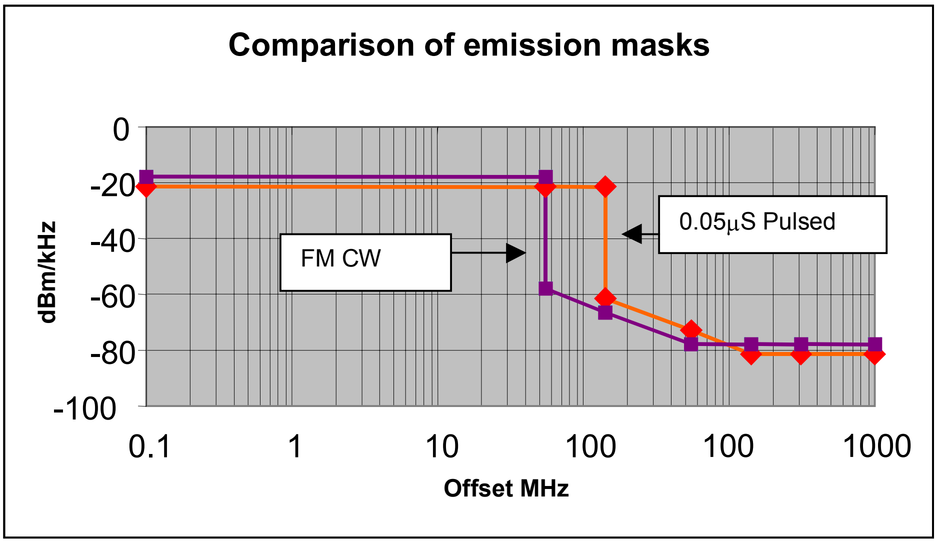


Figure 3.1.2-34 shows the comparison for the longest pulse of 1 µs to the 1 W radar. The pulsed radar also works with shorter pulses, Figure (3.1.2-37) shows the comparison for the 0.05µs pulse.

The pulse radar maximum spectral power density has decreased to -21.2 dBm/kHz below that of the LPI radars as a consequence of the reduction in pulse length and the use of a lower PRR. The PRR used with short pulses in marine radars is typically 3000 Hz.

Figure 3.1.2-37 Comparison of a 1W[47], 0.05 µs Pulsed and an LPI Radar



[47] When using short pulses the pulsed radar reduces the duty hence the mean power is no longer 1W

3.1.2.3.11 Monopulse Secondary Surveillance Radar (MSSR)

3.1.2.3.11.1 Selective Identification Feature (SIF) Modes (A,C)

Table 3.1.2-16 MSSR (L-Band) [48]

CHARACTERISTICS[48]	MSSR[49]
Tuning range (GHz)	None
Operational Frequencies Used	1 (1030 MHz)
Frequency Accuracy	0.2 MHz
Frequency Stability	NA[50]
Modulation	P0N
Transmitter Power into Antenna (kW)	2.5
Pulse width (μs)	0.8 ± 0.1
Pulse rise/Fall time (μs)	0.05 to 0.1
Pulse repetition rate (Hz)	450 max[51]
Duty cycle (%)	0.12
Chirp bandwidth MHz	NA
Compression ratio	NA
RF emission bandwidth (-3 dB) (MHz)	4.5[52]
RF emission bandwidth (-20 dB) (MHz)	20
RF emission bandwidth (-40 dB) (MHz)	80
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	$Cosec^2$
Antenna type (reflector, phased array, slotted array, etc.)	Passive Array
Antenna Horizontal beamwidth -3dB (degrees)	2.5
Antenna polarization	Vertical
Antenna mainbeam gain (dBi)	27
Antenna Vertical beamwidth -3dB (degrees)	5° $Cosec^2$
Antenna horizontal scan rate (degrees/sec)	36 to 90
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	360 degrees, Continuous
Antenna vertical scan rate (degrees/sec)	NA
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA
Antenna side-lobe levels (1st SLs and remote SLs) dB wrt main beam	-28 / -40
Antenna height (m) above ground	Variable

[48] SSR Characteristics are defined internationally in ICAO Annex 10

[49] Modes 3A & C only

[50] Included in accuracy figure

[51] Limited by international agreement

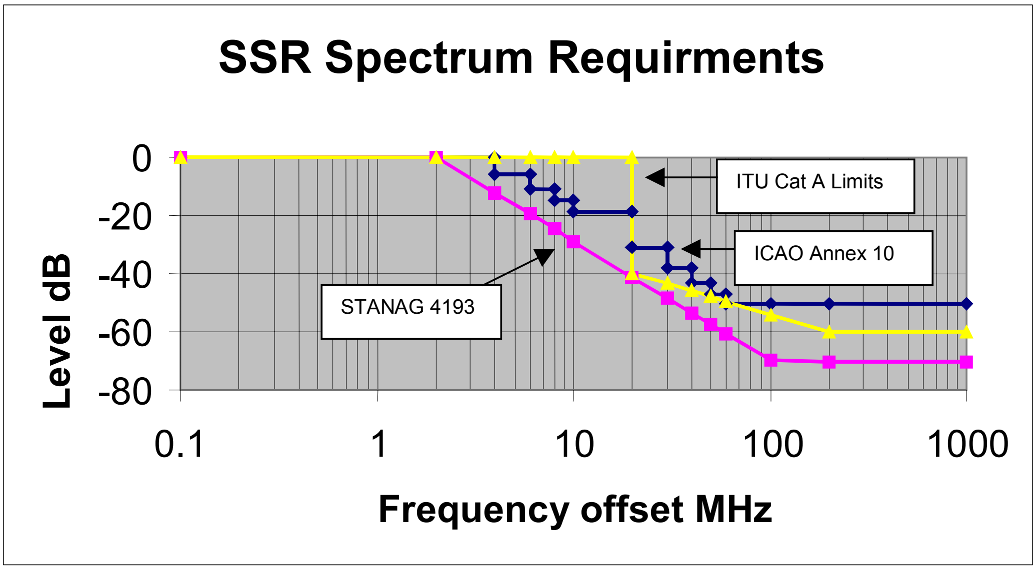
[52] Specified by STANAG 4193

The performance of MSSR interrogators is specified by international agreements (ICAO annex 10 and STANAG 4193). The PRR is limited to a maximum of 450 Hz by the ICAO. In the UK the systems operate with PRRs in the range 105 to 350 Hz.

3.1.2.3.11.2 Mode S SSR

The next generation of MSSR is currently under development in the UK. These systems will operate with a Mode A/C interrogation rate of 150 Hz and a selective interrogation rate of up to 250 Hz. The combined duty cycle in this enhanced surveillance mode is estimated at 1%. Mode S is also capable of data link applications. The data link messages are much longer than the surveillance messages and an average long-term duty cycle of 10% is estimated.

Figure 3.1.2-38 Spectral Requirements MSSR



3.1.2.4 Military Radar

Most of the characteristics of military radars are classified. What can be said, however, is that they generally use more power and require more bandwidth than civil radars. The majority of military systems are also transportable or mobile. In the UK the military have radars capable of operating in all bands from L to Ka-Band.

Table 3.1.2-17, below contains public domain data on the generic types of systems that could be operating in S-Band. No such detailed list has been published for other bands.

The design drivers for new military S-Band radars are all associated with the ability to detect very small targets at very long ranges and the ability to have the resolution to effectively image and classify targets. The need for the detection of smaller targets at long ranges is leading to a requirement for much higher EIRP, whilst the ability to provide the resolution needed to image and classify targets is leading to a need for wider bandwidths. The multifunction nature of modern radars[53] is also presenting a potential problem in determining the specification compliance of the radar. Specifications on Spurious Emissions (SE) and Out Of Band (OOB) emissions are generally related to specific pulse modes of the radar. Problems of interoperation of the specifications are presented when the radars normal mode of operation is to continuously adapt its transmitted waveform by changing the pulse lengths and PRR.

[53] IEE ECEJ Journal Dec 2001 Page 277

Table 3.1.2-17 Characteristics of generic military radiolocation radars in the band 2 700 - 3 400 MHz

	RADAR 1	RADAR 2	RADAR 3	RADAR 4
CHARACTERISTICS				
Platform type (airborne, shipborne, ground)	Ground, ATC Gap-filler Coastal	2D/3D Naval Surveillance Ground Air Defence	Ground Air Defence	Multifunction Various Types
Tuning range (MHz)	2 700 - 3 100	2 700 - 3 100	2 700 to 3 100 2 900 to 3 400	Whole band up to 25% BW
Operational Frequencies Min/Max	Min: 2 spaced at > 10 MHz Max: Fully agile	Min: 2 spaced at > 10 MHz Max: Fully agile	Min: Fixed Max: Fully Agile	Min: 2 spaced at > 10 MHz Max: Fully agile
Modulation	Non-linear FM P0N, Q3N	Non-linear FM P0N, Q3N	Non-linear FM Q3N	Mixed
Transmitter Power into Antenna (kW)	60 Typical	60 to 200	1000 Typical	30 to 100
Pulse width (μsec)	0.4[54] to 40	0.1[54] to 200	> 100	Up to 2000
Pulse rise/Fall time	10 to 30 ns typical	10 to 30 ns typical	NDA	NDA
Pulse repetition rate (Hz)	550 to 1100	300 to 10,000	< 300	Up to 20,000
Duty cycle (%)	2.5 Max	10 Max	Up to 3	30 Max
Chirp bandwidth	2.5 MHz	Up to 10 MHz	> 100 MHz	Depends on modulation
Phase-coded sub-pulse width	NA	NA	NA	NDA
Compression ratio	Up to 100	Up to 300	NA	NDA
RF emission bandwidth (-20 dB) (-3 dB)	3.5 MHz 2.5 MHz	15 MHz 10 MHz	> 100 MHz	NDA
Output device	TWT	TWT or Solid State	Klystron CFA	Active Elements
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Cosecant-squared	Pencil Beam 3D or Cosecant squared 2D	Swept Pencil Beam	Pencil Beam

[54] Uncompressed Pulse

	RADAR 1	RADAR 2	RADAR 3	RADAR 4
CHARACTERISTICS				
Antenna type (reflector, phased array, slotted array, etc.)	Shaped Reflector	Planar array or Shaped Reflector	Frequency Scanned Planar Array or Reflector	Active Array
Antenna azimuth beamwidth (degrees)	1.5	1.1 to 2	Typically 1.2	Depends on number of elements
Antenna polarization	Linear or Circular or Switched	Linear or Circular or Switched	Fixed Linear or Circular	Fixed Linear
Antenna mainbeam gain (dBi)	33.5 Typical	Up to 40	> 40	Up to 43
Antenna elevation beamwidth (degrees)	4.8	1.5 to 30	Typical 1	Depends on number of elements
Antenna horizontal scan rate (degrees/sec)	45 to 90	30 to 180	Typical 36	Sector scan Instantaneous Rotation scan up to 360 deg/sec
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous 360 degrees	Continuous 360 degrees + Sector scan	Continuous 360 degrees + Sector scan	Random Sector scan Sector scan + Rotation
Antenna vertical scan rate (degrees/sec)	NA	Instantaneous	Instantaneous	Instantaneous
Antenna vertical scan type (continuous, random, 360 degrees, sector, etc.)	NA	0 to 45 deg	0 to 30 deg	0 to 90 deg
Antenna side-lobe levels (1st SLs and remote SLs) below main beam	26 dB 35 dB	>32 dB Typical <-10dBi	>26 dB Typical < 0 dBi	NDA
Antenna height (m) above ground	4 to 30	4 to 20	5	upto 20

3.1.2.5 Calculation of Spectrum Parameters

3.1.2.5.1 Envelope of Trapezoidal Pulse

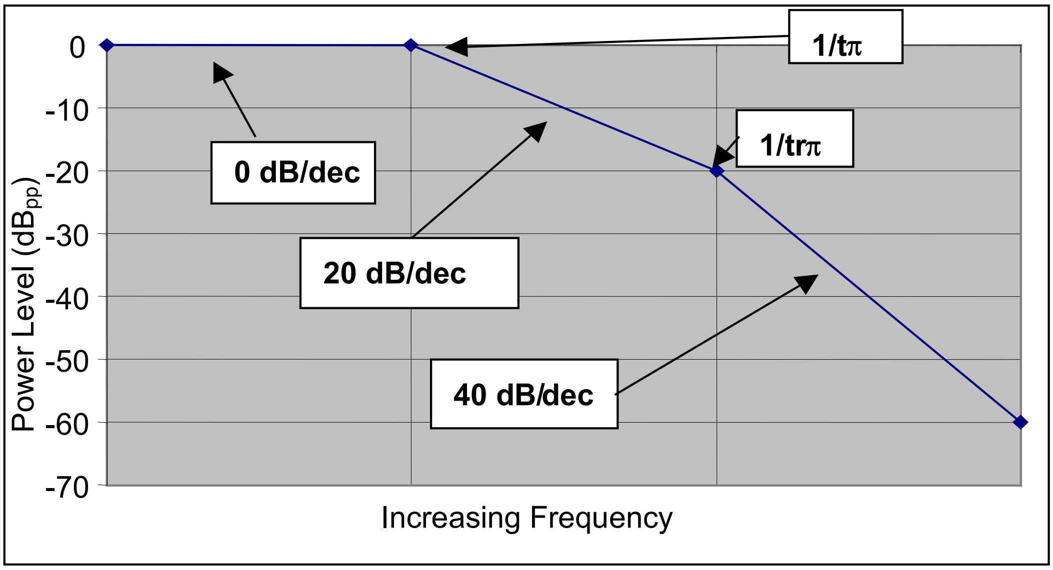
The envelope of the spectrum of a trapezoidal pulse can be defined by three asymptotes at 0, 20 & 40 dB/Decade respectively, these are shown in Figure 3.1.2-39. The asymptotes change slope at two breakpoints.

The breakpoints occur at: 0 dB = $1/t\pi = 0.32/t$

20 dB = $1/t_r\pi = 0.32/t_r$

Where t is the pulse duration (at half amplitude) and t_r is the rise time, both in seconds[55].

Figure 3.1.2-39 Envelope of Spectrum of Trapezoidal Pulse



3.1.2.5.2 Formula for 20 dB Bandwidth

ITU-R Recommendation SM.853 provides guidance for determining the necessary bandwidth (20 dB below the peak envelope value) for rectangular and trapezoidal pulses. For these systems, the necessary bandwidth B_n is the smaller of:

$$B_n = \frac{1.79}{\sqrt{t \cdot t_r}} \text{ or } \frac{6.36}{t}$$

Equation 3.1.2-6

Necessary bandwidth formulas for frequency modulated pulse radars, frequency hopping radars, and CW radars, both un-modulated and frequency modulated are presented below.

[55] The pulse duration is the time, in seconds, between the 50% amplitude (voltage) points. For coded pulses, the pulse duration is the interval between 50% amplitude points of one chip (sub-pulse). The rise time is the time taken, in seconds, for the leading edge of the pulse to increase from 10% to 90% of the maximum amplitude on the leading edge. For coded pulses, it is the rise time of a sub-pulse; if the sub-pulse rise time is not discernible, assume that it is 40% of the time to switch from one phase or sub-pulse to the next. When the fall time of the radar is less than the rise time, it should be used in place of the rise time in these equations. Using the smaller of the two expressions in equation 3.1.2-6 avoids excessively large calculated necessary bandwidth when the rise time is very short.

For frequency modulated pulse radars, the necessary bandwidth (20 dB bandwidth) formula exceeds the symmetrical trapezoidal pulse case (equation 3.1.2-6) by twice the frequency deviation B_c [56]:

$$B_n = \frac{1.79}{\sqrt{t \cdot t_r}} + 2B_c$$

Equation 3.1.2-7

The formula for frequency hopping radars has an additional term B_s, the maximum range over which the carrier frequency will be shifted:

$$B_n = \frac{1.79}{\sqrt{t \cdot t_r}} + 2B_c + B_s$$

Equation 3.1.2-8

Although ITU-R Recommendation SM.1138 gives no formula under the heading of "continuous wave emission" (here meaning a carrier without modulation) a realistic value of necessary bandwidth for un-modulated CW radars depends on the frequency tolerance and noise. For frequency modulated CW radars, the necessary bandwidth is twice B_d, the maximum frequency deviation:

$$B_n = 2B_d$$

Equation 3.1.2-9

3.1.2.5.3 Formula for 40 dB Bandwidth

Since the ratio of the 40 dB and necessary bandwidths is not in general a constant, a formula for the 40 dB bandwidth is needed to relate the mask to necessary bandwidth. The following formulas for the 40 dB bandwidth (B_{-40}) of primary radar transmitters have been established.

For non-FM pulse radars, including spread spectrum or coded pulse radars, the bandwidth is the lesser of:

$$B_{-40} = \frac{K}{\sqrt{t \cdot t_r}} \text{ or } \frac{64}{t}$$

Equation 3.1.2-10

where the coefficient K is 6.2 for radars with output power greater than 100 kW and 7.6 for lower-power radars and radars operating in the Radionavigation Service in the 2900-

[56] This value is the total frequency shift during the pulse duration.

3100 MHz and 9200-9500 MHz bands[57]. The latter expression applies if the rise time t_r is less than about 0.0094*t* when *K* is 6.2, or about 0.014*t* when *K* is 7.6.

For FM-pulse radars, the 40 dB bandwidth is:

$$B_{-40} = \frac{K}{\sqrt{t.t_r}} + 2\left(B_c + \frac{A}{t_r}\right)$$ Equation 3.1.2-11

where A[58] is 0.105 when *K* = 6.2, and 0.065 when *K* = 7.6.

For FM-pulse radars with frequency hopping[59]:

$$B_{-40} = \frac{K}{\sqrt{t.t_r}} + 2\left(B_c + \frac{A}{t_r}\right) + B_s$$ Equation 3.1.2-12

For frequency hopping radars using non-FM pulses, including spread spectrum or coded pulses:

$$B_{-40} = \frac{K}{\sqrt{t \cdot t_r}} + B_s$$

Equation 3.1.2-13

---

[57] These coefficients, K = 6.2 or 7.6 and 64, are related to theoretical values that would prevail in the case of constant frequency trapezoidal and rectangular pulses, respectively. Also, in the case of the trapezoidal pulses, the coefficient K has been increased somewhat to allow for implementing output device characteristics, the value of K for trapezoidal pulses being dependent on the transmitter power.

For ideal rectangular pulses, the spectrum falls off at 20 dB per decade leading to a 20 dB bandwidth of 6.4/t and a 40 dB bandwidth ten times as large, i.e. 64/t. To discourage the use of pulses with abrupt rise and fall times, no margin is allowed. The spectra of trapezoidal pulses fall off firstly at 20 dB per decade and then ultimately at 40 dB per decade. If the ratio of rise time to pulse width exceeds 0.008 the 40 dB points will fall on the 40 dB per decade slope, in which case the B_{-40} would be:

$$\frac{5.7}{\sqrt{t \cdot t_r}}$$

Allowance for unavoidable imperfections in implementation requires that the mask be based on values of at least:

$$\frac{6.2}{\sqrt{t \cdot t_r}} \text{ or } \frac{7.6}{\sqrt{t \cdot t_r}}$$

depending upon the category of radar.

[58] The term A/t_r adjusts the value of B_{-40} to account for the influence of the rise time, which is substantial when the time-bandwidth product $B_c t$, is small or moderate and the rise time is short.

[59] Equations 3.1.2-12 and 3.1.2-13 yield the total composite B–40 bandwidth of a frequency hopping radar as if all channels included within Bs were operating simultaneously. For frequency hopping radars, the out-of-band emission mask falls off from the edge of the 40 dB bandwidth as though the radar were a single frequency radar tuned to the edge of the frequency hopping range.

For un-modulated CW radars:

$$B_{-40} = 0.0003F_0$$ Equation 3.1.2-14

For FM/CW radars:

$$B_{-40} = 0.0003F_0 + 2B_d$$ Equation 3.1.2-15

In equations 3.1.2-14 and 15, F_0 is the operating frequency.

For radars with multiple pulse waveforms, the B_{-40} dB bandwidth should be calculated for each individual pulse type and the maximum B_{-40} dB bandwidth obtained shall be used to establish the shape of the emission mask.

3.1.2.6 Limits on Unwanted Emissions

In order to facilitate sharing and to improve spectral usage and reduce interference the ITU and the CEPT have agreed new limits on unwanted emissions for all radio services. As from the start of 2003 all new equipments introduced into service will have to meet the new limits on spurious emissions (SE). Two categories of SE pertain to radar services Category A and Category B.

The ITU have proposed a set of unwanted emission limits for Category A radars which roll-off from the frequency at which the 40 dB bandwidth is reached down to the SE level. This sets the regions over which the SE limits apply. CEPT working group SE 21 has agreed the unwanted emission limits for Primary radars that fall into the Category B[60] SE.

The Category B limits follow those recommended by the ITU down to the Category A levels of -60dB and extend them down to the Category B -100 dB limits.

The approach for Category B follows that taken by the ITU for Category A and a hard limit is given for existing radars along with a design aim for new designs. In the future the design aim will replace the current limit in a timescale not as yet defined. The Category A design aim is likely to be adopted as a recommendation after 2006.

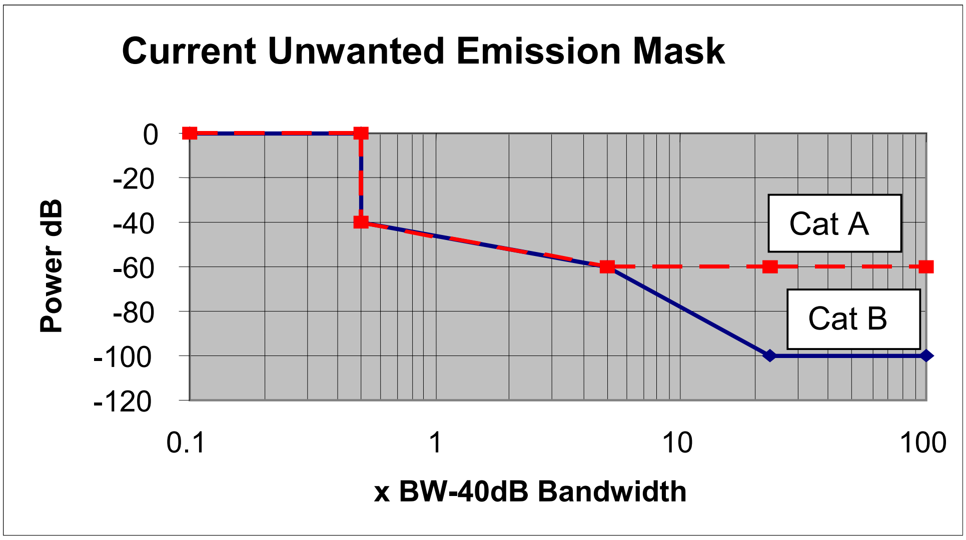
The limits have the following status:

As stated in ECC[61] Recommendation 74-01, from the start of 2003, all new radars have to meet the following spurious emission specifications, -60 dB for Category A radars & -100 dB for Category B radars.

The masks given below Figure (3.1.3 - 40) define the boundary of the SE domain over which the limits apply.

The current mask has a Roll off at 20 dB/dec from the -40dB point down to the current Cat A limit of -60 dB. If the Cat B limit applies then the roll off from the -60 to the -100 dB level is at 60 dB/dec.

Figure 3.1.2-40 Unwanted Emission mask for New Radars from the start of 2003 and all radars from the start of 2012



[60] All fixed radars excluding multifrequency, windsheer & active array radars. Administrations may also exempt VTS systems to allow the use of Maritime surveillance radars in this role.

[61] CEPT Electronic Communications Committee

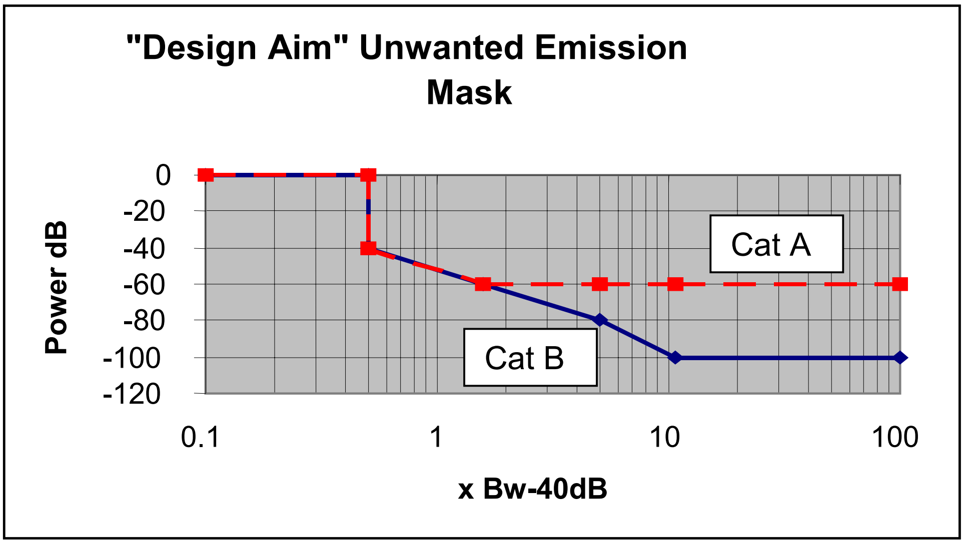
The shape of the masks within the OOB region is currently a recommendation and applies to radars operating at the edge of exclusive "radiodetermination bands", or everywhere where radar bands are shared with other services. From 2012 all the radars in service have to meet these requirements.

A design aim has also been agreed which will replace the existing limits in the future. This is shown in Figure 3.1.2-41.

The current unwanted emission limits, set the start of the SE domain (i.e. the region where the -60 dB limit needs to be maintained) at a frequency excursion from the carrier of 5 times the BW_{-40dB} [62] for Cat A radars. For Cat B radars the current unwanted emission limits, set the start of the SE domain (i.e. the region where the -100 dB limit needs to be maintained) at a frequency excursion from the carrier of 23.2 times the BW_{-40dB} .

This design aim sets the start of the SE domain (i.e. the region where the -60 dB limit needs to be maintained) at a frequency excursion from the carrier of 3.2 times the BW_{-40dB} for Cat A radars. For Cat B radars the design aim sets the start of the SE domain (i.e. the region where the -100 dB limit needs to be maintained) at a frequency excursion from the carrier of 10.75 times the BW_{-40dB} .

Figure 3.1.2-41 Design Aim for Future Adoption



The mask for the design aim rolls off at 40 dB/dec down to the current Cat A limit of -60dB, if Cat B limits apply then the 40 dB/dec roll-off is extended down to the -80 dB level. The roll-off from -80 to -100 dB is at 60 dB/dec.

3.1.2.7 Applicability of Cat A & B Limits to UK Systems.

Table 3.1.2-18 gives the current applicability of Cat A and Cat B limits for new UK radars going into service from the start of 2003.

[62] The BW_{-40dB} is defined in annex 8 of ITU-R SM1541

Table 3.1.2-18 Applicability of CAT A & B SE Limits

Radar Type	CAT A	CAT B	Comments
L-Band ATC	✓		Multifrequency Radar
S-Band ATC	✓		Multifrequency Radar
X-Band ATC	✓		Multifrequency Radar
PAR	✓		Active Array
Airborne Weather	✓		Not Fixed
Maritime	✓	✓	Not Fixed
ASDE	✓	★✓	*Single Frequency Systems Only
VTS	✓		Subject to local exemptions
Altimeters	✓		Not Fixed
SSR Ground Interrogator		✓	See Notes in Text
DME Ground Transponder	✓		Not a radar
Ground Weather		✓	Fixed Single Frequency

Of particular concern is the possible classification of SSR as Cat B.

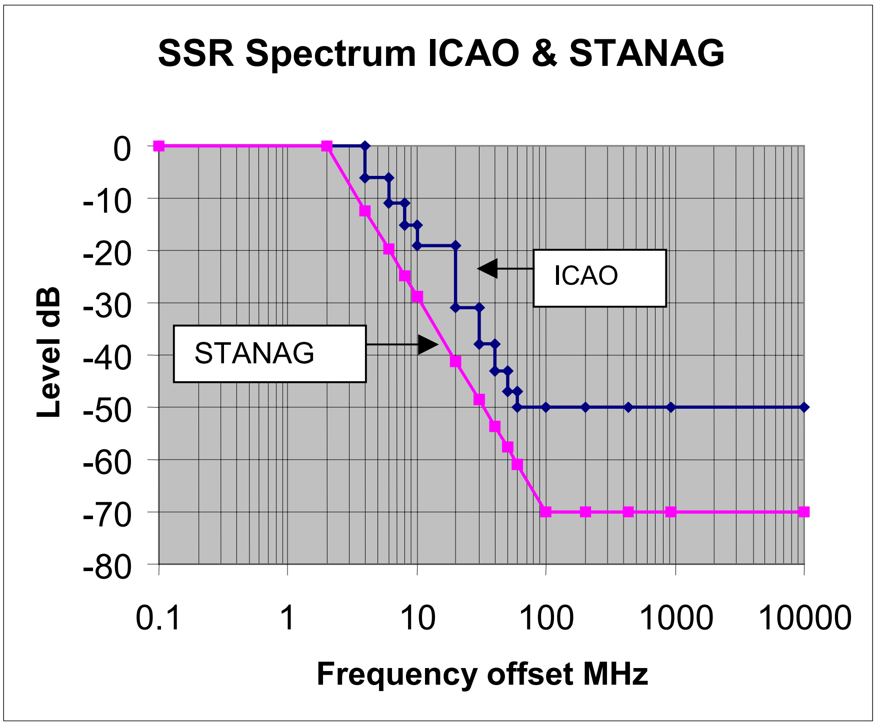
The unwanted emissions from SSR systems are controlled by the "signals in space" as defined in ICAO Annex 10. ICAO is a body that takes its authority from the UN.

The military version of Secondary Surveillance Radar (SSR) is called Identification Friend or Foe (IFF) and its signals in space are defined by STANAG 4169, a Nato document.

Because of the need for the systems to inter-operate, most SSR systems meet the requirements of both and where there are differences meet the more stringent requirements.

In terms of unwanted emissions the two documents give differing requirements for the current Mode S interrogators. See Figure 3.1.2-42 below.

Figure 3.1.2-42 ICAO & STANAG Limits



It can be seen that the STANAG limits are considerably tighter than the ICAO ones.

ITU Limits Cat A

If these limits are compared to the current ITU Cat A limits that are for new systems from the start of 2003, then we see in Figure 3.1.2-43 that the STANAG limit exceeds Cat A by a considerable amount.

However, the Cat A limits in the OOB region are subject to a new design aim proposed for introduction in 2006. This increases the roll-off from 20dB/decade to 40 dB/decade this is shown in Figure 3.1.2-44.

Again the STANAG meets the current proposed Design Aim for ITU Cat A limits.

ITU Limits Cat B

However we must now consider Cat B limits. Some states, particularly the EU, have expressed the view that Cat B limits will be applied where appropriate. These limits set the SE level at -100 dB as opposed to the -60 dB of the Cat A.

SSR is a Secondary Radar System and comes under the Radiodetermination service.

SSR is defined as:

- S1.102 *secondary radar*: A *radiodetermination* system based on the comparison of reference signals with radio signals retransmitted from the position to be determined.

It is also classed as a radar by:

- S1.100 *radar*: A *radiodetermination* system based on the comparison of reference signals with radio signals reflected or retransmitted from the position to be determined.

In the UK the band allocation for SSR is given as:

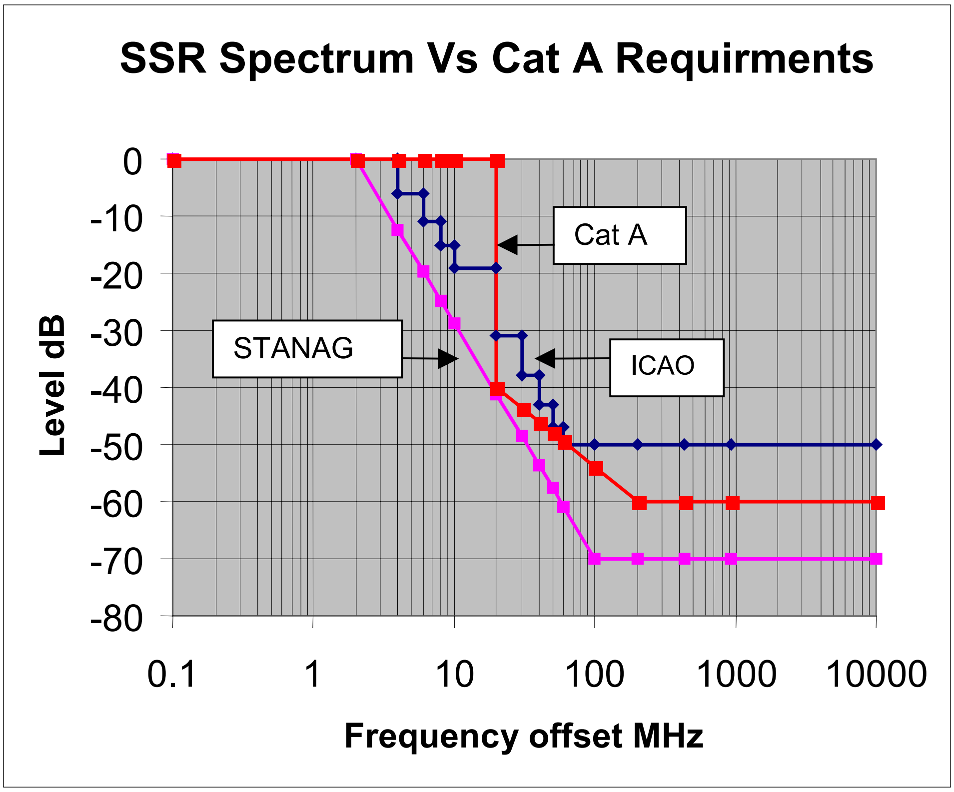
960-1215 MHz AERONAUTICAL RADIONAVIGATION S5.328	Military and civil radionavigation; S5.328 refers. Used for DME/TACAN and military identification systems. Radioastronomy on 962-970 MHz - used for pulsars.

S5.328	The band 960 - 1 215 MHz is reserved on a world-wide basis for the use and development of airborne electronic aids to air navigation and any directly associated ground-based facilities.

These define SSR as part of the *Radionavigation service* that is a sub-service of *Radiodetermination* along with *Radiolocation*.

Therefore SSR can be defined as a *Radar* that is part of the *Radiodetrmination* service. As it is a fixed service it comes under Cat B limits. There are some exclusions[63] however, SSR does not appear to be covered (unless the term multi-frequency is applied to both the transmission and reception of the radar). Cat B limits are shown in Figure 3.1.2-45 below.

Figure 3.1.2-43 Cat A Limits



[63] Wind profiler, multifrequency and active array radars

Figure 3.1.2-44 Cat A Design Aim

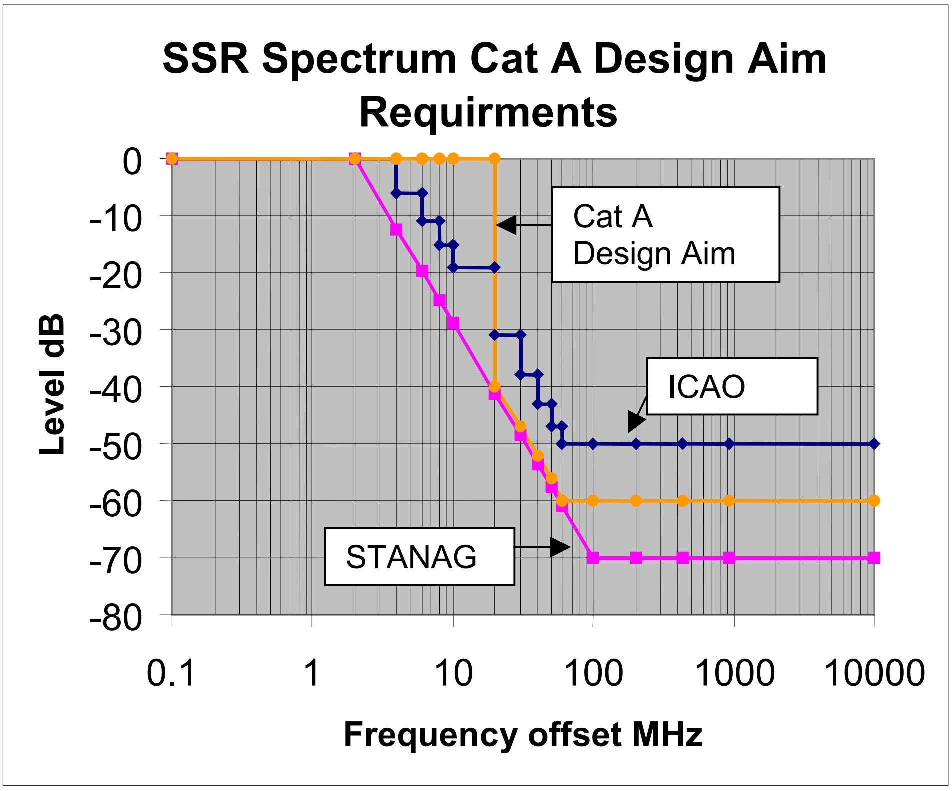
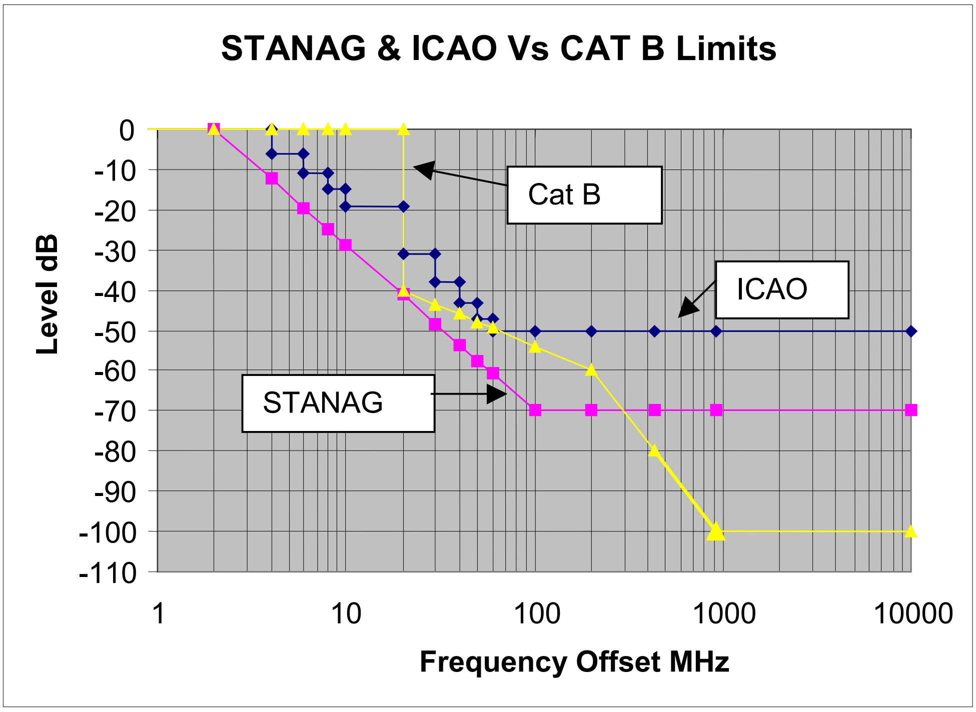


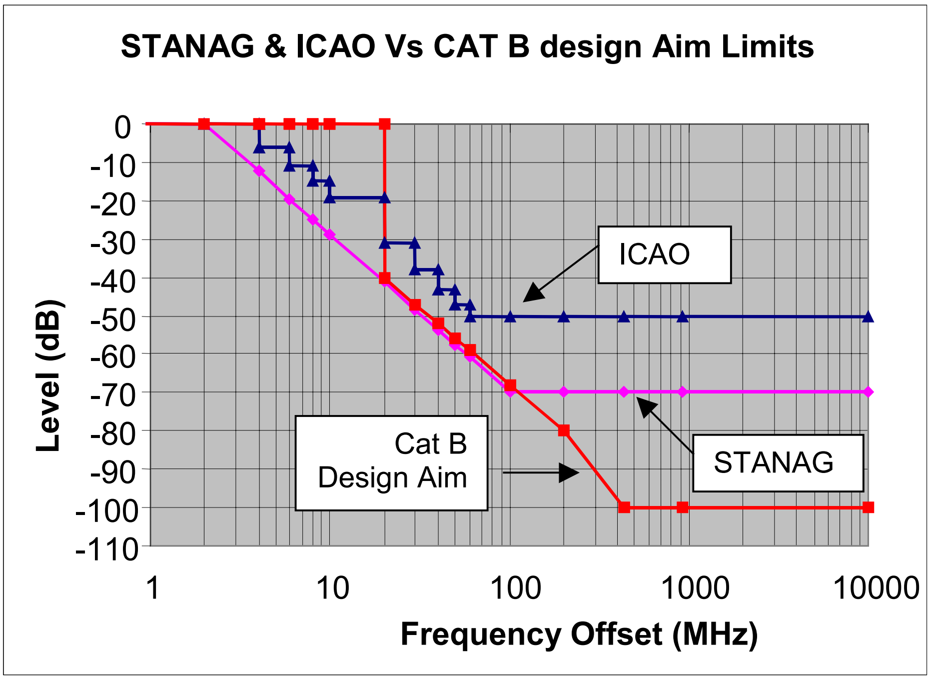
Figure 3.1.2-45 Cat B Limits



The STANAG limit is tighter than ITU Cat B until a frequency offset of 300MHz, where the Cat B exceeds -70 dB. The Cat B limits also have a design aim based on those for Cat A and extending the current Cat A design aim down to the -100 dB SE level.

Figure 3.1.2-46 shows a comparison of the ITU Cat B design aim with the STANAG and ICAO limits.

Figure 3.1.2-46 Cat B Design Aim



The STANAG limit is marginally tighter down to the -70 dB point whereas the Cat B design aim continues down to the -100 dB level.

In conclusion the currently specified international limit for SSR based on STANAG 4193 exceeds the current ITU Cat A limit and its proposed design aim.

The STANAG limit exceeds the CAT B limit down to the -70 dB level for both the current limit and the design aim. Below this level it is not specified.

The question needs to be posed however whether SSR systems should strictly be covered by the Cat B limits given that their performance is specified internationally.

This assessment however is based on specified limits only. It may be that in practice SSR systems exceed the specified limit by such a margin that they meet the Cat B limit for SE as they are today.

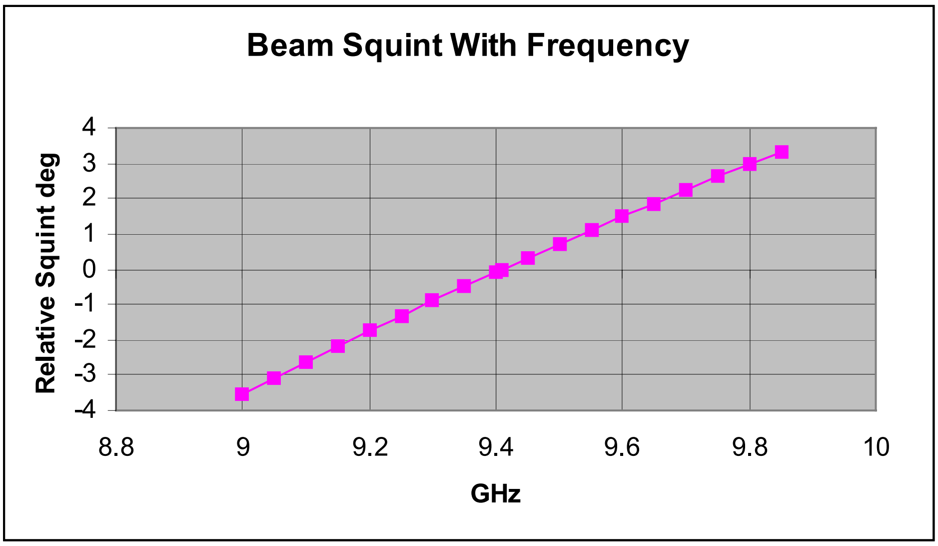
3.1.2.8 Antenna Modulation

Antennas that squint with frequency can modulate the radiated spectrum seen at a given point in the far-field. The effect seen depends on the width of the spectrum, the beamwidth of the antenna and the rate the antenna squints with frequency.

Take for example an open array antenna used on maritime navigational radars. These are generally constructed in the form of an end fed travelling wave array using alternating "left" & "right" slots nominally spaced at $\lambda_g/2$, where λ_g is the wavelength of the electromagnetic wave within the waveguide.[64] Such an antenna would produce a beam broadside to the side-wall of the waveguide.

However such designs are generally avoided due to the high Voltage Standing Wave Ratio (VSWR) seen at the input of the waveguide when the condition for broadside radiation is achieved. This occurs because the internal reflections from all the slots add up in phase. To avoid the poor VSWR, slots are generally spaced at a distance greater than $\lambda_g/2$, traditionally the slots are spaced a $5\lambda_g/9$. This spacing, when used with WG 16 (R 100)[65], (the traditional waveguide size used for this application) and operating at 9.41 GHz gives a forward[66] squint of 4.1 degrees. This is defined as the electrical boresight of the antenna. If the frequency is changed then the beam will squint to a different azimuth position. At lower frequencies (< 9.41 GHz) the beam squints backwards, at higher frequencies (> 9.41 GHz) the beam squints further forwards as shown in Figure 3.1.2-47.

Figure 3.1.2-47 Illustration of the beam squint law



If we consider a 1 μs pulse with a 15 ns rise-time, this has Bw_{-40dB} of 62 MHz. For figures over this 62 MHz, the beam would squint ± 0.25° as shown in Figure 3.1.2-48 below. The amount of modulation caused by this squint is dependent on the beam width of the array. If the antenna had a 0.5° beamwidth, then a modulation or suppression of 3dB at the Bw_{-40dB} points would occur. For a 5° antenna virtually no affect would occur. Thus for anything but the largest of antennas, the beam modulation would have very little effect on the -40dB limit on the emission mask. However in the OOB region out to $10xBw_{-40dB}$ points, even the widest beams would provide some modulation as the squint is ± 2.5° as shown in Figure 3.1.2-49. Narrow beamwidth antennas (approximately less than 2°) would squint so far that the energy at the SE boundary would be radiated in the side-lobes of the antenna giving an apparent reduction of level of approximately 25 dB.

[64] This is related to the frequency and the size of the waveguide and differs from the "free space" wavelength.

[65] This refers to the size of the waveguide being used, details can be found in manufacturers data sheets or "Microwave Engineers Handbook Vol 1" ARTECH HOUSE, Inc

[66] Forward Squint is defined as away from the generator towards the load .

Figure 3.1.2-48 Showing the beam squint law for a system with a 1μs pulse

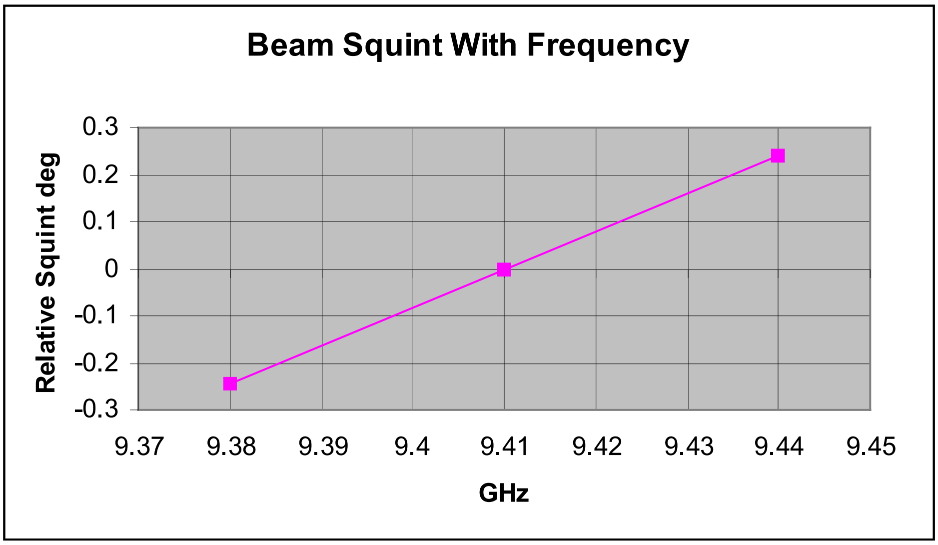
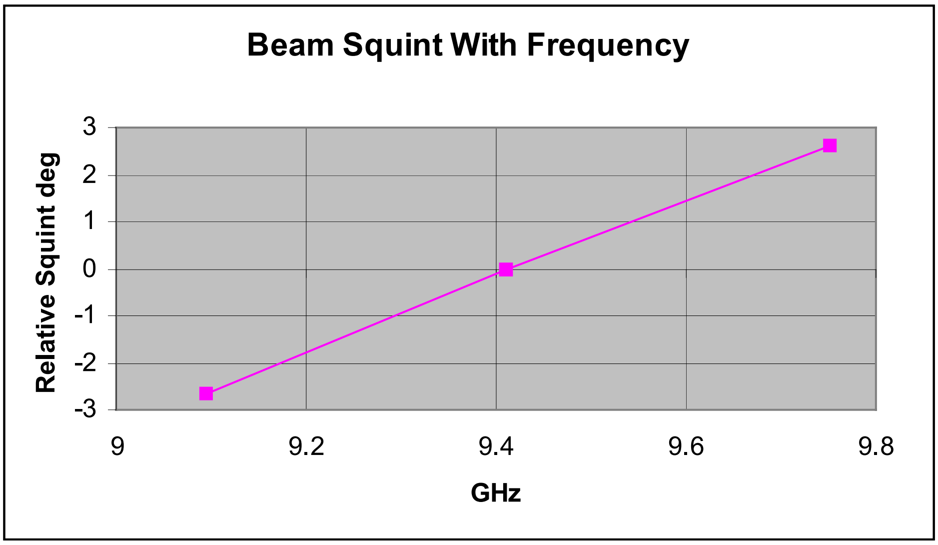


Figure 3.1.2-49 Showing the beam squint law for the OOB region



3.1.2.9 Summary

This section has reviewed the wanted transmission characteristics of radars in current use and has included an analysis of the unwanted transmission characteristics in the OOB region. Additionally a section on the SE requirements for future systems has been included for completeness.

This section shows that there is very wide range of variations depending mostly on the radar's role. The wanted characteristics that result come from one of two design drivers:

- The system requirements, detection, resolution etc,
- The implementing technology.

Where the characteristics are driven essentially by the technology (as, for example, in the case of magnetrons) there are generally other issues which drive their use over and above the basic system requirements. Issues such as cost, or non-availability of an alternative, are the most common. In these cases it is necessary to suffer perhaps what may be considered excessive use of spectrum in order to have either a radar that can be provided at a cost effective price, or in some cases a radar at all. In such cases the use of spectrum must be weighed against the economic and safety benefits of the use of radar.

In systems that are essentially driven by the system requirements then providing the technology and cost allows, much tighter control of the wanted characteristics can be achieved. A prime example of a radar where the wanted emissions are strictly tailored to meet its role is the modern solid-state S-Band ATC radar. In this case, the radars have been designed to use the minimum bandwidth to fulfil the role and they currently represent the 'state of the art'.

The spectral emission masks given in section 3.1.2.5 generally provide a good guide to the amount of spectrum used by the radars. They do however start to become inaccurate when the pulse deviates significantly from the trapezoidal. This is the case for radars such as ASDE where the rise times are a significant part of the normal pulse length.

It must also be remembered that many of the systems listed in this chapter are relatively old, some having been in service since the 1960's. When these radars were designed the requirement to limit the use of spectrum was not present.

This section illustrates that if consideration is given to the topic at an early stage in the radar design, then measures to control and reduce the unwanted emissions are possible.

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Section 3.1.3

The Measured Characteristics of a Sample of Commercial Radars in use in the UK.

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3.1.3 Measured Characteristics of a Sample of Commercial Radars in use in the UK.

3.1.3.1 Introduction

A measurement programme was undertaken by QinetiQ (Funtington) to assess the unwanted emissions of a sample of civil radar systems used in the UK. The campaign was performed on behalf of AMS formally BAE Systems (Combat and Radar Systems) Ltd.

The purpose of the measurement campaign was twofold:

- To characterise the emissions from a cross section of the UK civil radar systems.
- To gain experience and provide advice on the recommended technique for the measurement of unwanted emissions of radar systems.

The International Telecommunication Union (ITU) Recommendation for the measurement of Unwanted Emissions is presented in the document ITU-R Recommendation M.1177-2 "Techniques for the measurement of unwanted emissions from radar systems". This document is currently under review and therefore for the purpose of this package of work the version used was the Preliminary Draft Revision of ITU-R Recommendation M.1177-2 (document 8B/Temp/72-2) dated 30th October 2001. The recommendations for changes to, and interpretation of ITU-R Recommendation M.1177-2 are presented in a separate section 3.4 of this report.

The unwanted emissions of radar systems are defined as both Out Of Band (OOB) emissions and Spurious Emissions (SE). An OOB emission is at a frequency immediately outside the Necessary Bandwidth (NB) that results from the modulation process but excluding spurious emissions. SE are the frequencies outside the Necessary Bandwidth including harmonics, parasitics, intermodulation products and frequency conversion products. Therefore the OOB region consists of two bands from the upper and lower limits of the Necessary Bandwidth to the start of the SE regions. The SE regions are all frequencies outside the OOB and Necessary Bandwidth regions.

As stated in ITU-R Recommendation SM.329-9 Spurious Emissions, the spurious domain emission levels for radio equipments are specified in certain reference bandwidths depending on the frequency. However in the case of radar measurements there is no specific reference bandwidth, e.g. 1MHz for frequencies above 1GHz, instead the spurious emission levels are specified in an appropriate measurement bandwidth. These are detailed in ITU-R Recommendation M.1177-2 for each radar type and are dependent upon modulation type, pulse width, rise time and fall time.

In the case of many measurement systems for spurious emissions, the receiver used is a spectrum analyser where the measurement bandwidth is commonly known as the Resolution Bandwidth (RBw).

This part of the report presents the measurement method used at the QinetiQ Funtington fixed test range and that employed on the recently commissioned mobile test facility. A summary of the measurement results and the conclusions from the measurement campaign are also supplied. A full set of measurement results has been supplied to the Radiocommunications Agency in the Confidential Annex 5 of this report.

3.1.3.2 Radars under test

A short list of radars for consideration in the measurement campaign was drawn up between AMS and the RA. The list encompassed all radars commonly or due to be commonly used in the UK in the frequency band 1 to 30GHz. The final list of five radar types were chosen to represent a cross section of radars based on usage, output device (i.e. magnetron, travelling wave tube (TWT) etc.) and technological complexity. They included a state-of-the-art solid state air traffic control radar through to a basic marine navigation radar. The list of radars chosen for the measurement campaign is shown below:

- Marine Navigation Radar – Ship borne (X-Band)
- Civil Air Traffic Control – Ground based (S-Band Solid state)
- Civil Air Traffic Control – Ground based (L-Band TWT)
- Airport Surface Detection Equipment – Ground based (Ku-Band Magnetron)
- Meteorological – Ground based (C-Band Magnetron)
- In addition to the five radars chosen measurements were also made on:-
- Civil Air Traffic Control – Ground based (S-Band TWT)

All but the marine navigation radar were installed radars and measured using the mobile measurement facility at the radar site. The marine radar was measured at the dedicated test range at QinetiQ Funtington and was the first to be tested.

3.1.3.3 QinetiQ Unwanted Emissions (UE) Measurement Facilities

3.1.3.3.1 Funtington Fixed UE Measurement Range

The Funtington fixed UE measurement range is one of eight facilities at Funtington dedicated to antenna, radar and radar cross section measurements. The 39 acre site has traditionally supported the requirements of the MoD for the characterisation of antenna systems and radar signatures for the Royal Navy.

The UE measurement facility has been developed over the last 18 months to satisfy the requirement for a UK test facility capable of Type Approving new radar systems for UE in preparation for the incoming regulations. Figure 3.1.3-1 below is a photograph of the Funtington ranges. The site lies between the road on the right and the copse of trees on the left. The majority of the fields surrounding the site are pig farms with the numerous pig pens clearly visible. As the site nestles in the middle of the West Sussex Downs, the EM environment is relatively quiet and free from interfering signals.

Figure 3.1.3-1 Photograph of the QinetiQ Funtington ranges

The two unwanted emission measurement ranges run diagonally across the site. The longer range, 460m, runs from top right to lower left in the photograph. The shorter range, 230m, runs from the centre of the site to the common receive site shown in the lower left of the photograph adjacent to the copse of trees and the perimeter road.

The peak emissions from a radar under test are a function of the power spectrum available at the antenna and the peak gain of the antenna across the frequency band. The required criteria for achieving peak gain of an antenna is that it must be illuminated by a plane wave, therefore on an open site the equipment under test must be at an infinite range! This is also true for a transmitting antenna as power transfer between two antennas is reciprocal. In practice it is normal to measure at a range that is practical and gives an acceptable reduction in gain. For the case of unwanted emission measurements made at Funtington the target criteria for the range, *R*, requirement is given in equation 3.1.3-1.

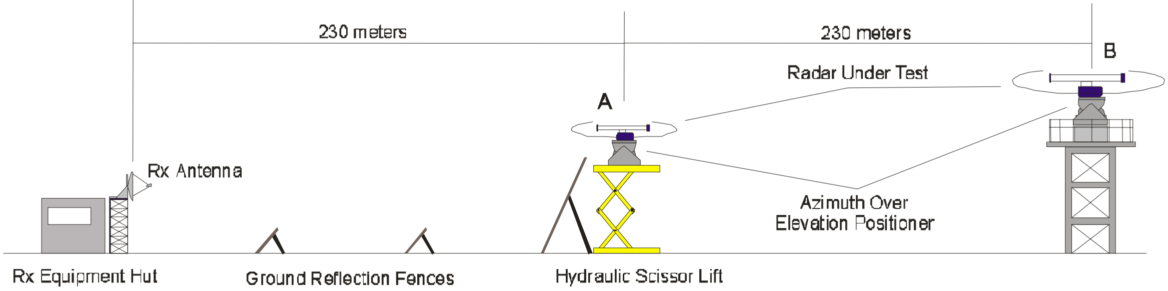
$$R \geq D^2/\lambda$$

Equation 3.1.3-1

Where *D* is the maximum dimension of the antenna under test and λ is the wavelength of the highest measurement frequency. It is not always possible to achieve the range criteria with large antennae and very wide band measurements, therefore an estimate of the gain reduction must be calculated.

A diagram of the measurement ranges is shown below Figure 3.1.3-2.

Figure 3.1.3-2 Diagram of the Unwanted Emissions Measurement Range



Transmit site A has predominately been used for the smaller X-band marine navigation radar units and site B has been used for the larger antennas typically installed on the S-Band marine navigation radar systems. The parabolic reflector antenna used as the receive antenna provides a high gain figure permitting a greater measurement dynamic range, and the narrow beamwidth provides discrimination against background signals as well as multipath reflections. The ground reflection fences and the large reflection fence in the centre of the range reduce the multipath effects still further. The larger fence also has a serrated top edge to minimise diffraction effects. When measuring a radar at transmit site B, the hydraulic scissor lift is lowered completely, allowing a clear, uninterrupted range.

Figure 3.1.3-3 Photograph of the Marine Navigation Radar on the measurement range at site A

The photograph above, Figure 3.1.3-3, shows the Marine Navigation Radar installed on the Funtington fixed UE range.

The measurement system is installed on a dedicated measurement range and has been carefully planned to minimise the radio frequency (RF) cable length. In particular the test cable from the receive antenna is only two metres long and this ensures the maximum dynamic range of the system is maintained. The receiver system and RF front-end devices are all integrated into one 19” rack to reduce cable lengths further. The rack is located in a cabin directly behind the receive antenna.

3.1.3.3.2 Funtington Mobile UE Facility

The new mobile facility was commissioned in time for this research package. The facility is quite simply all of the test equipment from the fixed range at Funtington compressed into a semi-portable rack and fitted into a LDV Convoy van. The van is also equipped with a 5kW petrol generator capable of being wheeled in and out of the van on ramps and an un-interruptible power supply to protect the PC in the event of power failure. The rear compartment of the van is lined with aluminium sheet and fine copper mesh to provide RF screening. This was designed to minimise the risk of RF leakage into the test equipment when measuring the high power radars, particularly the L-Band air traffic control (ATC) radar. External power and signal connections and additional heating, ventilation and lighting allow all the equipment to be integrated with the screening integrity intact.

The photograph below, Figure 3.1.3-4, shows the mobile UE facility deployed at one of the radar sites. The antenna shown is the 2 to 40GHz circularly polarised parabolic reflector. The antenna is secured and stabilised by the use of multiple ½ cwt-iron sinkers. The panel just behind the antenna is the main interface panel for the RF connections and polarisation control cables for the various receive antennas available.

Figure 3.1.3-4 Photograph of the mobile UE Measurement Facility

The generator is shown to the rear of the van and is capable of running the test equipment for approximately 8 to 9 hours on one full tank of fuel. This allows the equipment to be set-up and run overnight on some of the longer measurement runs.

3.1.3.3.3 The Measurement Test Equipment

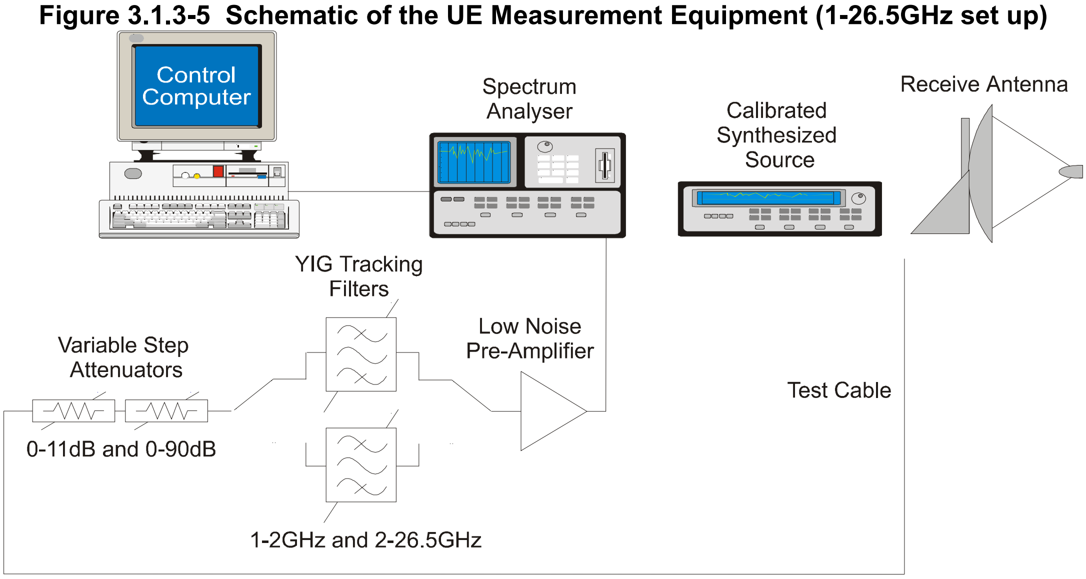
The measurement test equipment is essentially the same for both of the facilities available for UE measurements. The original test equipment rack was replaced by a smaller modified version to enable its use in the mobile facility. The rack can be exchanged from one facility to the other by means of a fork lift. The only difference between the two facilities is the mounting arrangements of the measuring antenna. On the fixed range the antenna is located on a small lattice mast, while when using the mobile facility the antenna is mounted on a tripod secured with ropes and sinkers.

The measurement system comprises of:-

- 2-40GHz circularly polarised parabolic dish receive antenna, or
- 1-18GHz parabolic dish antenna with a switchable linear and circularly polarised feed, or
- 18-26.5GHz parabolic dish antenna with manual setting of the linearly polarised feed
- computer controllable 0-90 dB and 0-11 dB attenuators
- Omni-Yig 2-26.5GHz or 1-2GHz computer controllable YIG band-pass filter
- low noise pre-amplifier
- 26.5GHz Hewlett Packard Modular Measurement System (MMS) spectrum analyser
- personal computer
- 10MHz – 40GHz synthesised calibration source
- 26.5 - 40GHz waveguide mixer
- 26.5 - 40GHz pre-amplifier

The measurement equipment schematic is shown in Figure 3.1.3-5 below for the standard configuration.

Figure 3.1.3-5 Schematic of the UE Measurement Equipment (1-26.5GHz set up)



For the purpose of the 26.5 to 30GHz measurements the standard RF front end shown above comprising the attenuators, filters and pre-amplifier, is replaced with a waveguide run, waveguide pre-amplifier and waveguide mixer. The broadband RF section on the spectrum analyser provides the local oscillator (LO) and intermediate frequency (IF) connections for the mixer.

The emphasis on the design of the equipment set up was to reduce losses due to cables and devices to a minimum while still maintaining a flexible mobile facility. The test cable from the receive antenna to the van is typically only two metres, this means that it has not been necessary to build a remote RF front-end. The RF front-end is built onto a single 19" rack panel and is within the van. The advantage of this is that a stable environment for the front-end devices is provided, particularly for the YIG filters.

All measurement equipment is calibrated, if required, in accordance with the manufacturers guidelines.

3.1.3.4 Unwanted Emissions Measurement Method

3.1.3.4.1 General

Although the measurement techniques and spectrum analyser settings are based on those described in the draft revision of ITU-R Recommendation M.1177-2, the measurements made during this campaign used best practice and settings gained from experience of UE measurements on previous projects. In some cases the radar spectra were measured with a number of equipment settings in order to verify optimum settings.

All measurements of Unwanted Emissions made by QinetiQ use a technique based upon the automatic direct method as described in ITU-R Recommendation M.1177-2.

The direct method involves measuring the power density across the frequency band of interest resulting from the radiated power spectra of the radar under test. The power is measured with an antenna and receiver system at some distance away. Typically the measurements of radars in the field are non-invasive, with them operating in their normal mode. However, at the dedicated range at Funtington it is possible to control the radar, and they are often measured in a number of different modes including the worst case mode, i.e. occupying the greatest amount of bandwidth.

In ITU-R Recommendation M.1177-2 the recommended settings for OOB and SE measurements are essentially the same and imply that they are in fact a single combined measurement. The measurement data can then be assessed for both OOB and SE performance. One of the purposes of this measurement programme was to verify whether this is, or is not, appropriate. The measurements of SE and OOB have therefore been separated and assessed individually with receiver bandwidth, measurement step size and measurement time being the three main areas of concern.

Before commencing a full measurement run of either SE or OOB a number of short investigative measurements are made. The purpose of this is two fold: firstly to ensure that the radar under test is in fact operating as expected, and secondly to optimise the settings of the test equipment to ensure efficient use of the measurement time while maintaining accurate measurements. This initial survey is particularly important if not all of the radar parameters are known.

The spectrum analyser is used in manual mode and a number of parameters are confirmed, listed below:-

- Fundamental Frequency / Frequencies
- Polarisation
- Rotation rate
- The narrowest resolution bandwidth possible for measurement of the maximum power at the fundamental frequency
- Pulse Repetition Rate

If it is possible, other parameters are measured with a broadband detector diode and oscilloscope including pulse width, rise time and fall time.

The steps taken in the unwanted emission measurement procedure carried out at Funtington are outlined below and apply to both OOB and SE measurements:-

- Switch on receive equipment and warm-up
- Perform spectrum analyser internal calibration
- Perform system calibration with synthesised source
- Record the background signals (if any) using a wide-band sweep
- Switch on the equipment under test and allow to warm-up
- Measure the peak power spectrum for a SE measurement (detail method shown below), or
- Measure the OOB pulse spectrum shape
- Apply the system calibration, antenna gain curve and range loss to the data
- Plot calibrated emitted spectrum

Before commencing a measurement run the receive system is calibrated across the full measurement band using the synthesised source. The frequency is stepped across the measurement band and the power recorded on the spectrum analyser at each step. The loss figure curve for the system against frequency is then calculated. One of the advantages of the MMS spectrum analyser system is that the low noise pre-amplifier is an integrated module and therefore the gain characteristics are contained within an internal calibration.

To measure the unwanted emissions of the equipment under test, the measurement system is required to measure the worst case power spectrum. The analyser is first set to the lowest frequency of the required measurement range with a frequency span of 0 Hz. The Resolution Bandwidth (RBw) is set to an appropriate value for the pulse width of the equipment under test, typically equal to $1/\tau$ for a simple pulse modulated radar (where τ = pulse width). The sweep time is set to a value greater than the time for one rotation of the radar antenna. If the radar is static then the sweep time is set to a time appropriate for the receive equipment to settle and for the spectrum analyser to receive a significant number of pulses - this is typically a minimum of 0.5s. (Note that if the radar switches mode on a revolution basis then it will be necessary to set the sweep time to a duration suitable for the radar to have performed all of the modes).

As the radar rotates, the analyser measures the received power against time. At the end of the sweep the peak value is recorded and down loaded to the PC. The PC then adjusts the front-end attenuation if the peak value does not fall into an optimum power band and the measurement is repeated. The power band or measurement window is variable and set with the control software, the peak value being below the 1dB compression point of the system and the size of the window being 6 to 10 dB. If the measured value is satisfactory the frequency is then stepped by the RBw and the procedure repeated. This method provides a continuous measurement of the spectrum. The procedure above continues until the analyser has stepped across the entire measurement range. For example in the case of a SE measurement of a S-Band marine navigation radar the number of steps is several thousand and can take up to seven hours depending on the speed of rotation of the equipment under test.

The settings that are common to both SE and OOB measurements are listed below:-

Detector Mode ⇒ Positive Peak

Video bandwidth ⇒ ≥ Measurement receiver bandwidth

Sweep time ⇒ > One radar revolution or one radar mode cycle or 0.5s

3.1.3.4.2 The Spurious Emissions Measurements

The measurement of spurious emissions is related to the measurement of the total power in the spurious bands compared to the peak power of the fundamental. It is therefore important to configure the test equipment to have sufficient bandwidth to measure the peak power of all signals including the fundamental, harmonics and other spurious spectra. However, it is equally important not to increase the bandwidth beyond the required value to measure peak power of the fundamental because this will result in the measured values of the noise emanating from the radar and the general noise in the spurious domain increasing at a rate of approximately 3dB per octave of bandwidth while the measured level of the fundamental will remain constant. (This will not be the case for very strong harmonic signals which, like the fundamental, will remain unchanged by an increase in bandwidth).

To adequately measure the peak power of a pulsed spectrum, the impulse bandwidth of the receiver must be wide enough to sum the power in the majority of the spectral components. This occurs when the receiver impulse bandwidth exceeds $1/\tau$ for the case of unmodulated pulsed radars.

The measurement settings for the SE measurements are listed below:-

Receiver bandwidth	⇒	$1/\tau$ for fixed frequency, non-pulse coded radars
	⇒	1/t for fixed frequency, phased-coded pulse radars
	⇒	$(B/\tau)^{1/2}$ for FM or chirped radars
	⇒	or value ascertained during survey
Receiver / preamplifier Saturation Level	⇒	-50dBm

(Note: τ = pulse length, t = phase chip length and B = range of frequency sweep)

The spectrum analyser is limited to a resolution bandwidth of 3MHz equating to an impulse bandwidth of approximately 4.5MHz. Therefore when measuring radars with short pulse modes, i.e. pulse width < 200ns the peak power measured is lowered by the pulse desensitisation figure. It is possible to calculate the desensitisation figure for the spectrum analyser; or alternatively the MMS analyser has a wide IF bandwidth module with a calibrated linear detector which can measure the desensitisation figure directly by using bandwidths up to 100MHz. (The spectrum analyser cannot be used directly in the wide bandwidth mode for the measurement of the SE as the dynamic range is very limited by the linear detector, approximately 30dB).

The receiver / preamplifier saturation level is the maximum value allowed into the front end of the pre-amplifier module that gives rise to negligible compression. This corresponds to the top value of the software measurement window, the point at which attenuation is switched in.

3.1.3.4.3 The Out of Band Measurements

Out of Band (OOB) measurements are related to measuring the transmitted spectrum of the fundamental radar emission to ascertain if the energy is contained within specified limits of amplitude and frequency, essentially between the Necessary Bandwidth region and the Spurious Emission region. The requirements of this measurement are to accurately ascertain the shape of the transmitted spectrum close to the carrier.

The measurement settings for the OOB measurements are listed below:-

Receiver Bandwidth(theoretical ideal)	⇒	< 5% of main spectral lobe width between 1st nulls.
Saturation level	⇒	(-50 dB) - 6dB per octave of bandwidth less than $1/\tau$

The assessment of the saturation level is important for these measurements because if the requirement for the receiver bandwidth is very narrow, i.e. tens of kHz, then the measured value on the spectrum analyser could be considerably desensitised, (tens of dBs). However the pre-amplifier is still subjected to the peak power, as the pre-selection of the YIG filters is not sufficiently narrow. The saturation level used for the measurements has to be adjusted by the desensitisation figure or approximately –6dB per octave of bandwidth less than the receiver bandwidth = $1/\tau$.

When selecting the resolution bandwidth to use for the measurement of the pulse spectrum shape, it is also important to consider the dynamic range required for the measurement. When measuring a simple pulsed signal with a receiver of variable bandwidth the maximum instantaneous dynamic range is achieved when the Bw=$1/\tau$.

Figure 3.1.3-6 Graph of the Effect of Receiver Bandwidth on Signal Responses

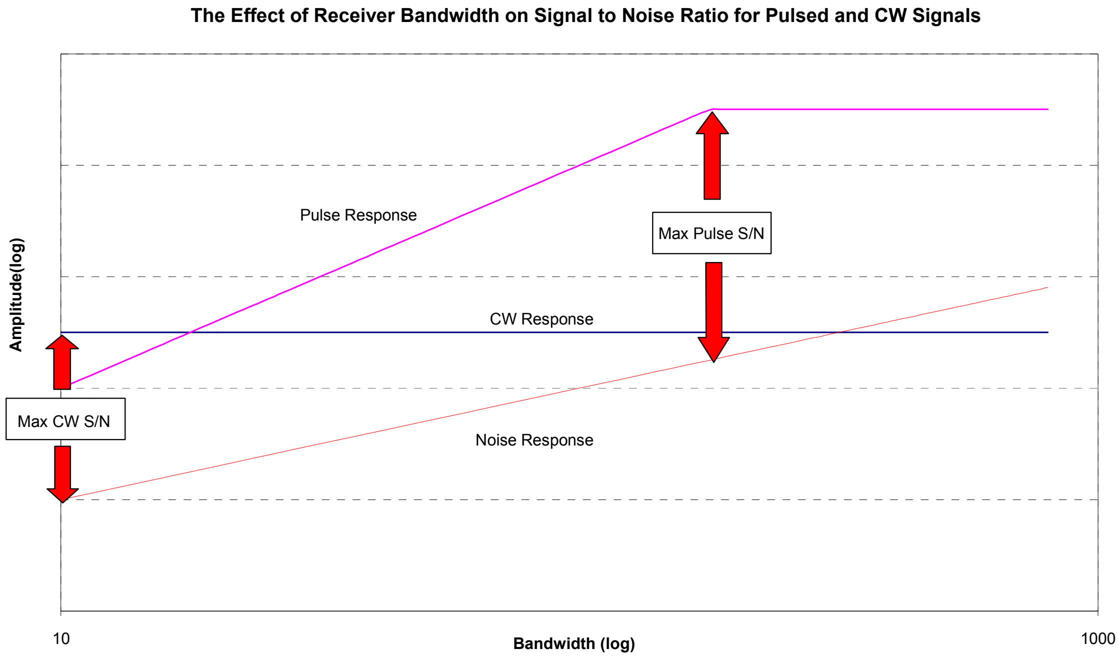


Figure 3.1.3-6 above shows a graph of the responses of noise, a pulsed signal and a CW signal with different receiver bandwidths. Although when using narrower bandwidths the noise floor decreases, the response to pulsed signal is desensitised even more. The noise floor decreases at a rate of 10dB per decade of bandwidth down, while the response to the pulse signal reduces at a rate of 20dB per decade. Therefore the dynamic range for high resolution measurements is decreased considerably.

3.1.3.4.4 Measurement Uncertainties and Repeatability

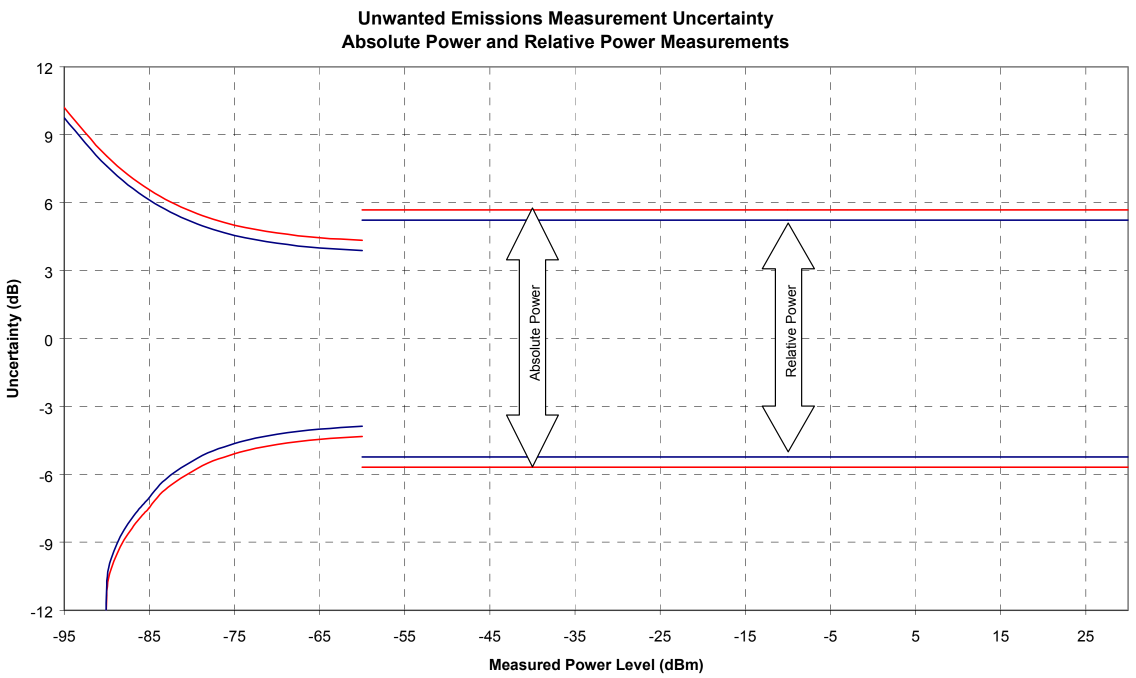
The measurement uncertainties have been calculated for the Funtington fixed range and the contributions to this are presented below in Table 3.1.3-1. The uncertainties for the Unwanted Emissions (UE) emissions have been calculated for the absolute power measurement, (i.e. Equivalent Isotropically Radiated Power (EIRP)), and for relative power measurements, i.e. normalised plots.

Table 3.1.3-1 Contributions included in the measurement uncertainty (Uc)

No	Source of Uncertainty	Absolute Power Uc (dB)	Relative Power Uc (dB)
1	Multipath	±0.5	±0.5
2	Gain of Rx dish	±0.5	±0.5
3	System Calibration	±0.5	±0.5
4	Connector Repeatability	±0.15	N/A
5	Attenuator 1	±0.5	±0.5
6	Attenuator 2	±1	±1
7	YIG pass band ripple	±0.5	±0.5
8	Spectrum analyser frequency response	±1	±1
9	Spectrum analyser absolute power calibrator	±0.3	N/A
10	Spectrum Analyser Marker resolution	±0.03	±0.03
11	Spectrum Analyser scale fidelity	±0.2	±0.2

Figure 3.1.3-7 below, is a graph of the worst case relative and absolute power measurement uncertainties. The constant uncertainty region is for radiated powers sufficient to warrant attenuation at the RF front end. The non–linear region in the uncertainty graph is a result of very low powers requiring no attenuation and therefore approaching the noise floor of the analyser. The discontinuities in the plots are due to the additional uncertainty when using the attenuators.

Figure 3.1.3-7 Graph of Worst Case Measurement Uncertainties



The point at which the discontinuity occurs in terms of measured input power is dependent on the software selection of saturation level and measured window size.

For the measurement of the pulse width and rise time, the uncertainty resulting from the test equipment was ±1.5% of the measured value while for the measurement of the Pulse Repetition Rate (PRR) the uncertainty was ±2% of the measured value.

The estimation of measurement uncertainties is specific to the fixed range at Funtington. However the sources of uncertainty apply equally to the mobile facility apart from the contribution from multipath. The assessment of the contribution from multipath signals at radar installations is difficult, however it is possible to estimate a probable worst case. If a reflected signal equal in power to the direct signal coinciding with the first sidelobe of the receive antenna is considered, the resulting uncertainty would be approximately +1dB/–1.3dB.

The measurement uncertainties presented in this section do not consider the range geometry at the radar installation sites or the possible direction of peak emissions from the radar. These have to be considered on a case by case basis and in some instances this is impossible without measuring the radar at all azimuth and elevation angles i.e. over the entire radiating sphere!

The effects of weather on the measurement uncertainties have not been quantitatively addressed. The weather has to be assessed on a measurement to measurement basis to confirm that the conditions are within satisfactory bounds. The main weather sources of error are water and ice on the receive antenna, particularly the feed, and strong winds affecting the beam pointing of the receive antenna. Throughout the measurement campaign the weather was exceptionally good with only one wet day during the trials. Strong winds while measuring the weather radar were overcome by securely roping down the receive antenna.

Specific repeatability measurements with a single radar being repeatedly measured were not made within this campaign. However a number of repeat runs were made on some of the radars in the campaign for operational reasons, with a number of different test runs being performed at each installation. Also a number of the longer SE runs were broken up into shorter runs with overlapping sections. These breaks were due to practical issues including refuelling the generator and the ends of the working day.

A repeat OOB run of the marine navigation radar with the radar antenna fixed and raised onto the range 5 days later resulted in a measured spectrum with a repeatability of ±2dB. A repeat run of the meteorological radar in the region of the fundamental on the same day resulted in differences of less than ±1dB down to a level of –60dB reference to the peak of the fundamental, including the nulls. An overlapping section of the SE run of the meteorological radar measured on separate days resulted in a repeatability of ±1.5dB at a level of –80dB relative to the peak of the fundamental. Other overlapping sections of various measurement runs had repeatability of within ±1.5dB.

3.1.3.5 Measurement Results

3.1.3.5.1 General

The results in this section have the relevant masks applied to the plots. These have been calculated from the equations given in Annex 8 of ITU-R Recommendation SM.1541 using the measured pulse characteristics where available. Throughout the campaign, when measurements of the pulse characteristics were possible, the fall times were longer than the rise times. All of the radars measured except the meteorological radar are classified as Category A radars. Although the ATC radars are fixed, they have multiple frequency operation and are therefore exempt from the stricter category B regulations.

3.1.3.5.2 Marine Navigation Radar – X-Band Magnetron

The marine navigation radar was measured on the Funtington fixed range over the period of a few weeks. The radar was located at transmit site A on the range diagram shown earlier (Figure 3.1.3-3), the centre of the Funtington range, which gave a measurement range of 230m.

The relevant radar characteristics for the calculation of the UE masks are presented below in Table 3.1.3-2.

Table 3.1.3-2 Characteristics of the Marine Navigation Radar

Parameter	Mode	
	Long Pulse	**Short Pulse**
Frequency (MHz)	9415	
Peak Power (kW)	10	
Pulse Width (ns)	640	65
Rise Time (ns)	14	19

The extended period that the radar was available for, enabled measurements to be made with both the test equipment and the radar in different configurations. In particular it was possible to investigate the question of resolution bandwidth (RBw), and a number of measurement runs were performed with differing RBw close to the fundamental region. The following figures show the results of different RBw runs with the data normalised so that the main lobe width and sidelobe levels can be compared.

The Figure 3.1.3-8 shows a comparison of the normalised measured data and highlights the effect on the sidelobe levels which can be seen to be as much as 5dB different from a very narrow 51.1kHz (0.033/τ) bandwidth to the wide 825kHz (0.528/τ).

Figure 3.1.3-8 The measured spectrum, with different receiver bandwidths of the marine navigation radar with the antenna fixed

(Freq=9415MHz, Pw=640ns, Tr=14ns, PRR=375Hz)
(825kHz $\approx$ 0.528/τ, 316kHz $\approx$ 0.202/τ, 162kHz $\approx$ 0.104/τ, 82.5kHz $\approx$ 0.053/τ, 51.1kHz $\approx$ 0.033/τ)

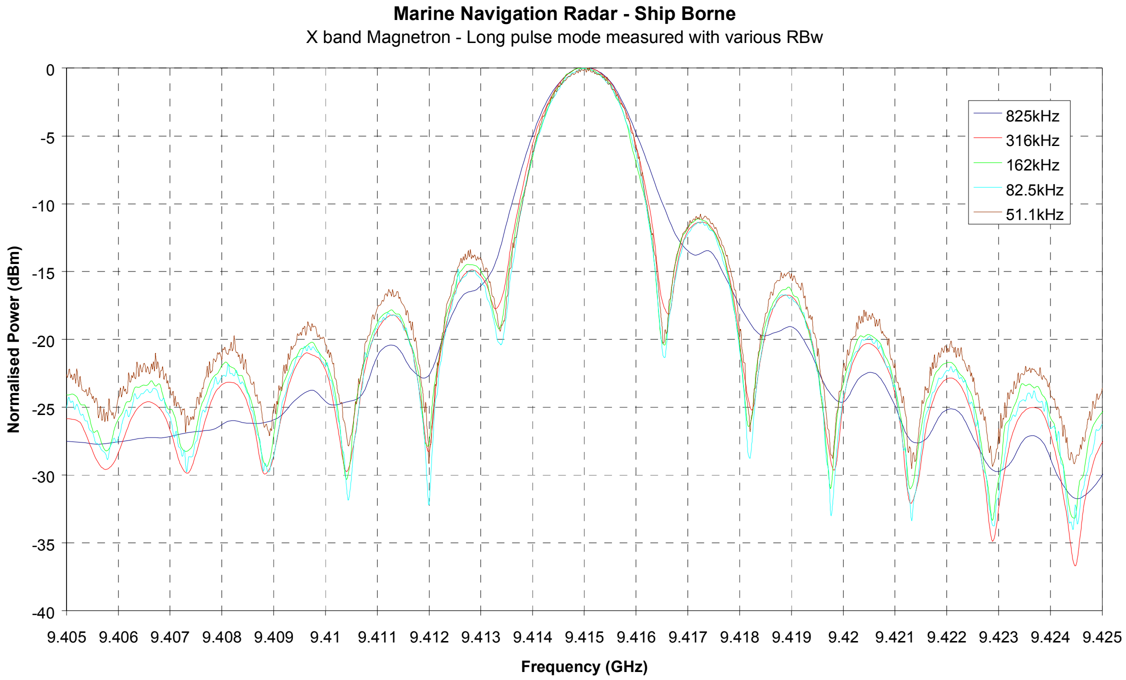
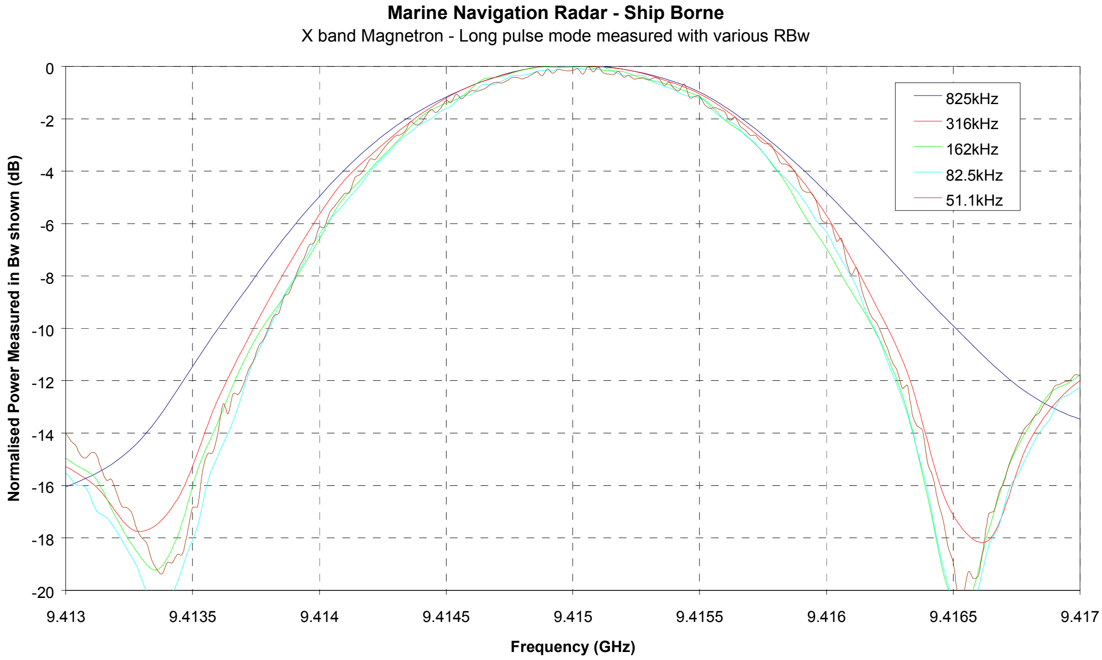


Figure 3.1.3-9 below is a zoomed in plot of the same measured data to demonstrate the impact of receiver bandwidth on the main lobe shape. It is clear in the plots that measurement has been greatly distorted by the receiver IF filter shape when set to 825kHz (0.528/τ). There is no apparent advantage in resolving the shape of the main lobe by decreasing the bandwidth any further than 316kHz (0.202/τ).

Figure 3.1.3-9 A zoomed plot of the main lobe region of the measured spectrum of the marine navigation radar with the antenna fixed
(Freq=9415MHz, Pw=640ns, Tr=14ns, PRR=375Hz)
(825kHz $\approx 0.528/\tau$, 316kHz $\approx 0.202/\tau$, 162kHz $\approx 0.104/\tau$, 82.5kHz $\approx 0.053/\tau$, 51.1kHz $\approx 0.033/\tau$)



Marine navigation radars can switch operating modes when the user selects different range and resolution settings on the front panel of the display unit. The particular navigation radar tested had four operating modes with different pulse widths (PW) and Pulse Repetition Rates (PRRs). For the purpose of Type Approval it is normal for marine radars to be tested in the mode that occupies the most bandwidth, typically the short pulse mode only. In this measurement campaign the radar was measured in two modes, short and long pulse.

Figure 3.1.3-10 SE measurement of the marine navigation radar in short pulse mode with the antenna rotating
(Freq=9415MHz, Pw=65ns, Tr=19ns, PRR=3000Hz)

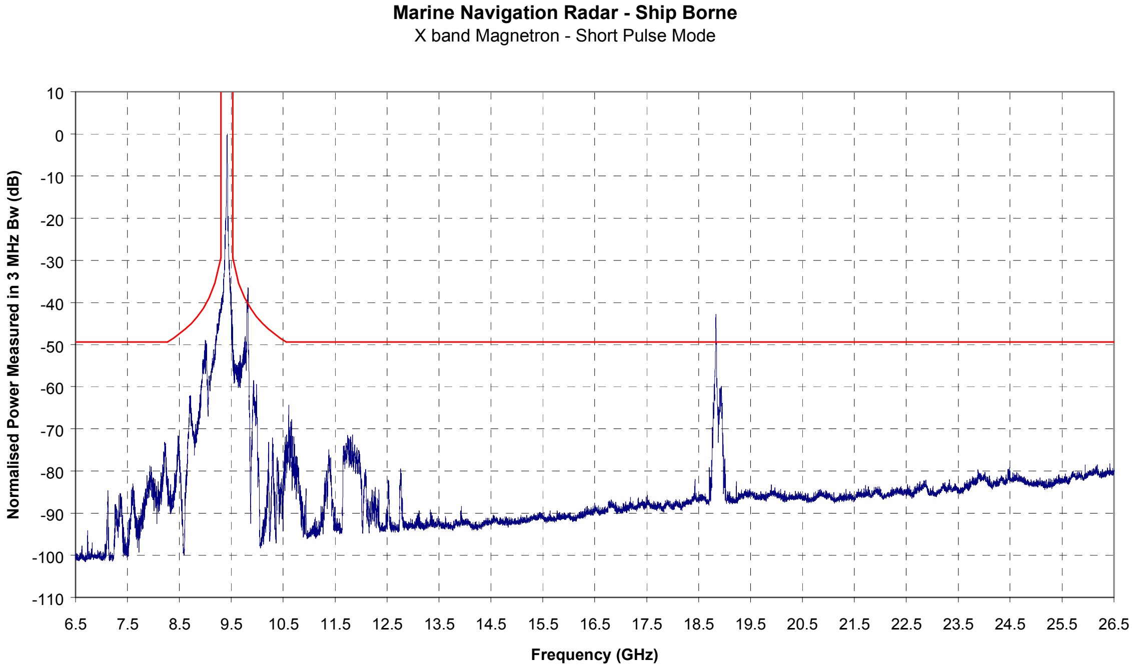
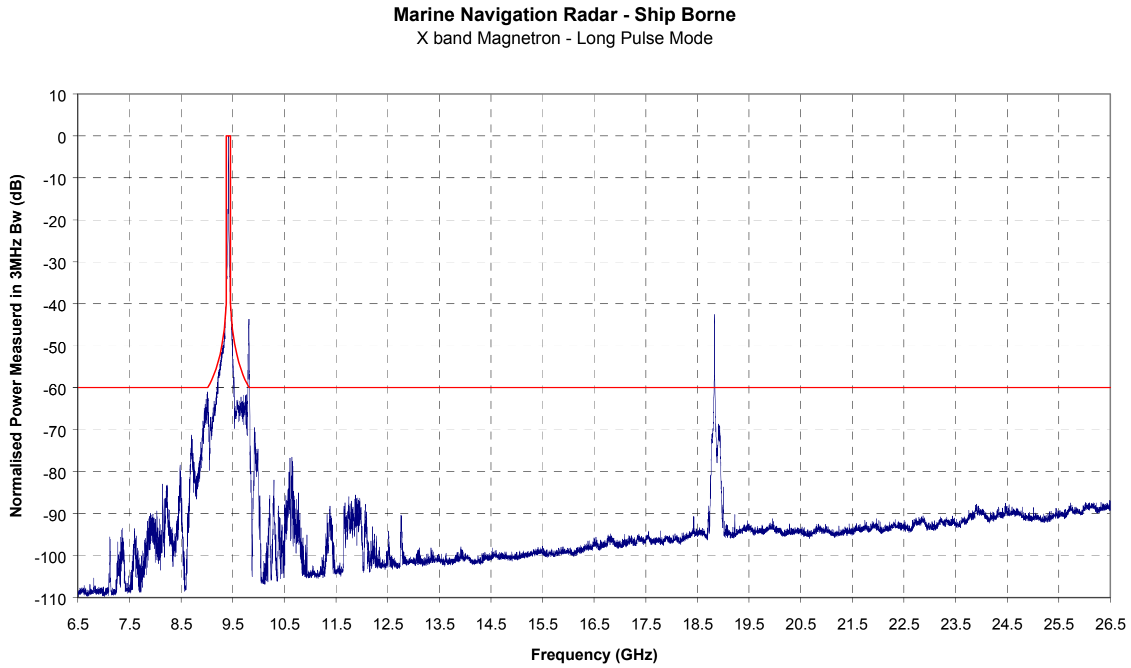


Figure 3.1.3-11 SE measurement of the marine navigation radar in long pulse mode with the antenna rotating
(Freq=9415MHz, Pw=640ns, Tr=14ns, PRR=375Hz)



The two figures above, (Figure 3.1.3-10 and Figure 3.1.3-11), for the SE measurements of marine navigation radar highlight the impact of having a too narrow receiver bandwidth to measure the peak power satisfactorily. In short pulse mode the spectrum analyser is desensitised therefore when the data is presented as a normalised plot the apparent noise floor of the measurement rises, in this case by approximately 8 –10 dB.

The slope of the noise floor is a result of the calibration corrections to the measurement data. The noise floor of the spectrum analyser is almost constant across the frequency band. The calibration correction is a sum of a number of contributions, with the dominant values being the range loss and receive antenna gain. The two calibration curves would cancel out if the antenna gain followed the curve of a perfect parabolic reflector. The receive antennas used for the measurement of UE have to be very broadband and are unlikely to approximate to a perfect parabolic antenna. This is normally caused by the feed arrangement, with spill at the lower frequencies and under illumination of the dish at the higher frequencies.

Figure 3.1.3-12 shows the SE plot of a second marine navigation radar in short pulse mode. The measurement was made in two stages, the first stage, (from 7 to 26.5GHz), used the spectrum analyser in the conventional fashion as previously described while the second stage, (from 26.5 to 30GHz), used an external mixer system. The external mixer system comprised a waveguide transition, a waveguide low noise pre-amplifier, a short waveguide section and then a 26.5 to 40GHz waveguide harmonic mixer designed to work with the spectrum analyser. The waveguide transition was connected directly to the back of the receive antenna and hence the losses associated with the cable runs, the attenuators and the insertion loss of the YIG filter were not present. The difference in system losses between the conventional and the mixer system combined with different gain and noise characteristics of the two pre-amplifiers resulted in a different noise floor and hence the discontinuity in the plot shown. It is clear from the plot that if the conventional system had a slightly extended frequency range, the 3rd harmonic might have been unobserved because of the higher noise floor.

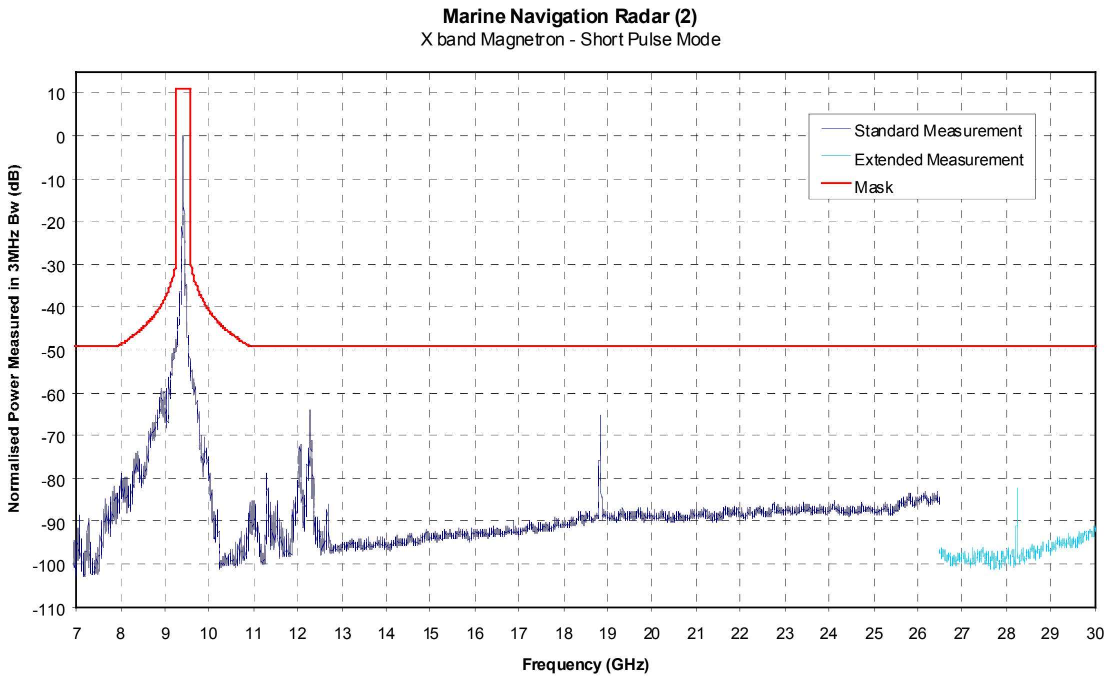
The relevant radar characteristics for the calculation of the (unwanted emission (UE) masks are presented below in Table 3.1.3-3.

Table 3.1.3-3 Characteristics of second Marine Navigation radar

Parameter	Mode
	Short Pulse
Frequency (MHz)	9417.5
Peak Power (kW)	10
Pulse Width (ns)	60
Rise Time (ns)	10.5

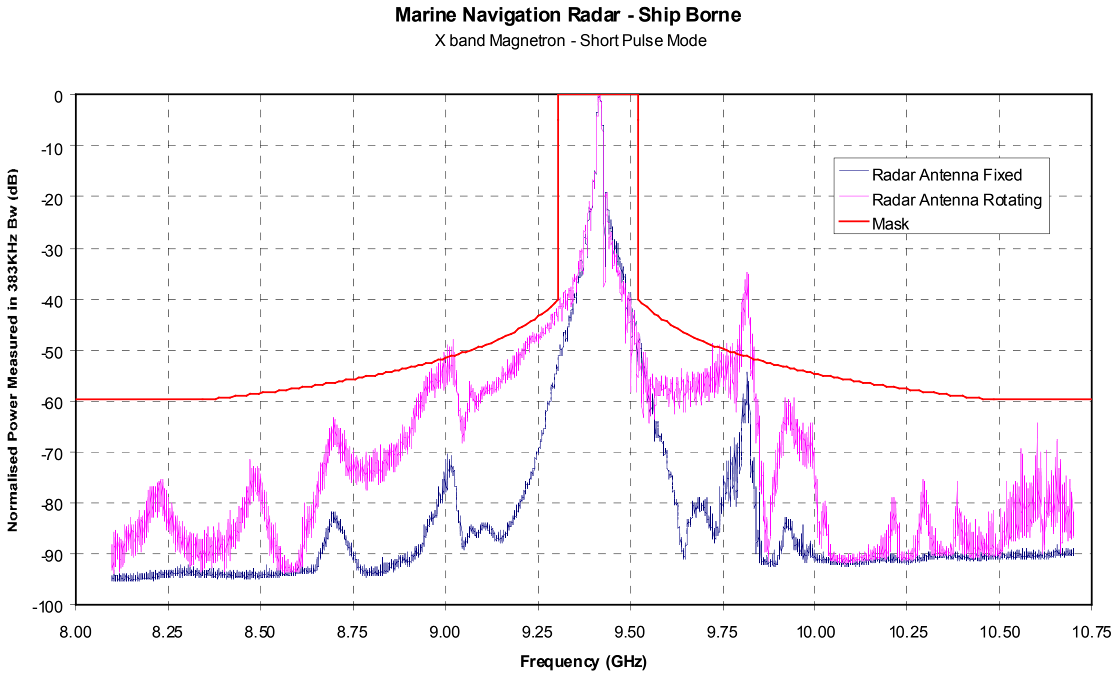
Figure 3.1.3-12 SE measurement of a second marine navigation radar in short pulse mode with an extended frequency range from 26.5GHz to 30GHz using an external mixer system

(Freq=9417.5MHz, Pw=60ns, Tr=10.5nS, PRR=1800Hz)



To highlight the impact of the antenna type on the direction of interference, a number of measurement runs were made with the antenna fixed, peaked up at the fundamental frequency on the receive site, and with the antenna rotating. The following Figure 3.1.3-13 shows the difference in the measured spectrums in the OOB region. The resolution bandwidth (RBw) was set to 383kHz, chosen as a good compromise between measurement time and resolution required from experience of the earlier RBw investigations.

Figure 3.1.3-13 Plots highlighting the difference between a radar fixed and rotating
(Freq=9415MHz, Pw=65ns, Tr=19ns, PRR=3000Hz)



The enormous differences particularly in the OOB are due to the antenna being an end fed slotted waveguide design. The differing frequencies either side of the fundamental frequency result in a different phase distribution down the length of the antenna resulting in a beam steering effect. In the case here, the beam has apparently moved a considerable azimuth angle, well into the sidelobe region of the fundamental antenna pattern which results in a 25-30 dB difference with the antenna fixed compared to the antenna rotating. The same effect will affect the measurement of any harmonics. In the case of these types of marine navigation radars it is possible that the harmonics will be unobserved with the antenna fixed because they may not be transmitted in the direction of the observation. These measurements demonstrate that it is very important even for the assessment of the OOB region that with certain types of radar antenna the radar must be rotating. The mask has been fitted to this plot to demonstrate that with the antenna fixed the radar comfortably meets the mask limits. However, with the antenna rotating the characteristic magnetron spike/hump to the right of the fundamental emission exceeds the mask by 15dB in the 20dB per decade roll off region.

Marine Navigation Radars are currently tested to Annex D, which forms a part of ITU-R Recommendation M.1177-2, in which there are guidelines to what is required for type approval testing. Although it is vital for the radar to be measured on the full azimuth plane, this is not the case for the elevation. The reasons for this are that the antenna has slots only in azimuth plane and these are very narrow in the elevation plane. The resulting antenna pattern is a fan beam that squints in azimuth with frequency but not in elevation. Also the second reason is that the designed usage of such a radar means that the only probable chance of interference is in the azimuth or horizontal plane.

3.1.3.5.3 Civil Air Traffic Control - S-Band Solid State

The S-Band solid state was measured on site at an airport. The measurement range was approximately 840m across a runway. This site gave a completely unobstructed view of the radar with very little clutter in between the radar and the receive antenna.

The geometry of the set up was not ideal but still suitable to measure the radar main beam. The range length was a little short resulting in the receive antenna having a look up angle of approximately 0.8°, therefore looking at the underside of the main beam of the radar which has an elevation cosecant squared pattern and a 3dB elevation beam-width of 4.5°.

The relevant radar characteristics for the calculation of the unwanted emission (UE) masks are presented below in Table 3.1.3-4.

Table 3.1.3-4 Characteristics of the ATC S-Band Solid State Radar

Parameter	Mode	
	Long Pulse	**Short Pulse**
Frequencies (MHz)	2784.5, 2785.5, 2809.5 and 2810.5	
Peak Power (kW)	15	
Pulse Width (μs)	100	1.0
Rise Time (ns)	169	169
Chirp (MHz)	1.0	0.0

The S-Band solid state radar was surveyed initially using the spectrum analyser in a manual mode. The optimum resolution bandwidth (RBw) setting of 1MHz was chosen to measure the peak power for the SE measurements. This was considered a good compromise between the two different requirements for the long and short pulse modes. A wider bandwidth would have introduced errors in the SE measurement of the spectra resulting from the long pulse emission while the desensitisation figure associated with the short pulse spectrum is calculable. RBw's of 21kHz and 511Hz were used to assess the pulse spectrum shape.

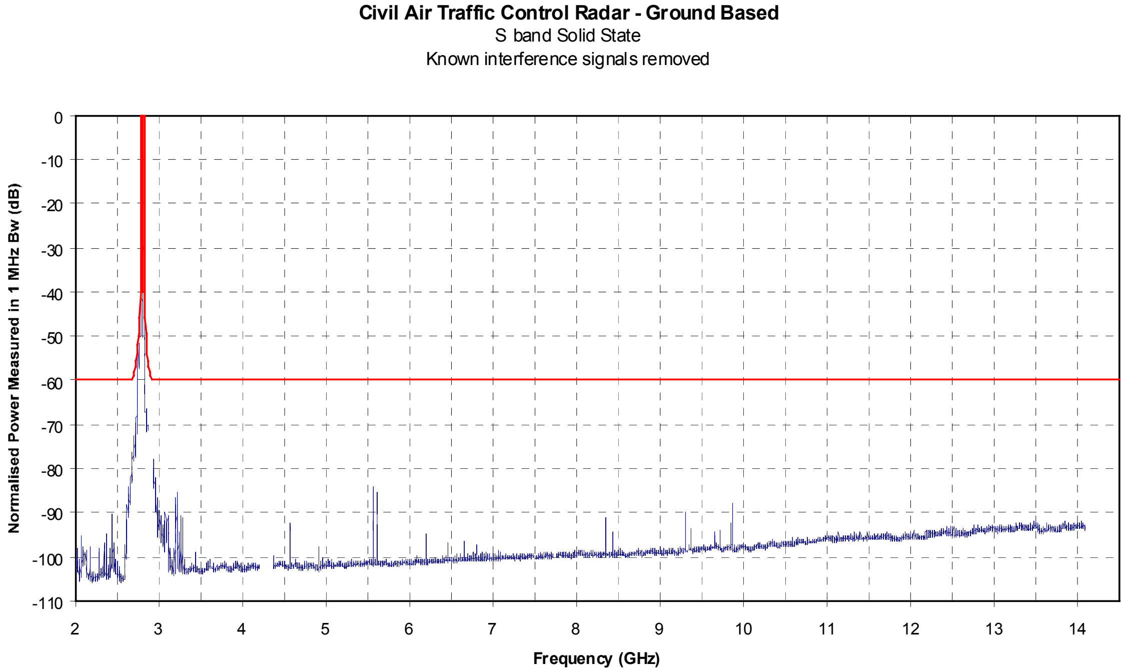
In total nine separate measurements were made with the SE run split into three parts. The total time for the SE run was 14.5 hours. The run was stopped just after reaching the 5th harmonic at approximately 14GHz.

The two pairs of transmit frequencies for this radar lay between the two transmit frequencies of the S-band TWT ATC radar also located at the Airport. Although the receive antenna provided angular discrimination against the TWT radar, the measurements away from the fundamental emission were subject to a considerable amount of interference.

Figure 3.1.3-14 below shows the SE measurement of the S-Band solid state radar with all the known interference sources removed from the plot including those from the S-Band TWT radar. The solid state radar has a very well controlled transmitted spectrum with the data comfortably satisfying the Category A specification for both OOB and SE. This is certainly due to the ability to control the rise and fall times, with the rise time approaching 200ns which is an order of magnitude longer than other similar radars with TWT output devices.

Figure 3.1.3-14 SE Plot of the S-Band Solid State ATC Radar with the known interference removed

(Freq=2784.5 & 2809.5MHz, Pw=100µs, Tr=169ns, Chirp=1MHz and Freq=2785.5 & 2810.5MHz, Pw=1µs, Tr=169ns, Chirp=1MHz, PRR=825Hz)



3.1.3.5.4 Civil Air Traffic Control - S-Band TWT

The S-Band TWT radar was measured on site at an airport. The measurement range was approximately 1660m down a runway with the radar on the opposite side to the receive site. This presented a small problem of the tail fins of landing aircraft obstructing the view of the radar when landing into an easterly wind. The blockage caused by the tail fins resulted in glitches in the measured data, however the aircraft were still travelling at a considerable speed and only one single data point was affected at a time. Due to the receive antenna looking down the runway the structures on the perimeter fence of the airport were close in terms of azimuth angle to the first sidelobes of the receive antenna.

The geometry of the set up was good with the extended range length (compared to the solid state radar set up) resulting in the receive antenna having a look up angle of approximately 0.4°. Therefore the receive antenna was looking slightly at the underside of the main beam of the radar which has an elevation cosecant squared pattern with a 3dB elevation beam-width of 4.8°.

The relevant radar characteristics for the calculation of the UE masks are presented below in Table 3.1.3-5.

Table 3.1.3-5 Characteristics of the ATC S-Band TWT Radar

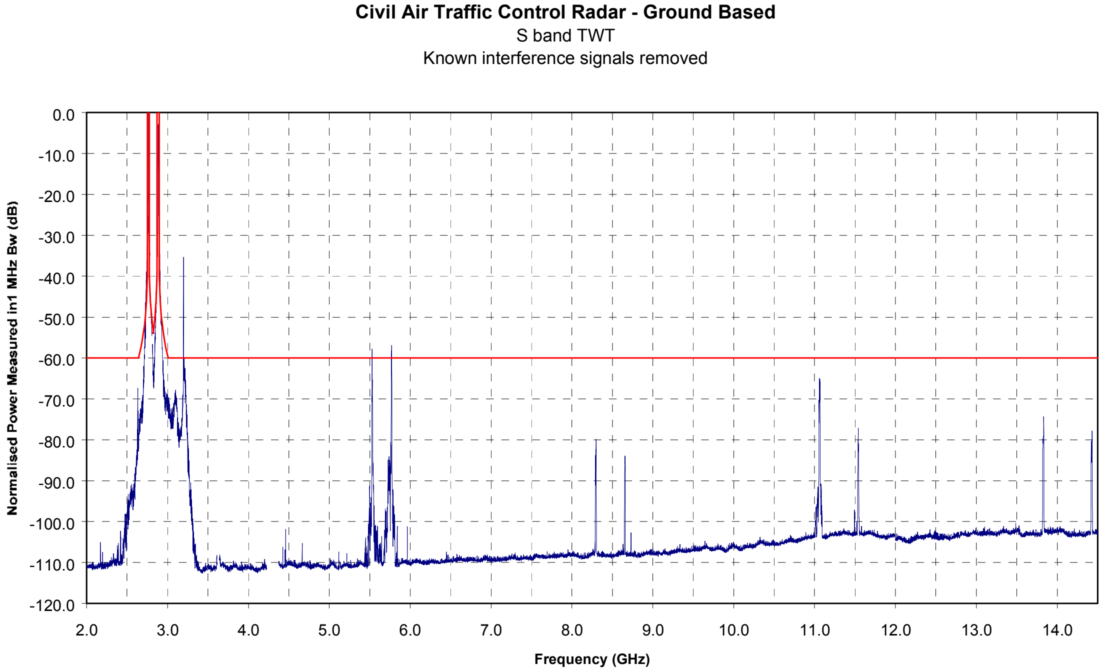
Parameter	Mode	
	Long Pulse	Short Pulse
Frequency (MHz)	2765 and 2885	2765 and 2885
Peak Power (kW)	60	
Pulse Width (μs)	19.3	0.33
Rise Time (ns)	18	18
Chirp (MHz)	2.5	0

The S-Band TWT radar was surveyed using the receive equipment in manual mode with optimum resolution bandwidth chosen to be 1MHz. The S-Band TWT radar has a fairly complex pulse train with different pulse widths interleaved on the same transmit frequencies. The short pulse mode would typically require a wider bandwidth than 1MHz as determined in the survey, however with the long pulse spectrum overlaid it is not possible to distinguish each of them separately. It was only possible to perform one full SE measurement with a run time of over 14 hours, and therefore the resolution bandwidth (RBw) of 1Mhz was chosen. It was however possible to perform a limited 2-4GHz SE run with a RBw of 3MHz.

Figure 3.1.3-15 below shows the SE measurement run of the S-Band TWT with all known interference signals removed. The harmonics within the spurious domain are clearly identifiable and just exceed the Category A specification. The SE run was halted at 14.5GHz just after the 5th harmonic. The source of the spike at 3.198GHz, approximately 35dB lower than the fundamental emission of the radar under test, was not identified and has therefore not been removed from the plot as a known interfering signal. Subsequent analysis of all the data measured at the site suggests that the spike does not emanate from the S-Band TWT radar being measured although the actual source remains unknown.

The mask for the OOB region is a complex composite specification to account for the different pulse widths and modulations used and the resolution bandwidth (RBw) of the receiver system.

Figure 3.1.3-15 SE Plot of the S-Band TWT ATC Radar with the known interference removed (Freq=2765 & 2885MHz, Pw=19.3µs, Tr=18ns, Chirp=2.5MHz and Freq=2765 & 2885MHz, Pw=0.33µs, Tr=18ns, PRR=1100Hz with stagger)



3.1.3.5.5 Civil Air Traffic Control - L-Band TWT

The L-Band TWT radar was measured on site at an airport. The measurement range was approximately 700m directly across a runway. This site gave a completely unobstructed view of the radar with very little clutter in between the radar and the receive antenna.

The geometry of the set-up was not ideal but still suitable to measure the radar main beam. The range length was short, resulting in the receive antenna having look up angle of approximately 1.4°, and therefore looking at the underside of the radar main beam which has an elevation cosecant squared pattern with a 3dB elevation beam-width of over 4°.

The relevant radar characteristics for the calculation of the UE masks are presented below in Table 3.1.3-6.

Table 3.1.3-6 Characteristics of ATC – L-Band TWT radar

Parameter	Mode	
	Long Pulse	Short Pulse
Frequency (MHz)	1269.77and 1332.77	1254.23 and 1317.23
Peak Power (kW)	75 per channel	
Pulse Width (µs)	33	1
Rise Time (ns)	30	30
Chirp (MHz)	1.0	N/A

As with the other ATC radars the L-Band TWT radar was surveyed manually to optimise the receiver settings. The resolution bandwidth (RBw) was confirmed at 1MHz for the measurement of peak power for the SE runs. Resolution bandwidths of 51kHz and 10kHz were used for the measurements of the short pulse and long pulse spectra shape respectively.

The total number of different measurements made on the L-Band TWT radar were eight with the three SE parts taking over 11 hours and the OOB assessment of the four frequencies taking 5 hours.

The greatest difficulty in assessing the performance of the L-Band TWT radar was the considerable number of interfering signals. These included aeronautical navigation aids up to 1200MHz, the GSM 1800 up and downlink for all the mobile phone service providers, the S-Band ATC radars and the aircraft altimeters. As well as the fundamental emissions from the interfering sources many had interfering harmonics too.

Figure 3.1.3-16 and Figure 3.1.3-17 show plots of the SE run on the L-Band TWT radar with and without the known interfering signals respectively. The plots highlight the difficulty in assessing radars on site in cluttered EM environments. The plot in Figure 3.1.3-17 shows that the L-Band TWT radar meets the Category A specification satisfactorily for SE.

Figure 3.1.3-16 SE plot of the L band TWT ATC Radar as measured with interfering signals included

(Freq=1269.77 & 1332.77MHz, Pw=33μs, Tr=30ns, Chirp=1MHz and Freq=1254.23 & 1317.23MHz, Pw=1μs, Tr=30ns)

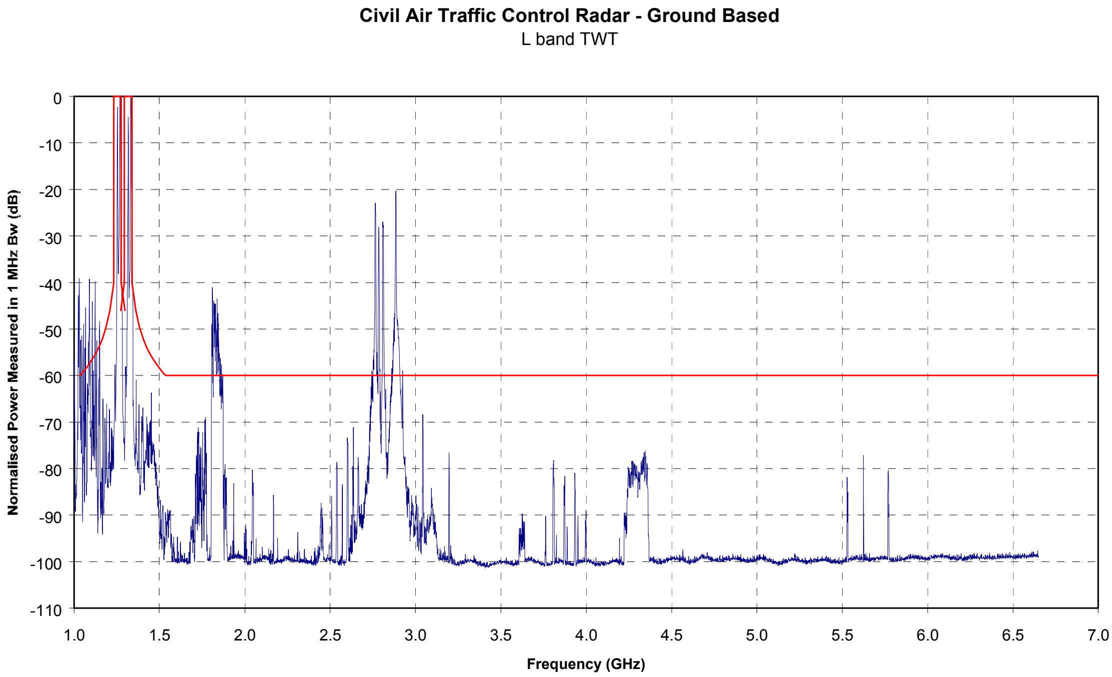
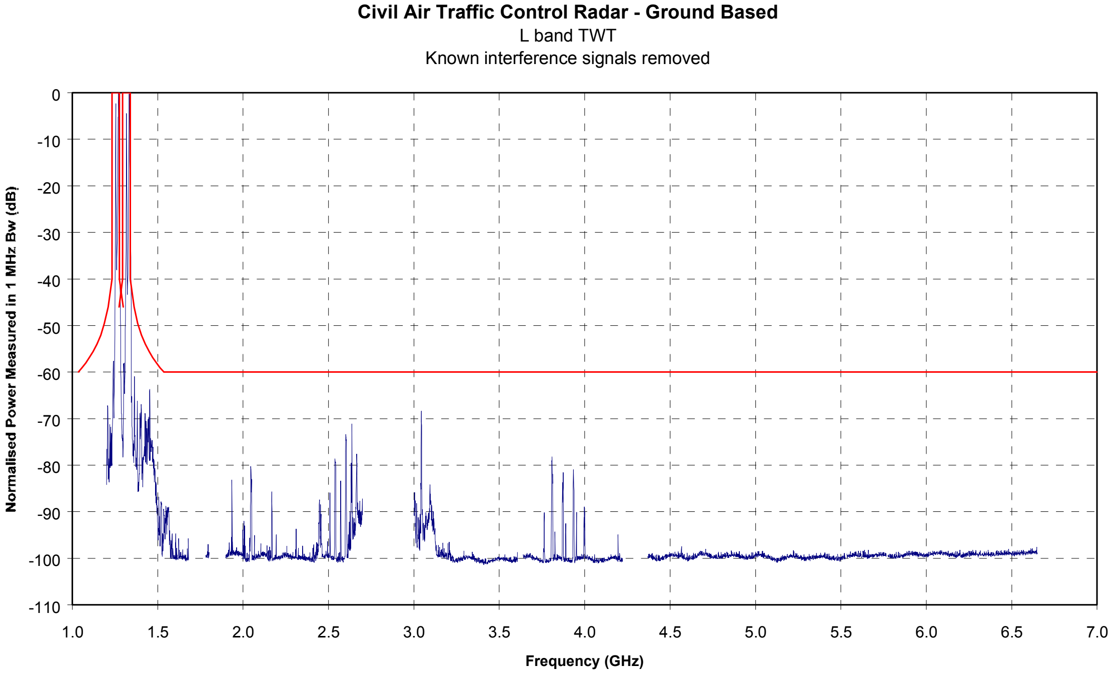


Figure 3.1.3-17 SE Plot of the L-Band TWT ATC Radar with the known interference removed
(Freq=1269.77 & 1332.77MHz, Pw=33μs, Tr=30ns, Chirp=1MHz and Freq=1254.23 & 1317.23MHz, Pw=1μs, Tr=30ns)



3.1.3.5.6 Airport Surface Detection Equipment – Ku-Band Magnetron

The ASDE was measured on site at an airport. The measurement range was approximately 980m across a runway and over the terminal area. The radar was located on top of the air traffic control tower at an estimated height of 30m. The site gave a completely unobstructed view of the radar with some clutter in between the radar and the receive antenna, including another radar tower.

Although the radar was very high up and the range length only 980m the geometry of the set up was considered to be very good because the antenna pattern of the ASDE is an inverse $cosec^{1.4}$ and designed to measure traffic on the ground. The resulting look up angle of the receive antenna was approximately 1.6° coupled with the radar's elevation 3dB beamwidth of 3.5° and down tilt of 1°.

The relevant radar characteristics for the calculation of the UE masks are presented below in Table 3.1.3-7.

Table 3.1.3-7 Characteristics of the ASDE Radar

Parameter	Mode	
	Freq 1	Freq 2
Frequency (MHz)	15650	16400
Peak Power (kW)	20	
Pulse Width (ns)	43	31
Rise Time (ns)	15	17

The ASDE was measured with two receive configurations for the assessment of the SE. Firstly, with the spectrum analyser set in the normal mode of operation with the resolution bandwidth (RBw) set to the maximum available bandwidth of 3MHz, and then secondly with the wide-band IF section selected with a bandwidth of 30MHz. The required bandwidth for the measurement of peak power would nominally need to have been 25MHz for the ASDE with a pulse width of 40ns, therefore the standard measurement was considerably desensitised.

Figure 3.1.3-18 below shows the result of the SE measurement run with a RBw of 3MHz and a SE mask applied to the plot. The reference level of the SE mask has been moved 15-20dB above the maximum measured power of the fundamental to account for the pulse desensitisation of the fundamental emission. The apparent noise of the measurement is also affected by the same desensitisation value. The OOB section of the mask has been removed for clarity and is covered later in this section.

Figure 3.1.3-18 SE Plot of the ASDE Ku-Band Radar

(Freq=15650MHz, Pw=43ns, Tr=15ns, Freq=16400MHz, Pw=31ns, Tr=17ns, PRR=8000Hz)

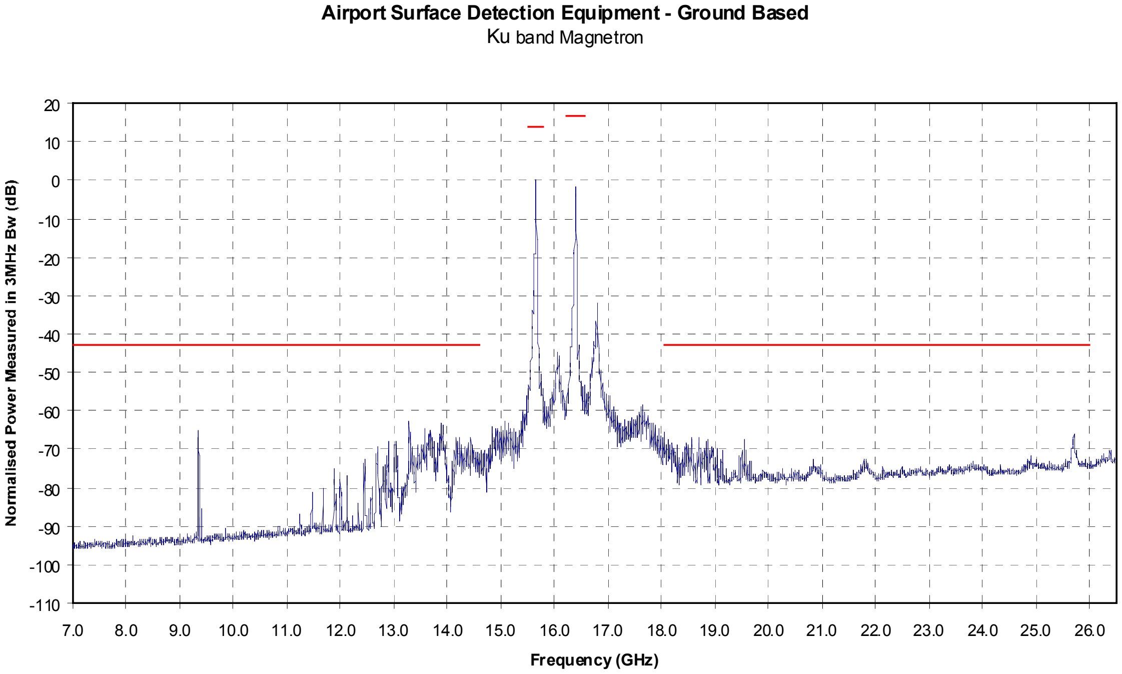
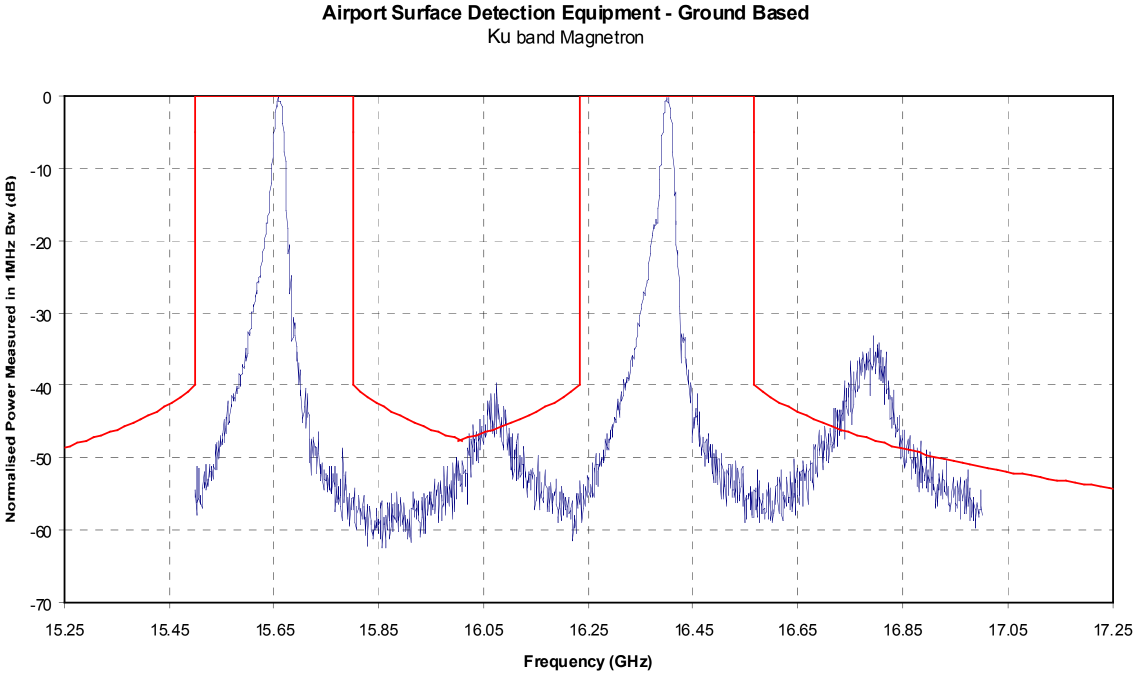


Figure 3.1.3-19 shows the result of the OOB measurement of the ASDE with a resolution bandwidth (RBw) of 1MHz. The OOB mask has been placed at the top of the fundamental emission as the spectrum within the OOB region is a direct result of the modulation. Therefore the relative shape of the pattern is independent of RBw and is not subject to the corrections for pulse desensitisation.

The hump to the right of the fundamental emission clearly exceeds the mask by over 10dB.

Figure 3.1.3-19 OOB plot of the ASDE Ku-Band radar
(Freq=15650MHz, Pw=43ns, Tr=15ns, Freq=16400MHz, Pw=31ns, Tr=17ns, PRR=8000Hz)



3.1.3.5.7 Meteorological - C-Band Co-axial Magnetron

The meteorological radar was measured on site at a Met Office research establishment. As the radar was not part of the UK weather radar network, the Met Office allowed the measurement team to have control over the positioning and transmission times of the radar. The radar was measured at a range of approximately 140m which was very close. The radar unfortunately had a lower elevation hard limit of 0° and therefore it was not possible to have the radar boresighted on the receive site. The resulting look up angle of the receive antenna meant that the fundamental emission was measured some way down the main beam and that it was very likely that the harmonics were measured in the sidelobe regions.

The meteorological radar is a single frequency, high power fixed installation and therefore falls into Category B which has a strict UE mask.

The relevant radar characteristics for the calculation of the UE masks are presented below in Table 3.1.3-8.

Table 3.1.3-8 Characteristics of the Meteorological Radar

Parameter	
Frequency (MHz)	5630
Peak Power (kW)	250
Pulse Width (µs)	2.03
Rise Time (ns)	60

The meteorological radar was manually surveyed with a resulting optimum resolution bandwidth (RBw) for the measurement of peak power being 511kHz. The RBw used for the pulse spectrum shape was 100kHz.

Figure 3.1.3-20 below shows the plot of the SE measurement run with the Category B mask applied. It is clear on the plot that the met radar occupies more bandwidth in the –70 to –100 dB relative to peak power region than the regulations allow.

Although it was very likely that the harmonics were not completely characterised to find the peak, the second harmonic still exceeds the mask by over 20dB .

Figure 3.1.3-20 The SE measurement of the meteorological radar
(Freq=5630MHz, Pw=2.03µs, Tr=60ns, PRR=300Hz)

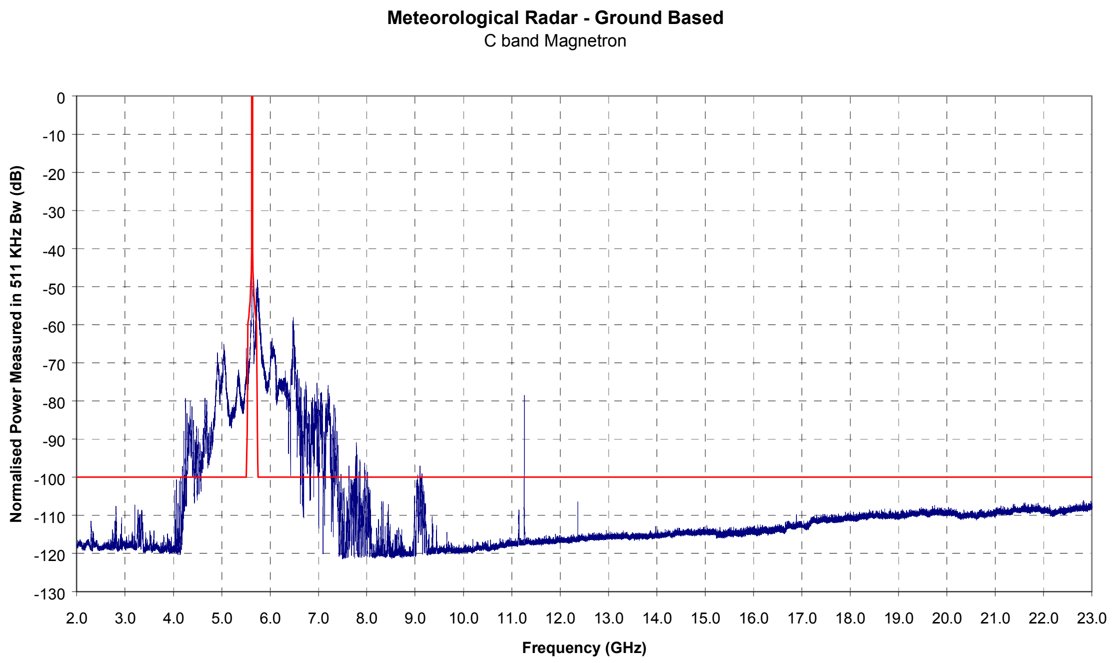


Figure 3.1.3-21 shows a zoomed-in plot of the OOB region and just into the SE region taken from the SE measurement run. The plot clearly shows the hump to the right of the fundamental emission that is a characteristic of the co-axial magnetron used. The hump exceeds the mask in the 60dB per decade region by 30 to 40dB.

Figure 3.1.3-21 A zoomed in plot of the SE measurement of the meteorological radar highlighting the fundamental and the OOB region
(Freq=5630MHz, Pw=2.03µs, Tr=60ns, PRR=300Hz)

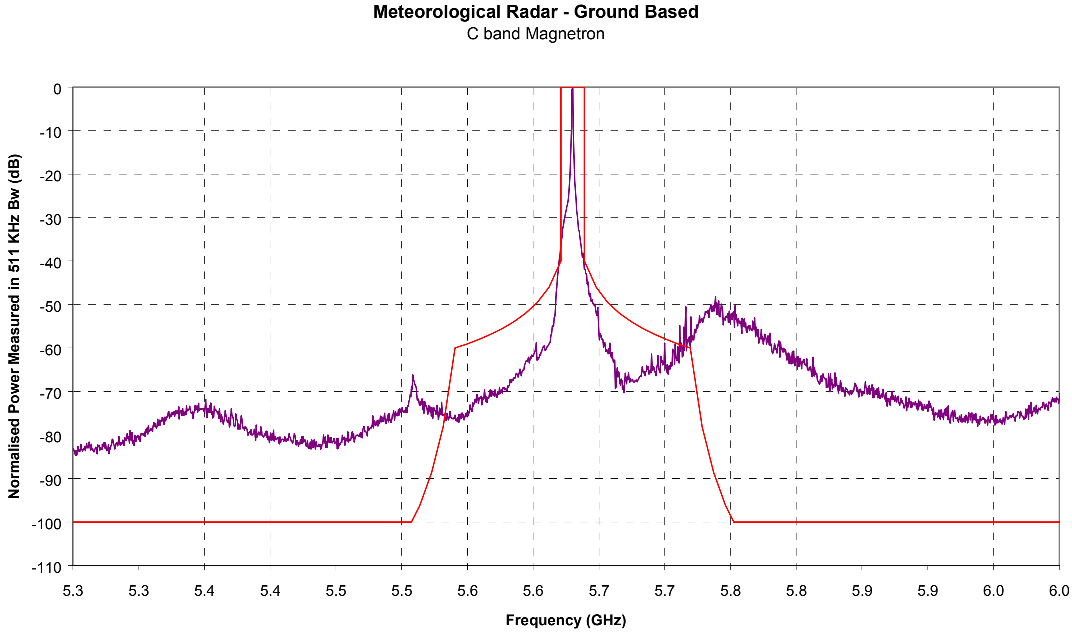
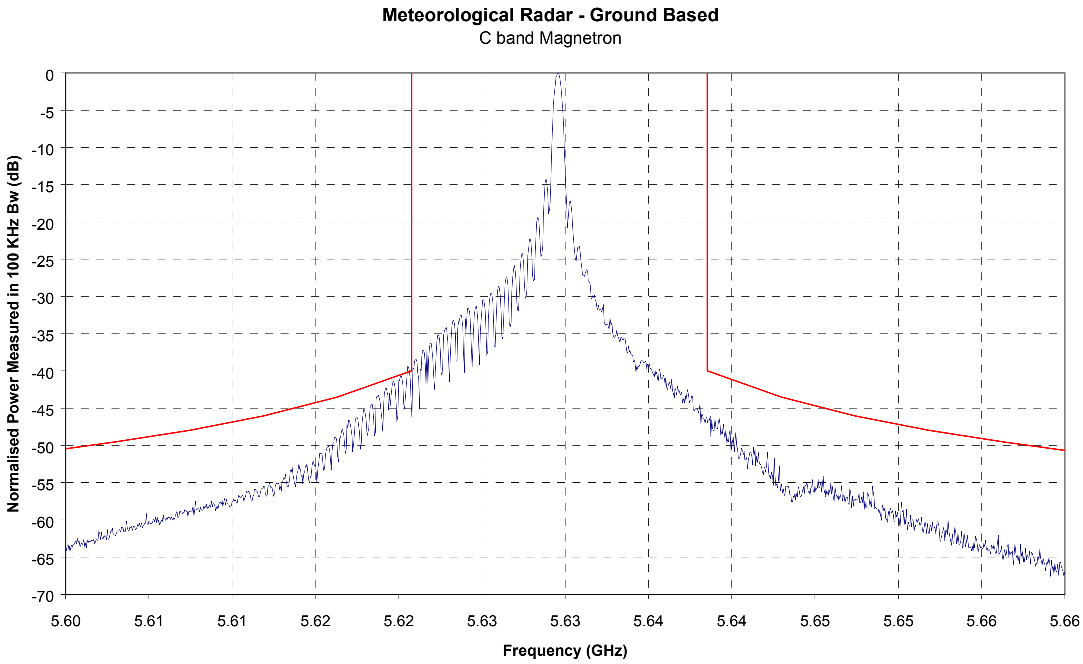


Figure 3.1.3-22 shows the high resolution measurement within the OOB region. The spectra close to the fundamental emission satisfy the mask. The 'porch' effect to the left of the fundamental is well demonstrated in this plot although it is more obvious in conventional magnetron radars.

Figure 3.1.3-22 The OOB measurement of the meteorological radar close to the fundamental
(Freq=5630MHz, Pw=2.03µs, Tr=60ns, PRR=300Hz)



3.1.3.6 Summary of measurement method adopted

3.1.3.6.1 Measurement Methods

The measurement methods employed in the campaign were based on the direct method as presented in the draft of ITU-R Recommendation M.1177-2 (document 8B/Temp/72-2) dated 30th October 2001. The implementation of the method was tailored to suit the specific spectrum analyser and the associated test equipment.

3.1.3.6.2 Measurement Settings

The method of performing a number of survey measurements with different receiver bandwidths to optimise the settings for both the SE and OOB runs proved to be an efficient use of measurement time. The full measurements were then performed at the widest bandwidth and hence with the biggest step size with no degradation in the quality of the data measured.

To assist with the data analysis after the measurements it would have been beneficial to have measured certain portions of the frequency bands with different bandwidths for the assessment of the SE. In particular the measurement of the fundamental and harmonic emissions. Unfortunately it was not possible to perform many measurements with different bandwidths due to the measurement times running into many hours.

The quality of the measurements was improved when using a measurement step size equal to half of the resolution bandwidth and was considered an acceptable trade off against measurement time in most cases.

3.1.3.6.3 Environment

The quality of the Electro Magnetic (EM) environment at the measurement site is very important if a quick, accurate and complete assessment of a radar installation is to be made. The EM environment encountered at the installed sites was extremely cluttered, and in some areas of the frequency band, totally unusable. When measuring a radar it is normal to use a high gain narrow beam receive antenna to provide very good discrimination against unwanted signals. However, at the airfield sites the unwanted signals were of such numbers that this was impossible. The main signals interfering with the measurements were identified at the sites were aircraft navigation aids, altimeters, weather radars and mobile phone up and downlinks. Many of the interfering fundamental signals also had interfering harmonic signals. The remote site used for the meteorological radar and the fixed range at Funtington did not suffer from interfering signals.

3.1.3.6.4 Range Geometry

The perfect measurement geometry is always extremely difficult to achieve without the use of a dedicated measurement range with positioner systems for the radar under test. When measuring an installed radar, the proposed measurement sites require surveying before the deployment of the test equipment. In the UK in particular, the choice of receive sites is often very limited, except at remote radar installations. In fact, for the measurement of the ATC and ASDE radars within this measurement campaign, the choice of available and suitable sites was limited to the choice of two, both with approximately the same geometry. In the case of the meteorological radar the site was limited by the available range. Therefore the majority of the measurements were made with the receive antenna looking up at the radar under test due to a lack of range and a lack of height of the receive antenna.

In practical terms it is better to configure the measurement geometry to best characterise the emissions that will most likely cause an interference problem. This will, in the case of installed radars, need to be performed on a case by case basis. As an example, the marine navigation radars are only measured in the azimuth or horizontal plane because in the marine environment this is the plane that interference is most likely to occur, ship to ship or ship to shore.

3.1.3.6.5 Repeatability and Measurement Uncertainty

The majority of repeat measurements made in the campaign with the same settings yielded a repeatability of ±1.5dB. A repeat measurement of the marine navigation radar 5 days later than the first measurement with the radar antenna realigned and then fixed resulted in a repeatability of ±2.0dB. The additional difference is believed to have been the error in azimuth alignment of the radar antenna. The majority of radar measurements are made with the radar rotating and therefore would not suffer the same problem.

The total worst case measurement uncertainty for absolute power measurement at any frequency was ±5.18dB with the major contributions arising from the receiver errors. The worst case uncertainty reduces to ±4.73dB for relative power measurements across the entire frequency band.

3.1.3.7 Additional measurements from the Radar Measurement Campaign.

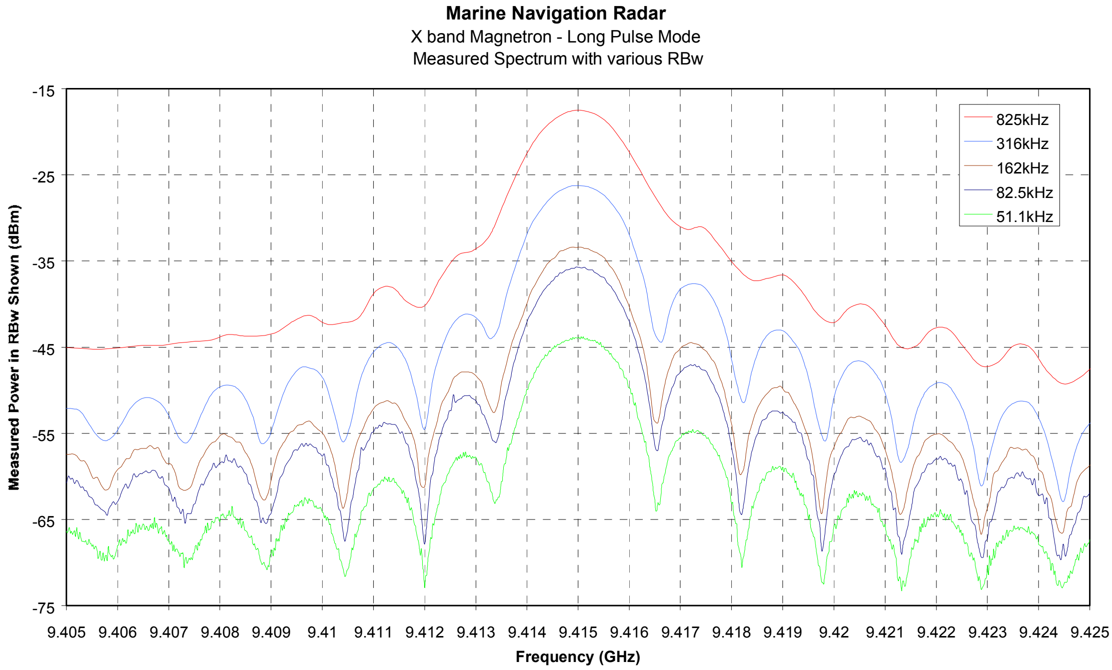
The following are measurements obtained during the measurement programme undertaken by QinetiQ which are not shown elsewhere in the section 3.1.3 discussion.

3.1.3.7.1 X-Band Marine Navigation Radar.

The characteristics of the Marine Navigation Radar measured are shown in Table 3.1.3-2.

Figure 3.1.3-23 The marine navigation radar spectrum measured with different receiver bandwidths

(Freq=9415MHz, Pw=640ns, Tr=14ns, PRR=375Hz)
(825kHz $\approx 0.528/\tau$, 316kHz $\approx 0.202/\tau$, 162kHz $\approx 0.104/\tau$, 82.5kHz $\approx 0.053/\tau$, 51.1kHz $\approx 0.033/\tau$)



3.1.3.7.2 S-Band Solid State ATC Radar

The characteristics of the S-Band Solid State ATC radar are shown in Table 3.1.3-4.

Figure 3.1.3-24 Plot of the spectrum from the S-Band Solid State ATC radar in the OOB region measured in a 1MHz receiver bandwidth.

(Freq=2784.5 & 2809.5MHz, Pw=100µs, Tr=169ns, Chirp=1MHz and Freq=2785.5 & 2810.5MHz, Pw=1µs, Tr=169ns, Chirp=1MHz, PRR=825Hz)

Figure 3.1.3-25 Plots of the upper frequency pair of the S-Band Solid State ATC radar measured with different receiver bandwidths

(Freq=2809.5MHz, Pw=100µs, Tr=169ns, Chirp=1MHz and Freq=2810.5MHz, Pw=1µs, Tr=169ns, Chirp=1MHz, PRR=825Hz)

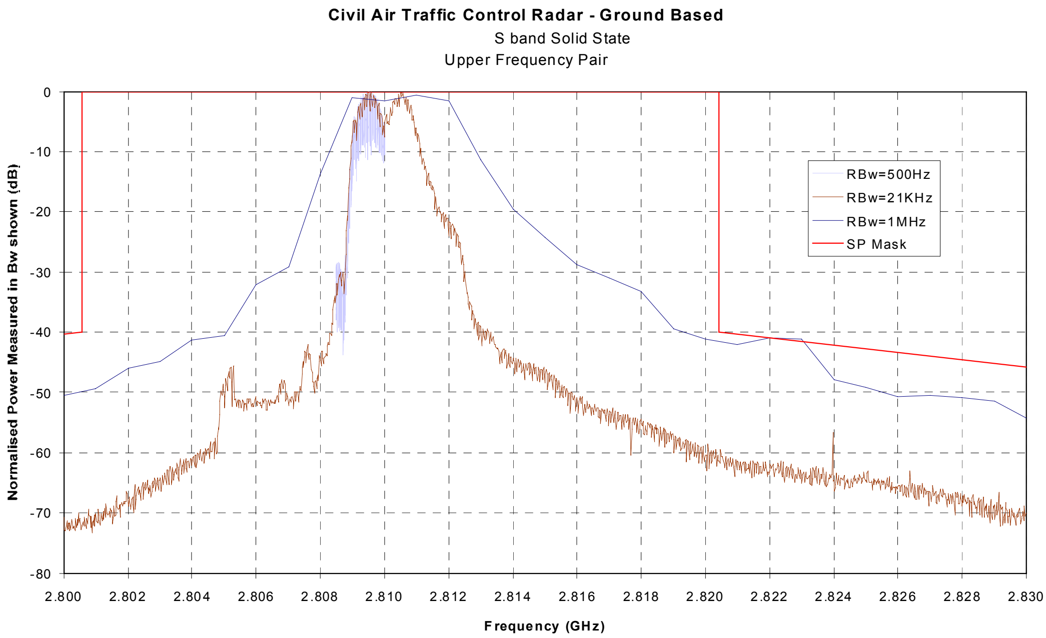


Figure 3.1.3-26 Plots of the lower frequency pair of the S-Band Solid State ATC radar measured with different receiver bandwidths

(Freq=2784.5MHz, Pw=100µs, Tr=169ns, Chirp=1MHz and Freq=2785.5MHz, Pw=1µs, Tr=169ns, Chirp=1MHz, PRR=825Hz)

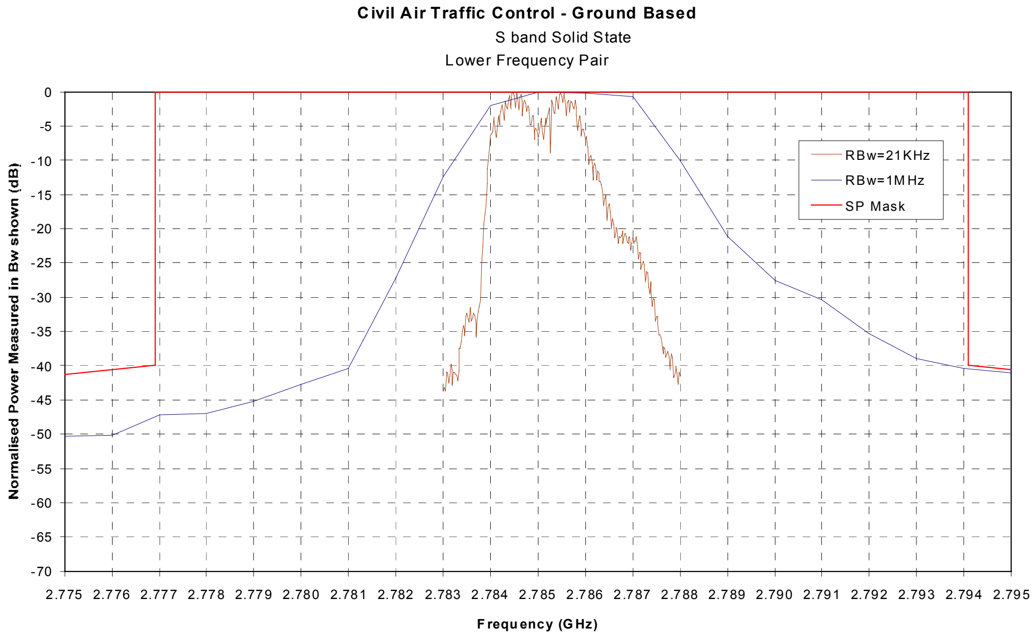
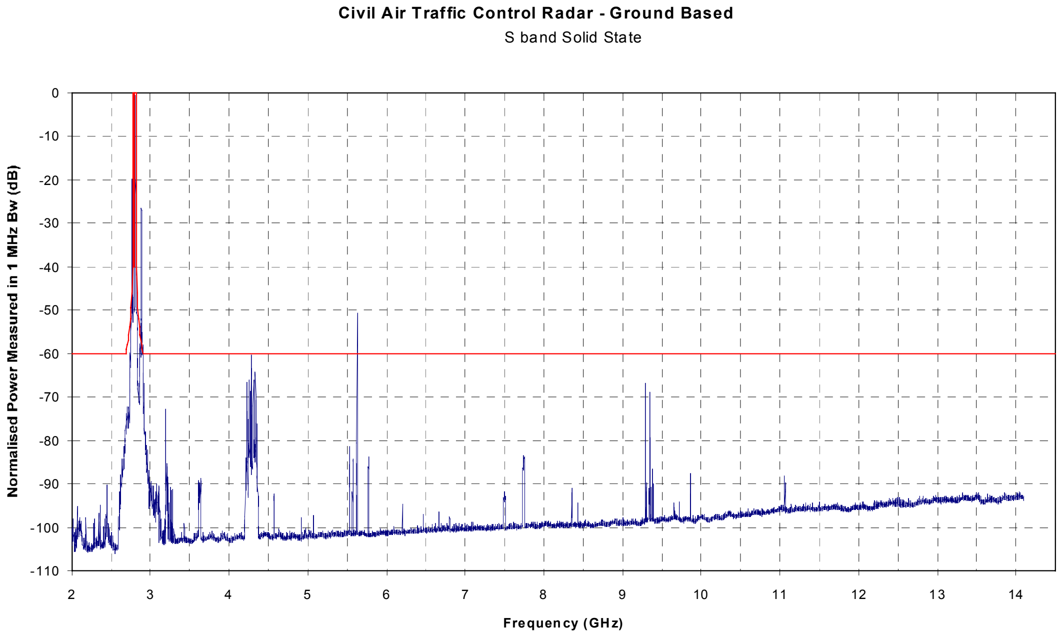


Figure 3.1.3-27 SE plot of the S-Band Solid State ATC radar up to and including the 5th harmonic

(Freq=2784.5 & 2809.5MHz, Pw=100µs, Tr=169ns, Chirp=1MHz and Freq=2785.5 & 2810.5MHz, Pw=1µs, Tr=169ns, Chirp=1MHz, PRR=825Hz)



3.1.3.7.3 S-Band TWT ATC Radar

The characteristics of the S-Band TWT ATC Radar measured are shown in Table 3.1.3-5.

Figure 3.1.3-28 Plot of the OOB region of the S-Band TWT ATC radar spectrum with a composite mask applied

(Freq=2765 & 2885MHz, Pw=19.3μs, Tr=18ns, Chirp=2.5MHz and Freq=2765 & 2885MHz, Pw=0.33μs, Tr=18ns, PRR=1100Hz with stagger)

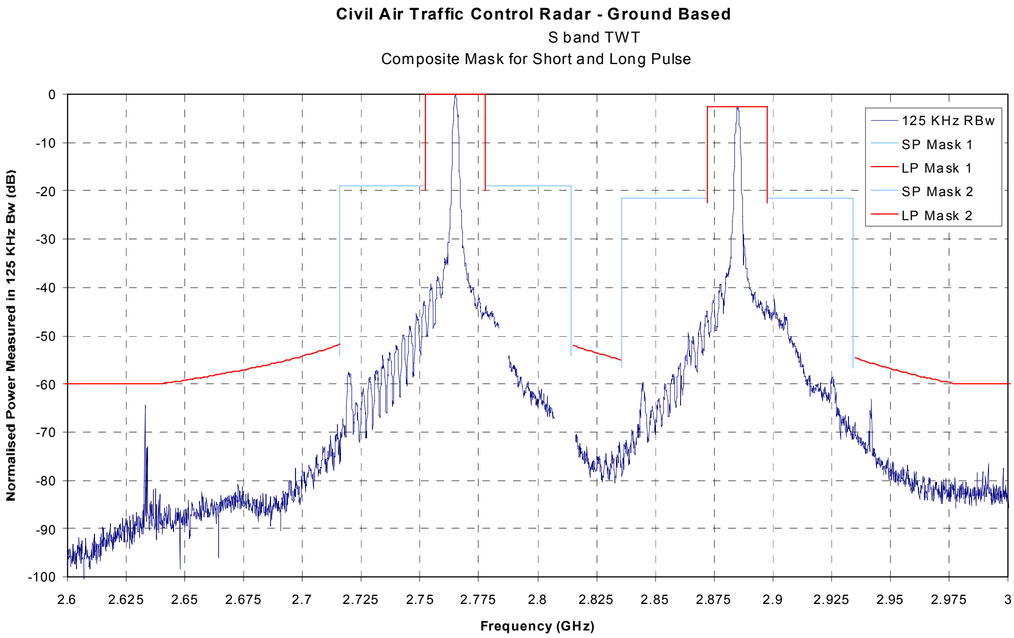


Figure 3.1.3-29 Plots of the S-Band TWT ATC radar lower frequency measured with two receiver bandwidths
(Freq=2765MHz, Pw=19.3μs, Tr=18ns, Chirp=2.5MHz and Freq=2765MHz, Pw=0.33μs, Tr=18ns, PRR=1100Hz with stagger)

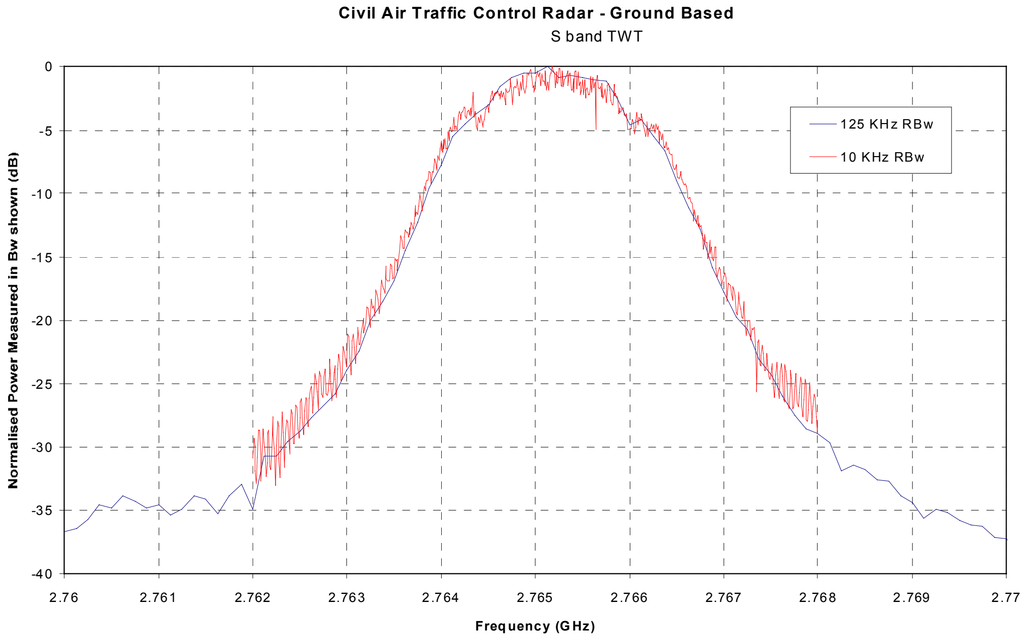


Figure 3.1.3-30 Plots of the S-Band TWT ATC radar upper frequency measured in two receiver bandwidths
(Freq=2885MHz, Pw=19.3μs, Tr=18ns, Chirp=2.5MHz and Freq=2885MHz, Pw=0.33μs, Tr=18ns, PRR=1100Hz with stagger)

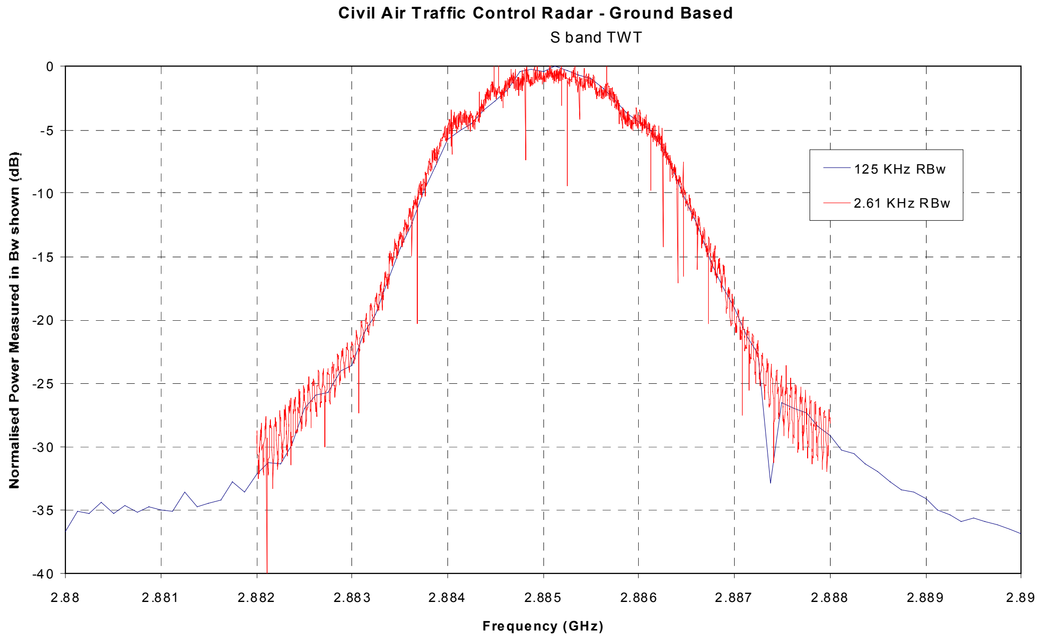
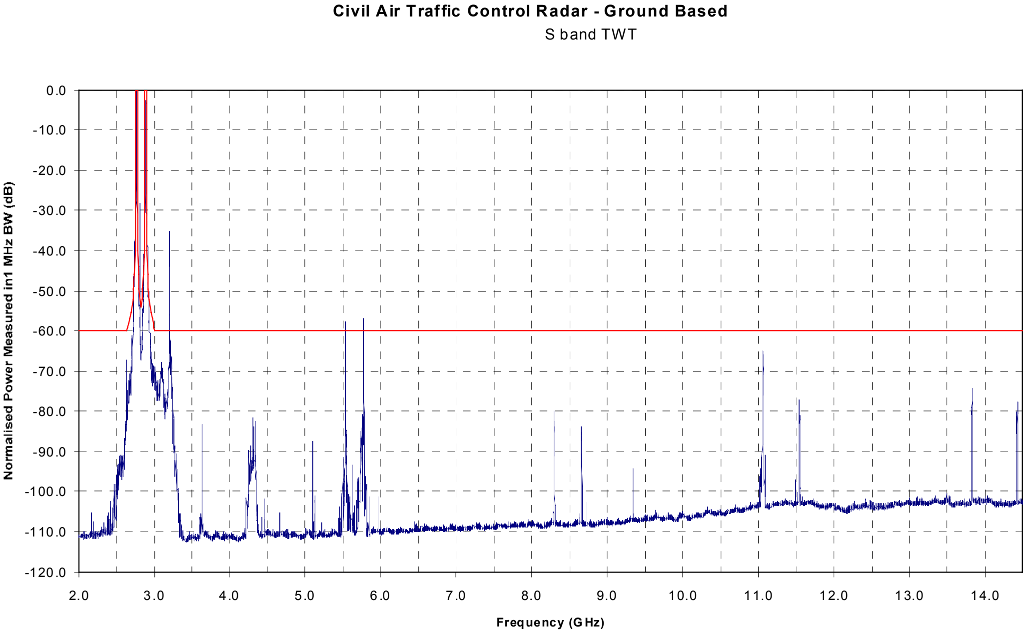


Figure 3.1.3-31 SE plot of the S-Band TWT ATC radar up to and including the 5th harmonic
(Freq=2765 & 2885MHz, Pw=19.3µs, Tr=18ns, Chirp=2.5MHz and Freq=2765 & 2885MHz, Pw=0.33µs, Tr=18ns, PRR=1100Hz with stagger)



3.1.3.7.4 L-Band Primary ATC Radar

The characteristics of the L-Band TWT ATC Radar measured are shown in Table 3.1.3-5. For clarity, the overlapping parts of the short and long pulse masks have not been shown.

Figure 3.1.3-32 Plot of the OOB region of the L-Band primary radar spectrum with a composite mask applied

(Freq=1269.77 & 1332.77MHz, Pw=33µs, Tr=30ns, Chirp=1MHz and Freq=1254.23 & 1317.23MHz, Pw=1µs, Tr=30ns)

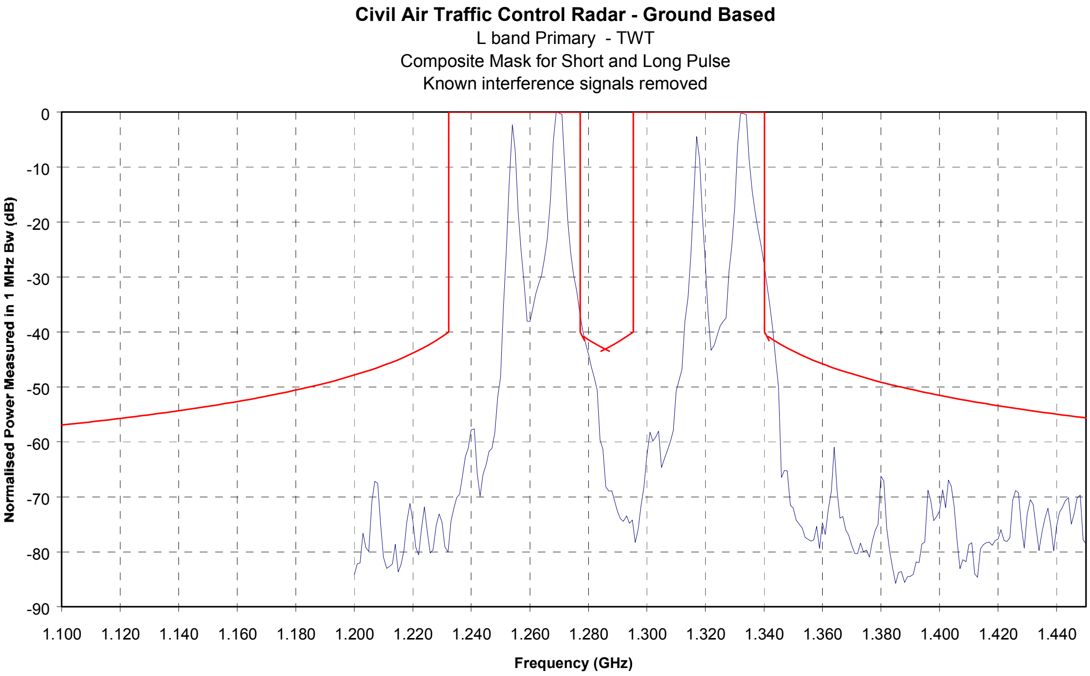


Figure 3.1.3-33 Plot of the short pulse spectrum of the lower frequency pair of the L-Band primary radar
(Freq=1269.77 & 1332.77MHz, Pw=33µs, Tr=30ns, Chirp=1MHz and Freq=1254.23 & 1317.23MHz, Pw=1µs, Tr=30ns)

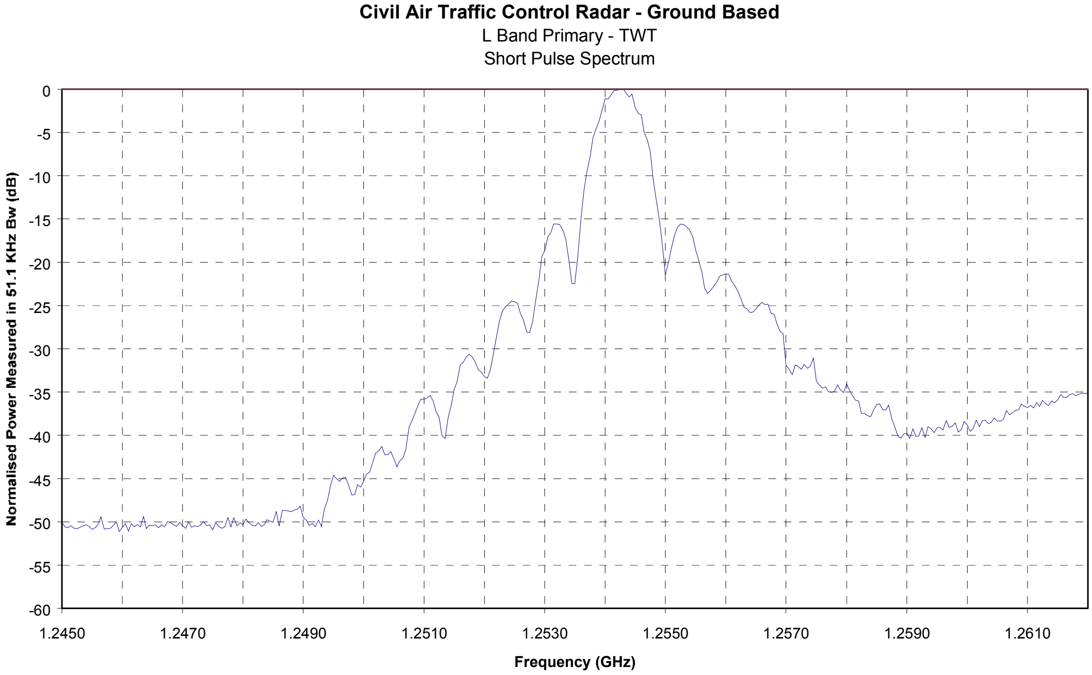
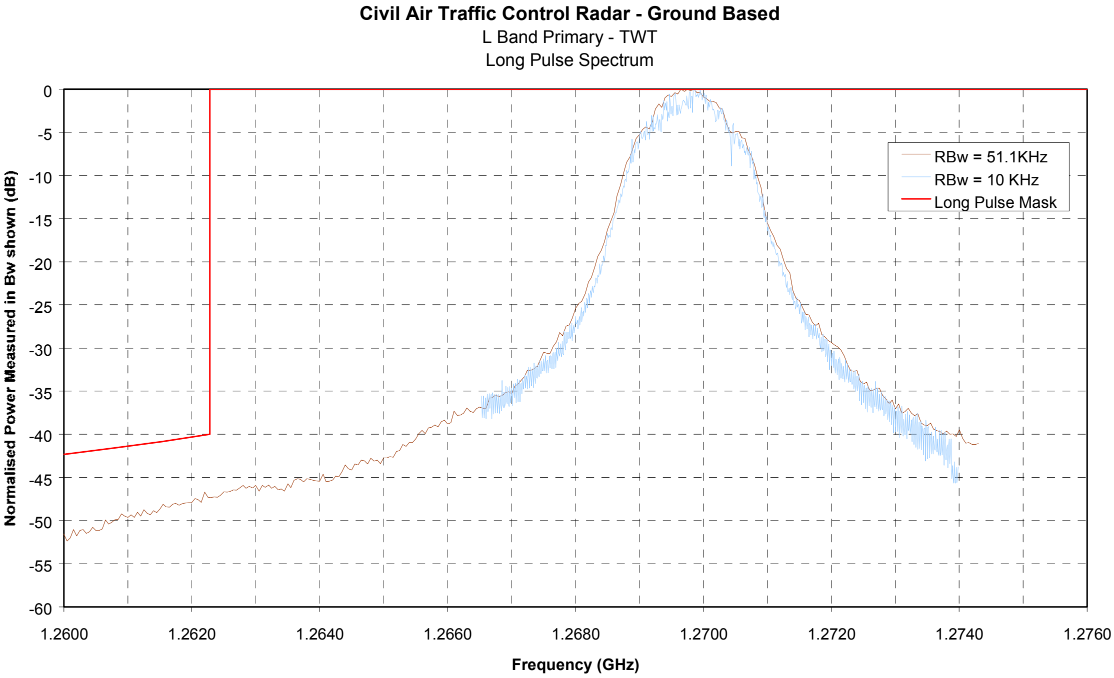


Figure 3.1.3-34 Plots of the long pulse spectrum of the lower frequency pair of the L-Band primary measured in two receiver bandwidths
(Freq=1269.77 & 1332.77MHz, Pw=33µs, Tr=30ns, Chirp=1MHz and Freq=1254.23 & 1317.23MHz, Pw=1µs, Tr=30ns)



3.1.3.7.5 ASDE Ku-Band Radar

The characteristics of the ASDE Ku-Band Radar measured are shown in Table 3.1.3-7.

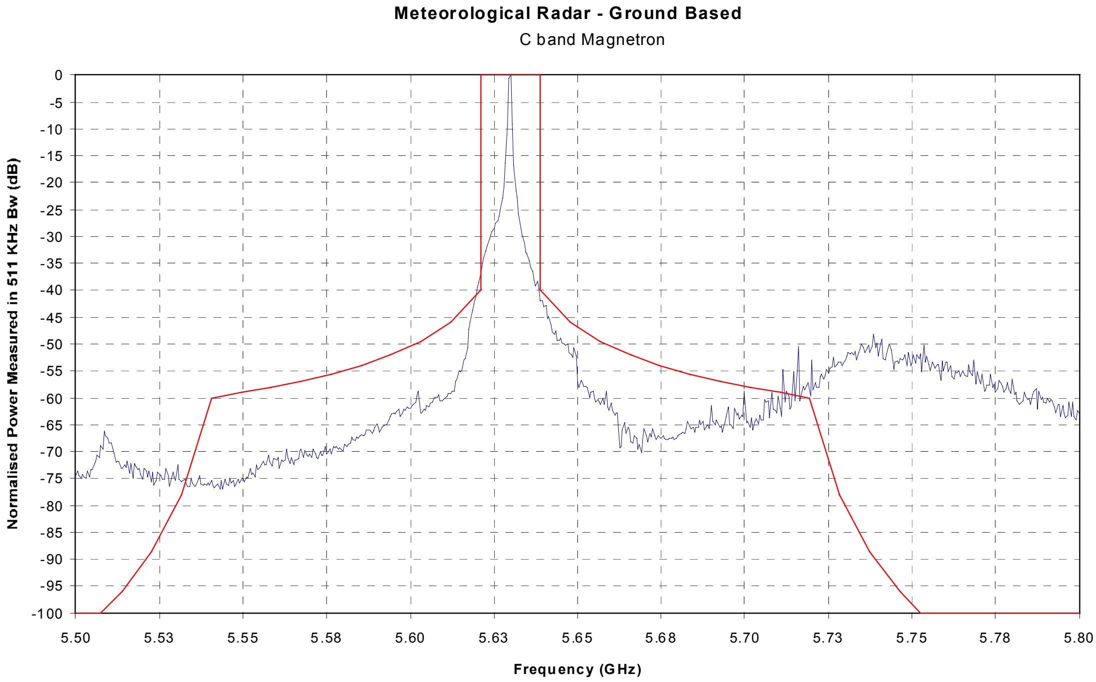
All the measurements are included elsewhere in section 3.1.3.

3.1.3.7.6 C-Band Meteorological Radar

The characteristics of the C-Band Meteorological Radar measured are shown in Table 3.1.3-7.

Figure 3.1.3-35 Plot of the OOB region of the C-Band weather radar measured in 511kHz bandwidth

(Freq=5630MHz, Pw=2.03μs, Tr=60ns, PRR=300Hz)



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Section 3.1.4

Summary of the Work Package outputs

Section 3.1 of this report has identified and studied the numbers, types and roles of the various types of radars in the UK that are in civil use.

Under section 3.1.1, the main roles of civil radar within the UK are identified and typical data presented. Using information available in the public domain, this section also identifies various military and experimental uses of radar within the UK. The use of radar by Band is examined and presented in both tabulated and geographic distribution form

Section 3.1.2 addresses the issue of wanted transmission characteristics of typical radar fulfilling the different roles within the different frequency bands. Measured spectra are included (where available), as are the calculated and (where available) measured emission masks.

Section 3.1.3 contains the background to, and the results of the radar measurement programme carried out by QinetiQ under this study. The measurement programme involved the measurement of the emissions from a number of installed and operational radars as well as one radar tested at the QinetiQ test range at Funtington. The results of the programme provided useful information regarding the actual emissions of different radar types and the practical problems/advantages of measuring a radar in its operational environment.

The uses identified in 3.1.1 have remained reasonably constant since the beginnings of the civil uses of radar in the 1950's; in fact some of the actual radars types identified in this study date from designs of that vintage. Radars, particularly the large types, tend to have a long service life, a fact that must be remembered when any changes to requirements are being considered. The current uses of civil radar (with the possible exception of police speed radars, GPR and the possible future use of radars for motor vehicle collision avoidance and intelligent cruise control), have changed little over the years. The performance, display and interface requirements may have been improved but the basic tasks being performed have not. Over the years, the major changes in technology have been in the areas of small signal electronics, digital signal processing and displays. In the area of high power transmitter design, it has only been over the past 10 years that the availability of solid state devices has led to the beginnings of significant changes in civil radar transmitter design.

In some areas, particularly ATC and VTS, the different equipments used are very similar and it is hard to distinguish any significant technical differences. It is the case that, with a few exceptions, the military are also users of the majority of radar types used for civil purposes. The military also has radars that have no civilian application and whose roles would only be fully used in wartime. It is worth noting that in the past many civil radars were often derived from military procurement programmes while in recent years the situation has become reversed with the military buying radars based on civil 'Commercial Off The Shelf' (COTS) products.

Table (3.1.1-25) lists the civil radars operating in the UK, and gives an estimate of the total number of radars involved. The largest numbers within a single band, are the X-Band marine, airborne weather and altimeters. Between these classes, the largest number are the small radars used by pleasure and fishing vessels. In terms of use of the spectrum these types of radar do not control their emissions particularly well with their magnetron transmitters being prone to producing wide band energy, particularly as the magnetrons get older. However, these radars do seem to operate together in a acceptable fashion using only a small number of the frequencies within the band. The small number of frequencies is a consequence of the availability of magnetrons and the manufacturers' need to limit the number of variants of the magnetrons for economic reasons. A point to note is that a large number of these radars are in the hands of users with no recourse to regular servicing. Magnetrons in particular, as they reach the end of their life, can produce a greater amount of unwanted emissions and these emissions are unlikely to be noticed by the user.

The types of civil radars and the roles they perform are wide and various, ranging from very large radars operating over ranges of 300 km to those designed to operate over a matter of metres. As a consequence, the range of peak power used is also large and ranges from watts to Megawatts. The bandwidths used vary enormously and to some extent are related to the role being carried out by the radar, however there is a wide variability of bandwidths within radars essentially carrying out the same role. This to some extent is historical, in that up until recently the requirements to achieve high resolution was inevitably associated with very high peak power short pulses, and the technology available to generate such pulses was not amenable to spectrum control. With the development of solid state technologies this is changing. The use of solid state by its nature does lead naturally to a more controlled spectrum. Thus between the old and the new systems there is a wide variation in the use of bandwidth. The same is true for frequency stability; modern synthesised sources used with driven transmitters naturally generate very stable signals with virtually no drift. In fact the signal processing requirements of the radar itself demand stabilities far in excess of anything required from a regulatory or interference control view point

When comparing the bandwidths used, it is important that comparisons are made on a like for like basis and that all the parameters of the radars are considered. Some radars were originally designed for a slightly different role which drove the original design in a particular way and these features may no longer be important or apparent in the current role of the radar but must be considered when comparisons are being made.

The work covered by Section 3.1 has shown that there is a wide variation in the necessary bandwidth (NB) or the occupied spectrum and that, to some extent, this is a historical phenomenon. This was compounded in the past by the fact that radars operated in dedicated frequency bands [1] and that radar to radar interference was not seen as a major issue. Thus historically reducing the occupied bandwidth was not seen as a major design driver and other technical drivers indirectly set the occupied bandwidth. The simple fact that the issue is now highlighted as one of the design drivers itself, will give benefits as it starts to become a consideration to the radar designer.

This section is not intended to present mitigation options, but as can be seen from the wide variety of radars presented, and the differing performance achieved, there must be some initial scope for mitigation in terms of unwanted emissions, just from the adoption of some of the best practice seen to date.

[1] Aviation Surveillance Systems IEE Colloquium 23rd Jan 2002 Paper 11

Section 3.2

Mitigation Options which could be considered in the design and implementation of radar systems to reduce unwanted emissions and/or occupied bandwidth.

Contents:

Figures:

Tables:

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3.2 Mitigation Options which could be considered in the design and implementation of radar systems to reduce unwanted emissions and/or occupied bandwidth.

3.2.1 Introduction

This chapter describes in outline the principles of radar design and the requirements for the transmitted pulse shapes and the associated spectrum of these pulses.

Both high power tube and solid-state types of transmitters are described, and also the methods that may be considered to control the spectrum of the transmitted pulses.

The use of radar is key to air-traffic safety, maritime safety and in times of international tension, the maintenance of national security, or the security of deployed forces. Increasingly, radar is also finding a policing role in the maintenance of economic integrity, or in the detection of the activities of organised crime. Pulse radars operate in several roles, air and sea surveillance or search, ground surveillance, tracking and aircraft precision approach. Radars are operated by the military and civil authorities and can be fixed or mobile.

Radar systems may operate in frequency bands allocated for radio-determination, specifically those for radio-navigation and radiolocation. In principle there is no basic difference between these two, only the different roles for which the radars are used. The different roles will result in a particular optimisation of the basic radar parameters.

Because each radar has a different role to fulfil, and is self sufficient, (that is, in general it only has to work with its own receiver), there is no, and there cannot be, any specific modulation defined and agreed nationally or internationally for use within the radar bands. This is in contrast to broadcast and communication transmitters or other NAVAIDS that have to operate with other equipment conforming to the same standard. An exception to this is the case of bistatic radars where the transmitter and receiver are not co-located, but are at either end of a baseline; there are at present no operational bistatic radars in the UK. The major use for bistatic radars is on semiactive homing missiles where the target is illuminated by a tracking radar and the receiver is mounted on the missile and homes in on the target.

There is no interoperability requirement for primary radar, unlike secondary radar that has to be able to operate with all transponder equipped aircraft, (it could even be argued that interoperability is a distinct disadvantage). This results in each radar having its individual peak power, pulse length, Pulse Repetition Rate (PRR), chirp or phase coding individually selected for its own mission. In some cases, international requirements do exist, but these generally concentrate on operational requirements and not the detailed design issues. Even in these cases there still remains a wide scope for radar designers to produce different modulation solutions. Primary radars are not designed and manufactured to a specific "formula". This means that there are no National or International standards for "signals in space".

Currently there are radars operating with pulse lengths ranging from approximately 40ns up to hundreds of μs, with peak powers from Watts to Megawatts, and mean powers from less than a Watt to hundreds of kilowatts. Frequency modulation ranges from none to hundreds of Megahertz (some effective pulse bandwidths at X-Band are greater than 1 GHz) and phase or bi-phase coding is also used. In addition to the various bandwidths, there are radars operating from fixed frequency to agile bandwidths exceeding 20%.

Because of the diversity of roles performed by different radars and the wide range of modulation techniques used, radar systems have not in general operated in a pre-described bandwidths or channels. A new land based radar is assigned an operating frequency or frequencies, based on the number of frequencies and bandwidths it uses, and the frequencies used by radars operating in the same area. For example medium and long range surveillance radars operate at approximately 1.3 GHz or 3 GHz, medium range approximately 3 or 5 GHz, short range or tracking radars operate approximately 9 and 10 GHz or approximately 14 GHz or above. Within the bands frequencies are generally assigned on a site by site basis in line with good engineering practice and the EM environment that exists at the time of installation, or in the case of mobile or transportable systems, the type of use or deployment.

Because of the nature of radar and the specific design and protection techniques applied to radar receivers, historically significant interference between radars was, and still is, rare. Where interference does occur, it generally does not result in any significant service reduction or equipment damage. In the very few cases that the radar service is significantly degraded, the problem is solved by mutual co-operation. These last cases generally relate to poor frequency planning.

However changes in the roles fulfilled by radar, particularly the requirement for more imaging capability require radars to use wider and wider bandwidths and/or more operating frequencies. The initial indications are that reduction of radar to radar interference may require more attention than has been previously given.

3.2.2 Radar design principles

The design of a radar is a complex procedure, but in broad outline the radar must meet the customer's requirements and satisfy the applicable regulatory requirements. This section outlines the decision process governing the initial design concepts of a radar system.

A customer's requirements can usually be summarised as a requirement to detect a target of a specific size at a specified range with a defined Probability of Detection (Pd) and a defined Probability of False Alarm (Pfa). These parameters are then used to scope the radar parameters and to determine the basic radar performance and detection range.

3.2.2.1 Radar Purpose

A radar is a measuring instrument used to measure properties associated with a reflecting object, at a position distant from the radar. In the simplest of systems the property measured may only be the target's existence and range. It is, however, possible to measure bearing, height, velocity, target size and shape and in the limit form an image of the target, depending on the complexity of the radar being used. The radar may also have to report target parameters in the presence of unwanted signals from other systems. Military radars may be specifically optimised for this purpose with some assumed, or known, jamming threat.

Primary radar is probably unique in pulse systems in that the information carried by the reflected signal is carried within the physical attributes of the RF pulse. These attributes are modulated on the pulse by the properties of the target e.g. its range, reflectivity, doppler modulation, size etc. Unlike other pulse modulation systems used for communications, it is not possible to reconstruct a distorted pulse and still retain information. Radar pulses are not encoded with any error correcting modulation or with data that can be recognised even when corrupted. A radar receiver and signal processor is designed to detect a reflected pulse that matches the transmitted pulse including any doppler modulation caused by the movement of the target or its components such as helicopter rotor blades.

In pulse compression systems modulation is applied to the pulse to aid the target detection process (section 3.2.2.9). This modulation is removed in the receiver and in itself carries no information. If the target information is not to be corrupted it is essential, however, that no distortion is added to the pulse following its generation and prior to its demodulation other than that produced by the target.

In order to detect a target it is necessary to deliver enough energy on to the target such that the echo can be received with a sufficient signal to noise ratio so as to produce an adequate probability of detection with a tolerable false alarm rate within a specific time. This detection has to be carried out in the presence of significant amounts of self-interference or clutter. Clutter returns come from ground, sea, rain, birds and man made objects like cars and ships. The returned energy from clutter can often be tens of dB stronger than the energy from the wanted target.

Most radars are also required to scan a given volume, or track a given number of targets, in a specific time (or scan). This imposes a limit on the time allowed for the detection of each target and hence defines the signal to noise requirements.

3.2.2.2 Detection Range

The detection range of a radar is a function of the 4th root of the product of the average RF power, P, the antenna size, A, and the dwell time, T, (the time to scan a beamwidth):

$$R^4 \propto P \times A \times T \qquad \text{Equation 3.2.2-1}$$

Another radar parameter that affects the detection range is the receiver sensitivity. This has a limit set by the thermal noise and radars generally work close to this limit. Therefore to increase the detection range of a radar for a given target size, the transmitted power, and/or the antenna size and dwell time, must be increased. Radars are required to have very high power transmitters with very low noise receivers, if detection at the required ranges is to be achieved. Peak powers in the region of MWs or hundreds of kW are common for long range surveillance radars.

Targets with Radar Cross Section (RCS), σ, vary from wanted targets as small as 0.001 m^2 up to unwanted targets (clutter) of 100 km^2. The problem of detection in clutter is made worse by the fact that two dimensional distributed targets such as land clutter tend to produce received signals that fall off as $1/R^3$ and volumetric clutter such as weather falls off as $1/R^2$, whilst the wanted aircraft target falls off at $1/R^4$.

3.2.2.3 Antenna Size and Transmitter Power

Increasing the antenna aperture size will increase the weight, size and overturning moment of the antenna; thus requiring a larger and more powerful turning gear and a stronger tower and/or the provision of a radome. This will increase the cost of these items significantly.

A larger antenna has an increased gain, but this is matched by a narrower beamwidth. To maintain the same number of hits per beamwidth (which may be required by the clutter filter) will therefore require a reduction in the antenna rotation rate. A reduction in the rotation rate, either to compensate for the increase in aperture, or to increase the range by increasing the dwell time, will have detrimental effects on the quality of the track data generated by the radar as the elapsed time between the track updates will increase, in turn increasing the track errors. The track update rate is usually specified, and this sets the antenna dwell time on a target and the rotation rate.

If a small antenna is considered, it will have a wider beamwidth reducing the angular accuracy and making it difficult to resolve two adjacent targets at the same range. It will also have less gain, giving a reduced detection range.

In summary, if the scan time is set, the radar range is a function of the power aperture product. Radar design therefore requires an optimisation of the cost and complexity between the extremes of a powerful expensive transmitter with a small cheap antenna, and a small cheap transmitter with a large expensive antenna.

Keeping the scan time and antenna size constant, a transmitter with a higher power output must be used to increase the detection range of a radar. Due to the R^4 relationship, in order to increase the detection range by 20% would require a doubling of the transmitter power. This would have a significant effect on the design and cost of the radar, implying that a radar transmitter must operate as efficiently as possible to minimise the size and cost of the transmitter.

Tube transmitters using magnetrons were used in the vast majority of radars for many years and many of these types of radars are still in production and operation throughout the world.

The limitations associated with these types of tube, i.e. lack of frequency stability and inherent fixed frequency operation, led to the concept of the use of the driven tube with coherent receivers. Whereas a magnetron is an oscillator that self starts when a high voltage pulse is applied, a driven tube transmitter is one where the final output device is a high power amplifier tube driven from a coherent oscillator to which the receiver is phase locked. The use of a coherent oscillator gives the ability to tune the radar within the pass band of the high power amplifier. Systems which operate with driven transmitters and high peak power short pulses (typically 1 MW at 1 µs) are generally based on Klystron amplifiers. Transmitters using Travelling Wave Tubes (TWTs) generally have lower peak power levels and longer pulse lengths to achieve the same mean power level. A typical TWT radar with the same performance as the Klyston type above would have a peak power of 50 kW and a 20 µs pulse.

Developments in high power transistors in recent years have led to the use of solid-state transmitters using an array of transmitter modules. These are mean power limited rather than having the peak power limitation of tube transmitters. They have lower peak power and use longer pulse lengths (approximately 100 µs). These long pulses are compressed in the receiver to achieve the required range resolution. Other short pulse lengths are used for surveillance in the eclipsed range region of the long pulses.

3.2.2.4 Moving Target Extraction

The ability to make phase measurements on the reflected signal means it is possible to extract information about the target's velocity and to use this to extract the target from the stationary clutter.

Air surveillance radars are designed to suppress all the echoes from the land and sea leaving only the echoes from the airborne targets. Two processes are used for this, either a Moving Target Indicator (MTI) which is a band-stop filter centred around zero metres/second doppler velocity to remove the echoes from the land and sea, or a Moving Target Detector (MTD) which is a bank of band-pass filters covering the expected range of doppler velocities.

The Sub-Clutter Visibility (SCV) of a radar is a measure of its ability to detect moving target signals superimposed on clutter signals. A radar with 20 dB SCV can detect an aircraft target flying over clutter whose signal return is 20 dB (100 times) stronger[1].

The SCV required varies with the type of radar, but is generally in the region of 40 to 90 dB for modern radars, and 20 to 40 dB for older radars. This places a very strict requirement on the stability of the transmission. In order to achieve this, it is essential that the phase coherence of the pulses is not distorted by the amplification chain.

However, recent advances in the ability to digitally capture the transmitted pulse from a magnetron radar and use this data to "correct" the received pulses, (reducing the pulse to pulse stability requirements), prior to comparison in a moving target extraction process has also led to the possibility of achieving much improved sub-clutter visibility. It may be that these modern signal processing techniques will extend further the useful life of such systems.

3.2.2.5 Bandwidth

The ITU specify two different types of bandwidths: the "Necessary Bandwidth" (NB) and the "Occupied Bandwidth"(OB):

The ITU Radio Regulations define the NB in article S1.152 as follows:

> "Necessary Bandwidth*: For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions."*

Another way to describe the NB is the width of a perfectly rectangular filter[2] that will pass the radar signal with an acceptable level of distortion.

The ITU Radio Regulations define the OB in article S1.153 as follows:

> "Occupied Bandwidth*" The width of a frequency band such that, below the lower and above the upper frequency limits, the mean powers emitted are each equal to a specified percentage $\beta/2$ of the total mean power of a given emission.*
>
> *Unless specified in an ITU-R Recommendation for the appropriate class of emission, the value of $\beta/2$ should be taken as 0.5%*

There are two bandwidths specifically associated with radar engineering; the operating bandwidth and the signal bandwidth.

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[1] "Radar Handbook"(2nd Edition) Merrill Skolnik p.15.13.

[2] It is necessary to define the form of the filter for the statement to be meaningful. Other filter shapes distort the signal in different ways. Filters also have their bandwidths specified in differing ways. Butterworth filters are specified at the 3 dB points, Tchebyshev at the equal ripple points, Gaussian at 2σ etc.

The operating bandwidth is sometimes referred to as the agile bandwidth and is the frequency range over which the radar operates on a pulse by pulse basis. This effectively is the changing, or tuning, of the carrier frequency[3]. Due allowance must also be made to add the signal bandwidth to the operating bandwidth to obtain the full extent of the spectrum that is occupied.

The signal bandwidth is the within pulse bandwidth (i.e. the instantaneous bandwidth of the transmitted pulse) and is related to the Necessary Bandwidth (NB), the exact relationship depending on the shape and modulation of the pulse. It is a function of the resolution required from the radar.

3.2.2.6 Operating Bandwidth

Due to the statistical nature of targets, there is great advantage to be had in countering fading, if the radar can operate on more than one frequency. If these frequencies can be made far enough apart, such that the target fluctuations are statistically de-correlated, then diversity gain can be achieved. Wide band operation also helps in countering target fading which is associated with multi-path reflections (lobing) and the fading associated with variations in atmospheric effects. Military radars have additional reasons, mainly related to ECCM (Electronic, Counter, Counter, Measures) for wanting to operate over as wide a band of frequencies as possible.

When considering the operating bandwidth it is necessary to consider the difference between agile frequency operation and multiple frequency operation.

In a frequency agile (frequency hopping) system, the transmitter is capable of being operated at any frequency within its band simply by changing the drive frequency. A single transmit chain is used.

Multi-frequency operation can be achieved by using multiple narrow band transmitters each tuned to a separate frequency combined in a single antenna. In this case the narrow band nature of the amplifiers and the possibility of some post amplification filtering could produce a narrower spectrum than could be achieved from a true wide band agile system. This is however achieved at the expense of a very limited frequency selection and a large increase in complexity.

Some military radars have multiple beams produced by the use of multiple frequencies.

3.2.2.7 Signal Bandwidth

The signal bandwidth is related to the radar pulse width, which is defined by the range resolution required. In a non-compressed pulse radar it is approximately the reciprocal of the pulse length at the -3dB points of the pulse spectrum. In a pulse compression radar the signal bandwidth is related to the reciprocal of the compressed pulse width.

For the purpose of consistency with other proposals in this paper the parameter Necessary Bandwidth (NB) will also be used. For the purpose of this paper the NB is defined as the bandwidth between the -20 dB points of the pulse spectrum envelope.

Recent target detection and classification requirements have led to the requirement to operate over as wide a signal band as is possible (or allowed) in order to achieve a range resolution much less than the physical extent of the target. This is achieved either by very wide band swept waveforms, or by stepped frequency pulses, which synthesise wide swept waveforms. In these types of radar, the signal bandwidth approaches the operating bandwidth.

3.2.2.8 Time / Pulse Width Limitations

Radar signals propagate at the speed of light which equates to a two way range traverse of 150 metres per microsecond. In a monostatic radar, using a common antenna for transmit

[3] ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain" addresses the operating bandwidth of a frequency hopping or agile radar

and receive, the minimum range of the radar is a function of the time taken to transmit the pulse, plus the time taken for the transmit/receive switch and any receiver delay to recover before the pulse can be received. Any feature that requires a long pulse to deliver the power on to the target will affect the minimum range of the radar. This effect is most predominant in short-range, high PRR radars.

The effective length of the pulse also determines the minimum range resolution which can be achieved; a 1 µs pulse has, for example, 150 m range resolution.

The signal bandwidth, pulse length (or compressed pulse length) and the range cell quantisation are all inter-related. The range cell size is determined by:

$$R_c = \frac{c}{2} \times \tau$$ Equation 3.2.2-2

where R_c = range cell

c = speed of light 3x10^8 m/s

τ = pulse length (or compressed pulse length)

and the bandwidth is the reciprocal of the pulse length, (or compressed pulse length):

$$BW = \frac{1}{\tau}$$ Equation 3.2.2-3

where BW = 3 dB signal bandwidth

Some typical radar parameters are:

Table 3.2.2-1 Signal Bandwidth v. Resolution

Pulse length (µs)	Signal 3 dB Bandwidth (MHz)	Range cell size (metres)
0.1	10	15
0.4	2.5	60
1.0	1.0	150
2.0	0.5	300
4.0	0.25	600

As well as affecting the minimum range the pulse length also affects the time taken for a radar to survey a given area. The radar is required to deliver sufficient energy in a given time to allow all targets to be detected. If it is not possible to deliver this energy efficiently, the peak power has to be increased or the dwell, or scan, time must be extended for a given Signal to Noise Ratio (S/N), or detectability, to be achieved.

3.2.2.9 Pulse Compression Radars

The need for a wide operating bandwidth has resulted in the use of amplifiers which generate much less peak power than the traditional narrow pulse length/operating bandwidth tubes such as the magnetron or the klystron. These transmitters are based on travelling wave tubes (TWTs) or their variants and more recently on solid-state devices. Such systems generate peak powers in the range 10 kW to greater than 100 kW and can operate over much wider bandwidths. These systems require much longer pulses to deliver the same amount of energy on the target. In order to achieve the range resolution such systems make use of pulse compression. In pulse compression systems the long transmitted pulse is generated by the use of frequency modulation or phase coding and compressed by the use of a dispersive filter matched to the required pulse length on receive. Such transmitters are usually non-linear, in that in order to obtain a flat power versus frequency characteristic, a usable efficiency and amplitude stability, it is necessary to drive the output of the amplifier heavily into limiting.

Such systems however are sensitive to pulse distortion and band limiting which can result in Time Sidelobes. Time Sidelobes are images of the target at ranges other than the true range caused by limitations in the pulse compression filters. They are at a lower, but still significant, level than the true compressed pulse. They are range analogies of the antenna Azimuth Sidelobes.

If Time Sidelobes are too high, targets can be spread into adjacent range cells, giving rise to multiple detections of a single target. Clutter is also similarly spread. Such effects can result in small targets being masked by larger targets or clutter at adjacent range cells.

3.2.2.10 Frequency Spectrum Issues

There is much discussion about the levels of radiated emission associated with radar transmissions and how they could be defined and specified.

The definitions currently being discussed seem to revolve around two proposals both relating to the concepts of Necessary Bandwidth (NB) and Spurious Emissions (SE). The intervening region being defined as the Out of Band (OOB) emission domain.

Before commenting on proposals it may be prudent to discuss what is meant by these terms.

3.2.2.10.1 Necessary Bandwidth (NB)

As has been stated before this is the bandwidth required to transmit sufficient information to / from the target, alternatively it is the bandwidth to which the radar can be limited without producing unacceptable distortion of the signal for a given set of radar parameters.

This bandwidth is a function of the modulation being used, pulse rise / fall-times and how much distortion can be tolerated. It is unique to each type of radar and even between the individual modes within a specific radar.

In general terms however, the NB required is related to the range resolution required. To a first order, the NB is similar for an uncompressed short pulse or a compressed long pulse for a given range resolution.

For the sake of convention/clarity, it is generally assumed for radar systems that the NB is approximately equal to the -20dB bandwidth of the transmitted power spectrum. It may be however that for some radars, depending on the sensitivity of the system to distortion, that a different definition would be more appropriate.

3.2.2.10.2 Spurious Emission Region (SE)

This is the region over which the radar's transmitted spectrum has fallen to the ITU limit of -60 dBc for Category A radars[4]. This is the requirement that determines the ability of the radar services to operate with other allocated services.

The ITU Radio Regulations define the SE in article S1.145 as follows:

> "Spurious emission*: Emission on a frequency or frequencies which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products, but exclude out-of-band emissions."*

Historically the SE region was defined to start at an excursion from the centre frequency of 250% of the NB. It was however recognised that many forms of pulse generation could not meet this definition. A new definition of the SE boundary is given in ITU-R Recommendation SM.1539 "Variation of the boundary between the out-of-band and

[4] ITU-R Recommendation SM.329 "Spurious Emissions"

spurious domains required for the application of ITU-R Recommendations SM.1541 and SM.329" Section 3.3 Primary Radars.

The outer limits on spurious domain emissions for radio equipment are considered to be applicable to the range 9 kHz to 300 GHz.

However, for practical measurement purposes only, the frequency range of the spurious domain may be restricted[4].

3.2.2.10.3 Out-of-Band Emission Region (OOB)

This is the region between the above two bands (NB-SE) where the spectral power falls off in some described manner. It is normally defined to allow for operation between channels within a band and controls the ability to allocate channels to geographically close users. It is interesting to note that in radar terms the word "band" usually refers to the complete band over which radar use is permitted not any individual frequency assigned within the band.

For a definition of the OOB region see ITU-R Recommendation SM.1541[3].

3.2.2.11 Transmitter Coherency

Magnetron transmitters are not coherent from pulse to pulse and therefore one of two methods are used in the receiver to produce pulse to pulse coherency. In the first method a receiver local oscillator is phase locked to the transmitted pulse every PRI, while in the second method the phase of the transmitted pulse is measured on each transmission and a phase correction applied to the received signal.

Driven transmitters, either tube or solid-state, use coherent oscillators that are common to the transmit and receive chains, and do not require the pulse to pulse phase correction (an exception to this is in some naval radars that use phase correction to compensate for the ship's motion).

Clutter suppression in primary radars relies on coherency over a batch of pulses, in the case of MTI clutter suppression systems generally 2 to 4 pulses; and in the case of MTD systems generally 4, 8, or 16 pulses.

This requires stability on the part of the transmitter. The pulse to pulse instability factor, I_s, is given by the following improvement factor limits[5]:

For the transmitter frequency:

$$I_s = 20\log\left(\frac{1}{\pi \Delta f \tau}\right) \qquad \text{Equation 3.2.2-4}$$

For the transmitter phase shift:

$$I_s = 20\log\left(\frac{1}{\Delta \phi}\right) \qquad \text{Equation 3.2.2-5}$$

where

$\Delta f =$ interpulse frequency change

$\tau =$ transmitted pulse length

$\Delta \phi =$ interpulse phase change

3.2.2.12 Information Content and Spectrum

Primary radar is unique in that a radar only communicates with itself, and there are no predefined signals in space. The system designer is restricted by the need to comply with the requirements of allocated frequency and spectrum mask; the designer is free to

[5] Radar Handbook, M.I. Skolnik, 2nd Edition page 15.52

optimise the detection performance of the radar by varying the transmitter parameters of pulse width, PRR, modulation, bandwidth etc.

Spectrum management concepts that are applicable to communications systems are not automatically applicable to primary radar systems. Radar systems are instruments for the measurement of the environment surrounding the radar, rather than for communication from A to B. The absence of a return signal is as significant as the presence of a target, indicating that no target has been detected in that area. Radars have to transmit relatively large signal levels due to the very low signal level that is reflected by the target. The received signal also reduces rapidly with range; the received signal level from a point target (aircraft or ship) varies inversely to the fourth power of the range (R^4). Communications systems signals only have a one way path loss with the signal varying inversely to the square of the range (R^2); also a communications transmitter only has to transmit a power level that is sufficient to meet the required bit error rate at the receiver which is designed to match the expected quality of transmission.

Radar transmitters, such as magnetrons or some klystrons, emit unmodulated pulses of RF radiation; while driven transmitters such as TWTs, klystrons and solid state emit pulses with a frequency or phase coding enabling the longer pulse used by these transmitters to be compressed on reception. This improves both the S/N ratio and the range resolution.

Narrow transmitter pulses, or coded pulses that can be compressed to a narrow pulse, occupy a wider spectrum which in turn enables the radar receiver to resolves the echoes to a finer range resolution.

The spectrum of a radar transmission is determined by the pulse width and modulation, and by the rise and fall-times of the pulse. In addition the transmitter tube or module may generate harmonics and spurii. Little energy is present in these out-of-band signals, and for the best signal to noise ratio on receive, the receiver bandwidth is matched to that of the transmitted pulse, including the modulation or coding for pulse compression. Therefore the out-of-band signals in the transmitter output can be filtered to improve the spectrum efficiency.

Primary radar transmits a known signal and monitors the return signal. Changes in the signal between transmission and reception correspond to changes in the channel; that is, they contain information about the path taken by the radiation from the transmitter to the receiver. The main change is that imposed on the signal by the target. Each part of the target illuminated will produce a reflection, and movement of the target towards or away from the radar will induce a doppler shift on the signal allowing the radar to separate moving from static targets. Radars use this principle to eliminate ground clutter echoes from a radar display leaving just the wanted moving targets.

Secondary Surveillance Radar (SSR) and the military Identification Friend or Foe (IFF) systems do transmit information in their train of interrogation pulses. They request transponders on aircraft and ships to reply with their identification, flight number or height; the transponders can also be used to signal a hi-jack or an emergency. The system is being developed to allow the transmission of further data, but any change to the spectrum usage would be unlikely due to the need for compatibility with the very large number of SSR transponders in use throughout the world.

Unlike communications systems where changes in the channel are seen as undesirable, radar is reliant on the changes in the channel. No channel equals no target, and depending on the manner in which the channel (the transmit and receive paths, and how the target reflects the radar signal) modulates the transmitted signal, thereby modifying (typically broadening) the transmitted signal bandwidth, and conveying information about the nature of any targets present. A moving target imparts frequency modulation to the signal, this is referred to as Doppler modulation and is a function of target velocity relative to the radar. Targets vibrate or move in all directions so the frequency of the radar signal can be increased or decreased so the bandwidth of the signal is typically broadened. Short pulses occupy a wider bandwidth, but allow a radar to measure the position of a target more accurately and to resolve closely spaced targets.

The capacity of a radar to infer information about a putative target therefore depends on the Signal-to-(Noise plus Interference) power at the receiver and the receiver bandwidth. Traditionally the majority of the bandwidth information has encoded details of the target range extent, but more modern radars also extract information about the target velocity (from the Doppler frequency shift imposed on the signal) and identity (from the Doppler induced spectral shape imposed on the received signal).

Amplitude modulation imposed by the channel (target) encodes information about the target spatial structure. Whilst the spectral spreads implied by this channel modulation are typically small, they are neither insignificant nor unimportant. Modern radars rely heavily on this extra information to reduce false alarms introduced by unwanted channel modulations (clutter) which is typically several orders of magnitude greater in effect than the noise.

When considering the effects of the above on the information content of a "radar return", it should be noted that the information comes from the channel not the radar. At its simplest, the channel consists of a free space path with no reflectors, giving no return signal. Such a non-signal still contains some information about the probability that no reflector (i.e. target) is present in the channel. Similarly where a reflector exists, the returned signal contains some information about the existence of the reflector at that location. The number of range resolution cells scanned per second is equal to C, the speed of light, divided by twice the range cell size; and the range cell size is equal to C divided by twice the transmitted bandwidth. So the radar receives data at a rate of one cell per second per Hertz.

A simple Marine Navigation radar, that only provides a binary decision about the presence or otherwise of an object at each range cell, would output 1 bit/sec/Hz. The information content of that data stream would depend on what prior knowledge was available about the channel. As an example, in open water on a calm day it would be expected that most of the cells would return no detections and it might be concluded that the information content of the return was very low. But in a crowded harbour there might be a 50% chance that any individual cell would be occupied by a target, giving almost one bit per cell of information even in this simple case. Given this philosophical problem of defining the information content of a radar signal, some simplifying assumptions can be made about what is meant when talking about its information content. It can be assumed that there is no prior knowledge of the channel (environment) and that the information content is that potentially impressed on the transmitted signal by the channel, not the information in the original transmission (as extracted by an Electronic Surveillance Measures (ESM) receiver for instance).

In order to reduce false alarm rates, radars usually integrate over many adjacent transmission/reception cycles. This increases the information content in each range cell but decreases the number of cells, maintaining a constant data rate per second per Hz.

The information content of the signal needs to be sufficient to meet the output requirements of the radar. Whilst a Marine Navigation radar could, at its simplest, have only a binary output for each cell, giving a information content of just under one bit per second per Hz, modern Marine Navigation radars generally provide more information than this simple binary output and give some indication of return strength. In such cases the information content per cell is increased to a few bits per cell.

Further information requirements apply to Air Traffic Control (ATC) Radars. ATC radars need to rapidly separate the moving reflectors from the stationary (clutter) reflectors. They do this by using extra information imposed on the signal by the moving target. Considering a moving reflector in the channel, it will apply at least a Doppler shift to the signal, and if it contains internal moving components, an additional Doppler spread. Such shifts and spreads are part of the information being looked for and radar receivers must be designed to accept a bandwidth equal to the transmitted bandwidth plus and minus the maximum expected Doppler shifts and spreads. Having done so it is necessary to implement a suitable scheme for separating the ‘fast’ targets from the ‘slow’ clutter. In principal this is a binary decision but in practice it involves separating the available velocity range into more than two regions and typically requires an additional two to three bits per second per Hz. In order to achieve the growing demand for faster, more accurate identification of aircraft tracks, more modern ATC radars go even further and output not only a binary decision on whether a target is moving or otherwise but some estimation of its radial range rate. This typically increases the data per cell by between 9 to 13 bits. This information is extracted over several transmission cycles and so increases the information rate by the order of no more than a bit or two per second per Hz. ATC systems require much lower false alarm rates and faster reporting times than Marine Navigation Radars pushing the minimum required information content of the return signals up still further. Typically a data rate of 8 to 10 bits per second per Hertz from the weakest expected return would meet the most stringent requirements for ATC radars.

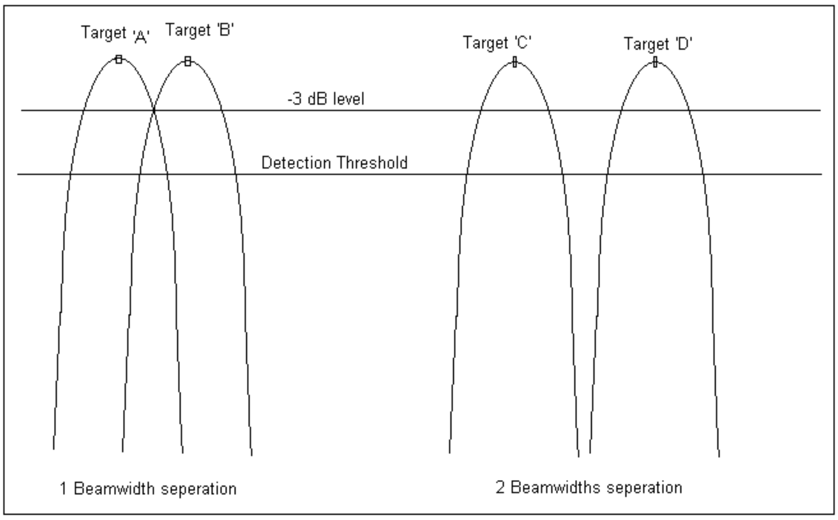
Military Radars have information rate requirements ranging from those of ATC radars up to about 16 bits per second per Hertz for specialist requirements such as advanced ballistic missile defence systems.

3.2.3 Radar Resolution Requirements

3.2.3.1 Azimuth resolution

The azimuth resolution of a radar is usually poor, being typically 2 x Azimuth Beamwidth x Range, noting that the azimuth beamwidth is related to the antenna size. Figure 3.2.3-1 shows that the radar echoes from two targets, A & B, separated by one beamwidth will overlap at the 3 dB point and the cusp between them will not go below the detection threshold causing a radar to see them as one target. The echoes from two targets separated by two beamwidths, C & D, will not overlap and a radar will see them as two distinct targets. Some modern radars have more complex data processing methods which can determine that two targets are present and separate them for display by matching the target returns from a number of pulses to the antenna's azimuth beamshape.

Figure 3.2.3-1 Azimuth Resolution



3.2.3.2 Range resolution

A small range cell is required for range resolution and accuracy, and to reduce the clutter cell size which enables the radar clutter processor to more easily separate wanted aircraft targets from the sea, ground and rain clutter.

A short range cell size implies the need for a short receive pulse, either transmitted, or compressed from a longer transmitted pulse. Both of these translate into a wide bandwidth.

The range cell size is defined as: (see Section 3.2.2.8)

Range cell = (c/2) x pulse length

Where c = speed of light

Some typical pulse lengths and their corresponding range cell sizes are:

0.1 μs = 15 metres

0.4 μs = 60 metres

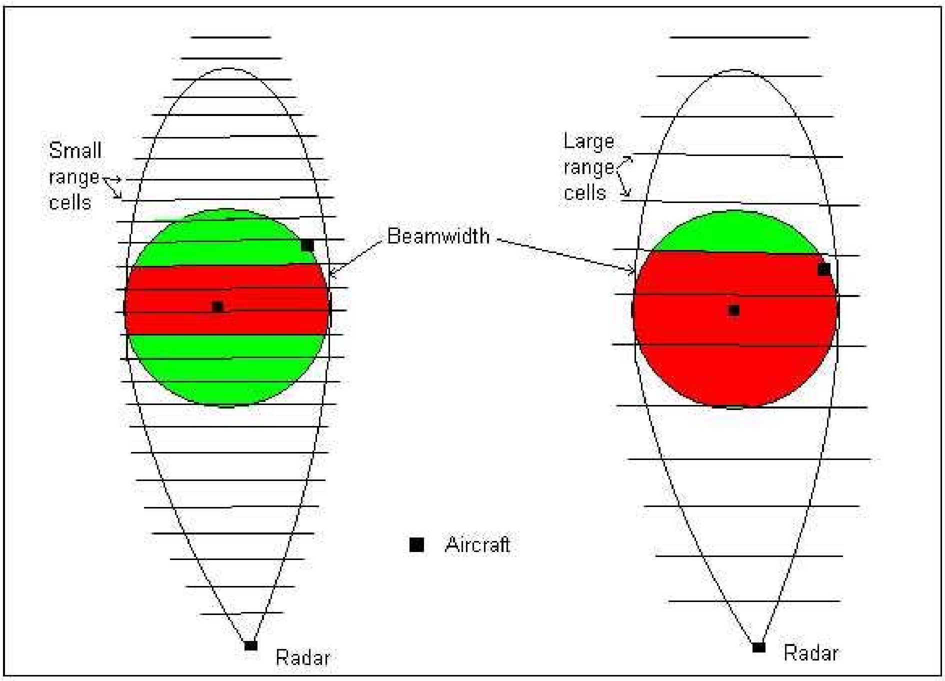
1.0 μs = 150 metres

2.0 μs = 300 metres

4.0 μs = 600 metres

3.2.3.3 Circular resolution

Figure 3.2.3-2 Circular Resolution



An example of circular resolution is the definition used by authorities where a radar is required to resolve, with a stated probability, two equal targets with a separation of ‘m’ nautical miles at a range of ‘n’ nautical miles. Typical values of ‘m’ and ‘n’ are 3 and 40. This can be achieved by azimuth resolution or range resolution If one target is at the centre of the circle and a second is anywhere on the circumference, then the probability of resolution is the amount of the circumference where the targets can be separated. In both the sketch diagrams in Figure 3.2.3-2, the two targets are in the same beamwidth, therefore there is no azimuth resolution.

To resolve the targets therefore requires good range resolution. In the right hand diagram the range cells are large and again the targets cannot be resolved in the dark shaded area (red) as they are not two range cells or more apart; only if the second aircraft is in the light shaded area (green) can they be resolved apart. While in the left hand diagram with smaller range cells, the two targets can be resolved when they are in different range cells with a one cell gap between them, shaded green. This allows the radar and operator to distinguish the two targets. If there was not an empty range cell between targets, the radar and operator would not be able to differentiate between two separate targets and one target spanning across range cell boundaries.

In an ATC radar with 60 metre range cells (such as the AMS Watchman Radar) the three mile separation circle will cover 185 range cells with only three range cells where the aircraft cannot be resolved. This gives a 98% probability of resolving the two.

In those range cells where the two cannot be resolved in range, they can be resolved in azimuth. A 1.5 degree beamwidth is 1.05 nautical miles wide at 40 nautical miles range. Aircraft with an azimuth separation of 3 nautical miles will be 2.9 beamwidths apart and will therefore be resolved. This radar thus meets the requirement.

3.2.3.4 Comparison of single frequency pulse shapes

Currently radar systems make use of rectangular (or trapezoidal) pulses with inherently fast rise and fall-times. The main reason for this is that high power is needed for target detection and in practice these powers can only be achieved for a short time.

There are several further reasons why this approach is taken :

- A rectangular pulse is the most time efficient way of delivering energy onto a target in a given time.
- It allows transmitters to be produced which have a minimal distortion effect at the power level required for detection.
- It uses transmitters with a maximum of efficiency in terms of converting prime power to RF energy.
- It allows operation over wide RF bandwidths with minimal amplitude variation between pulses being produced by the transmitter.
- It allows the delivery of short pulses or pulses with high PRRs.
- It simplifies the use of matched multiple amplifiers in antenna arrays, where the energy radiated by the individual transmitter modules combine in space to form a beam with the planned power, gain and side-lobes.
- Saturated operation of the amplifier provides a benefit because it contributes to the suppression of noise through the small signal suppression effect. This occurs when an input signal drives an amplifier into limit, which causes the gain of the amplifier to reduce. This in turn reduces the noise out of the amplifier by reducing the amplification gain of the noise.
- Fast turn on time can suppress spurious oscillation in some types of transmitter tube.

3.2.3.4.1 Spectrum of a pulse with square sides

Figure 3.2.3-3 shows a 400ns pulse which is almost rectangular having a 3.5 ns risetime, although this cannot be readily derived from the x-axis. The pulse width in this and subsequent pulses is defined as the half power width and the risetime is the time between the 10% and 90% amplitude levels.

The associated spectrum is also shown in Figure 3.2.3-4 indicating that the spectrum has significant energy beyond 200MHz from the carrier.

Figure 3.2.3-3 Square Pulse with a Risetime of 3.5ns

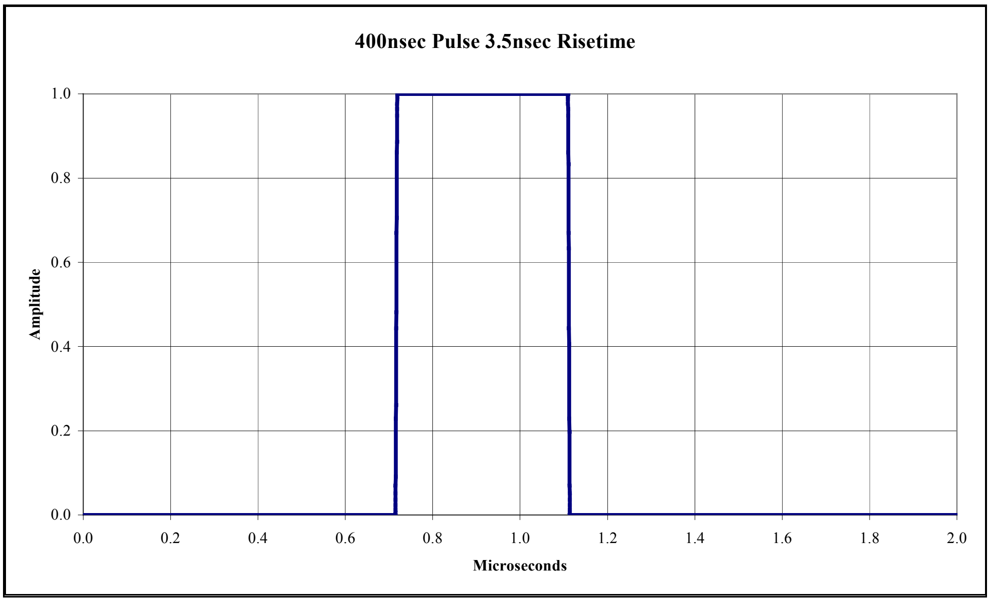
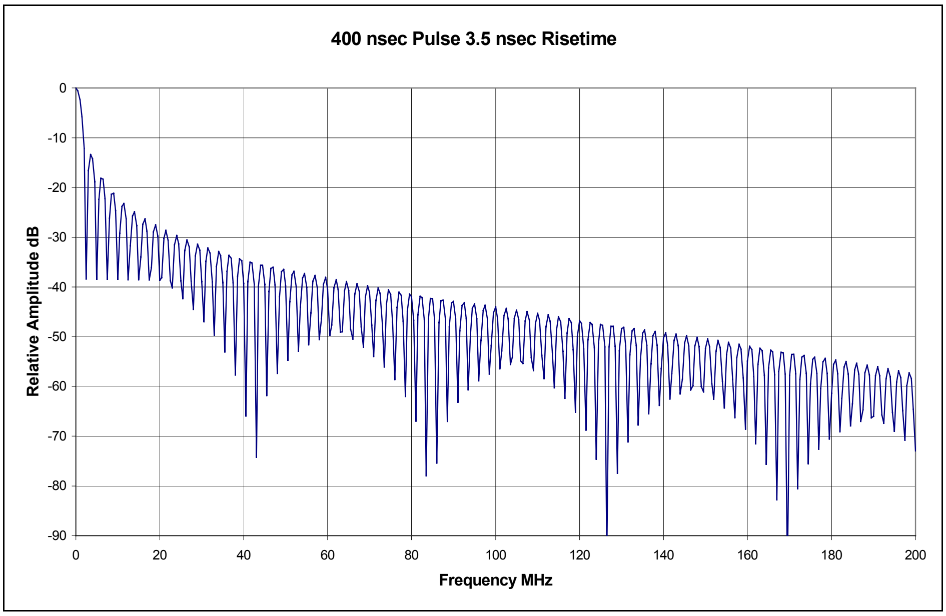


Figure 3.2.3-4 Square Pulse Spectrum with a Risetime of 3.5ns



3.2.3.4.2 Spectrum of pulses with equal tapered sides

Figure 3.2.3-5 and Figure 3.2.3-7 are two pulses with risetimes tapered to 30ns. and 50ns. Even with the longer risetimes, there is still significant energy out to 80MHz from the carrier as shown by the spectra in Figure 3.2.3-6 and Figure 3.2.3-8.

Figure 3.2.3-5 Pulse with a Risetime of 30ns

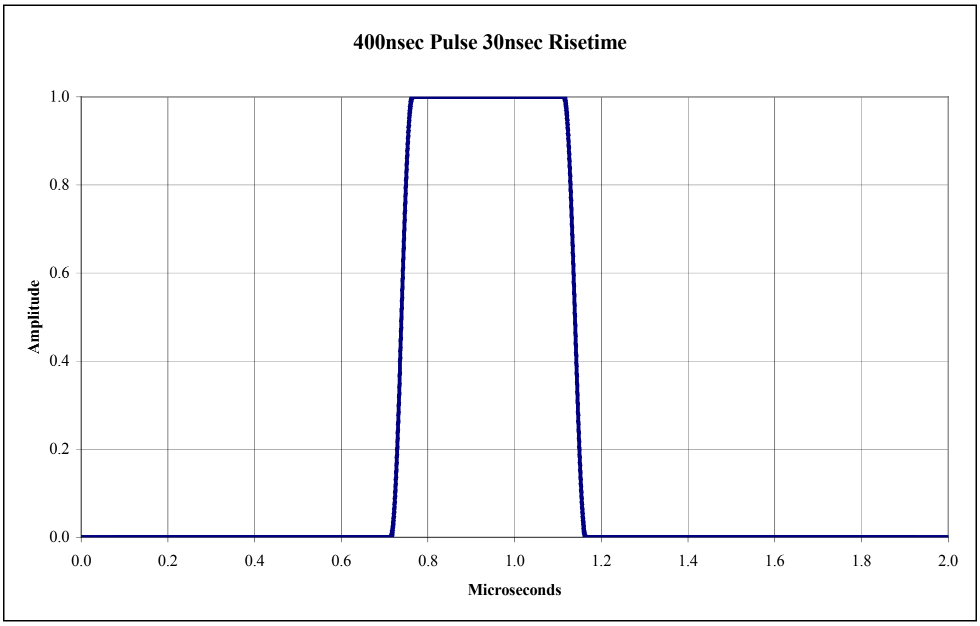


Figure 3.2.3-6 Spectrum of a Pulse with a Risetime of 30ns

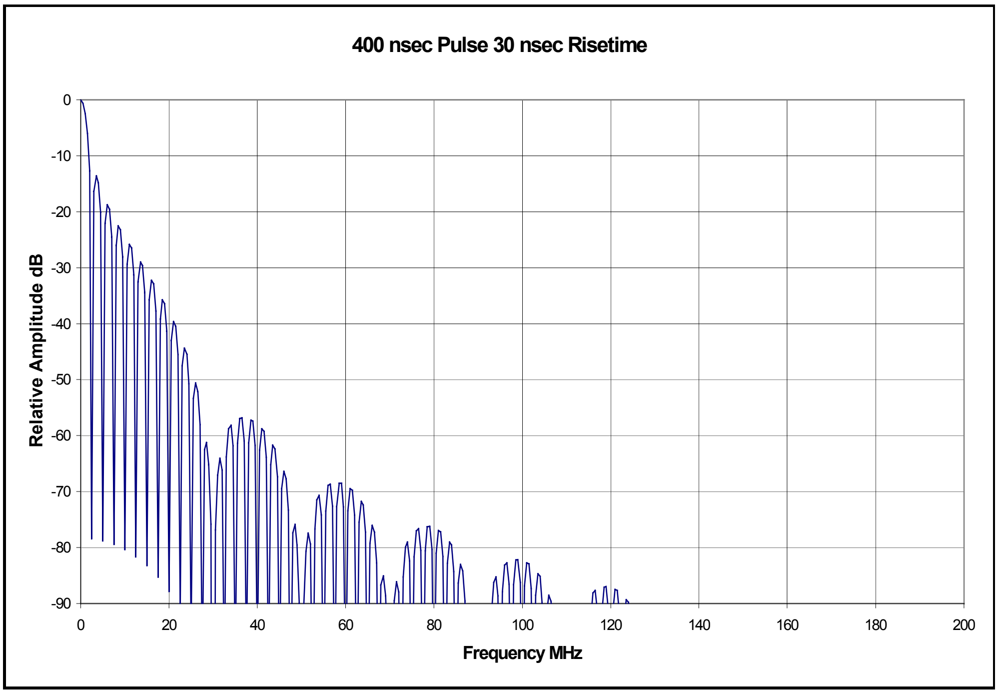


Figure 3.2.3-7 Pulse with a Risetime of 50ns

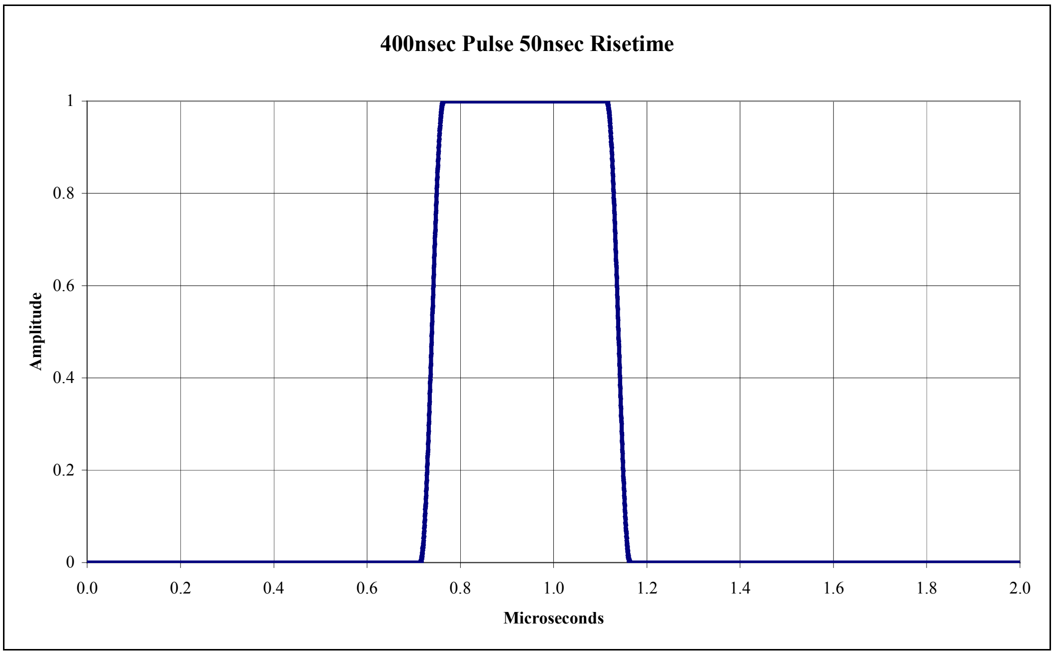
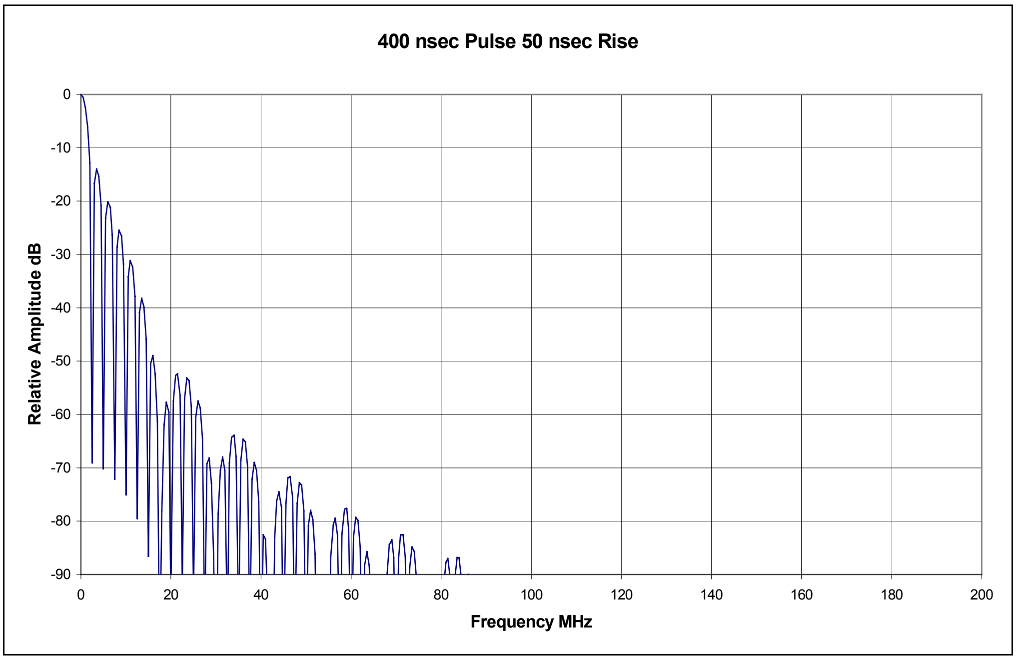


Figure 3.2.3-8 Spectrum of a Pulse with a Risetime of 50ns



3.2.3.4.3 Spectrum of pulses with unequal tapered sides

Figure 3.2.3-9 and Figure 3.2.3-11 are pulses where the falltimes (60 & 100ns) are twice that of the risetimes (30 & 50ns). Their spectra are shown in Figure 3.2.3-10 and Figure 3.2.3-12. The frequency components of the rise and fall-times are different and the spectra no longer have the dips that are shown in the previous spectra of the pulses with equal rise and fall-times;

Figure 3.2.3-9 Pulse with a 30ns Risetime and 60 ns Falltime

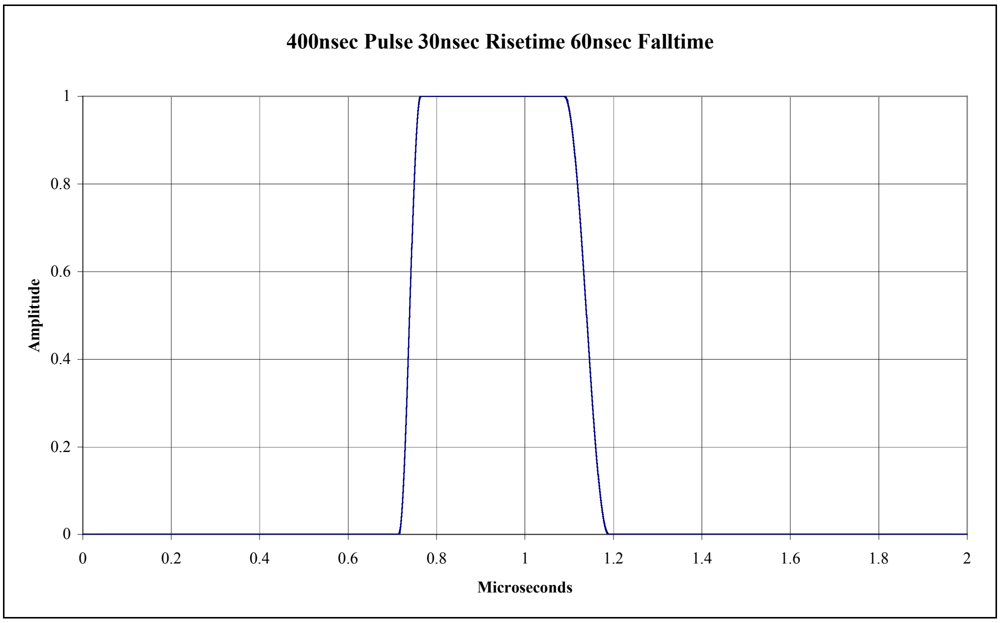


Figure 3.2.3-10 Spectrum of a Pulse with a 30ns Risetime and 60 ns Falltime

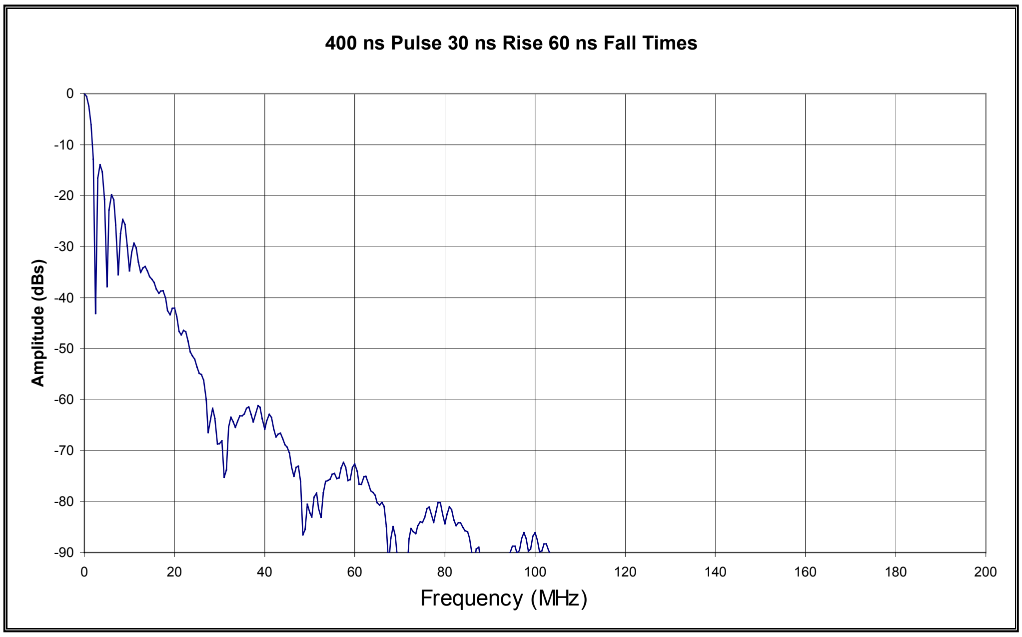


Figure 3.2.3-11 Pulse with a 50ns Risetime and 100 ns Falltime

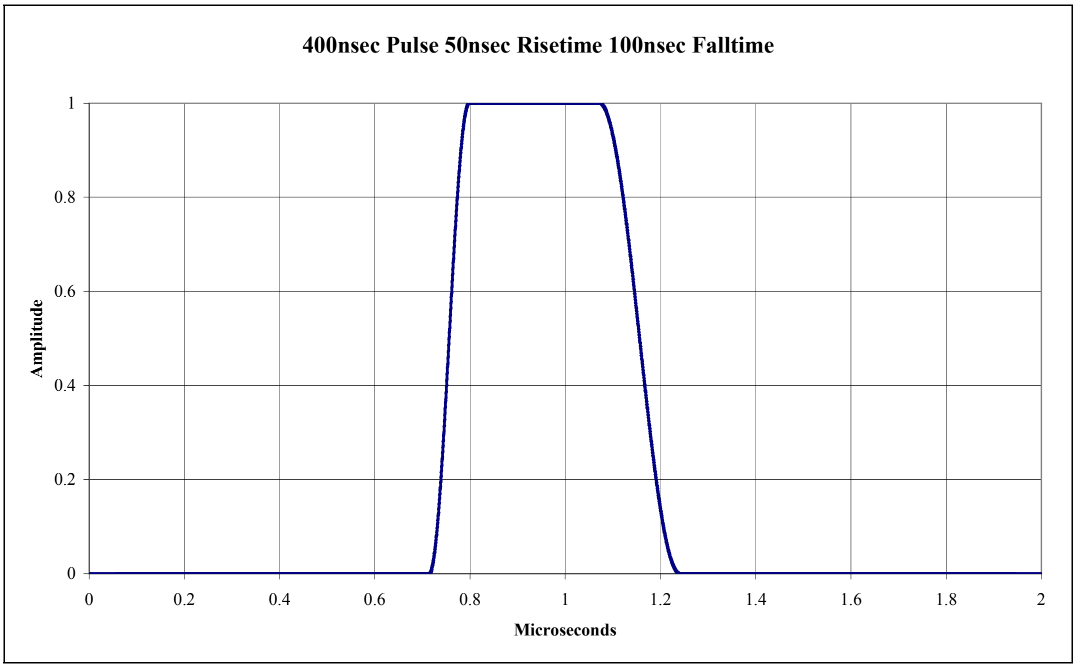
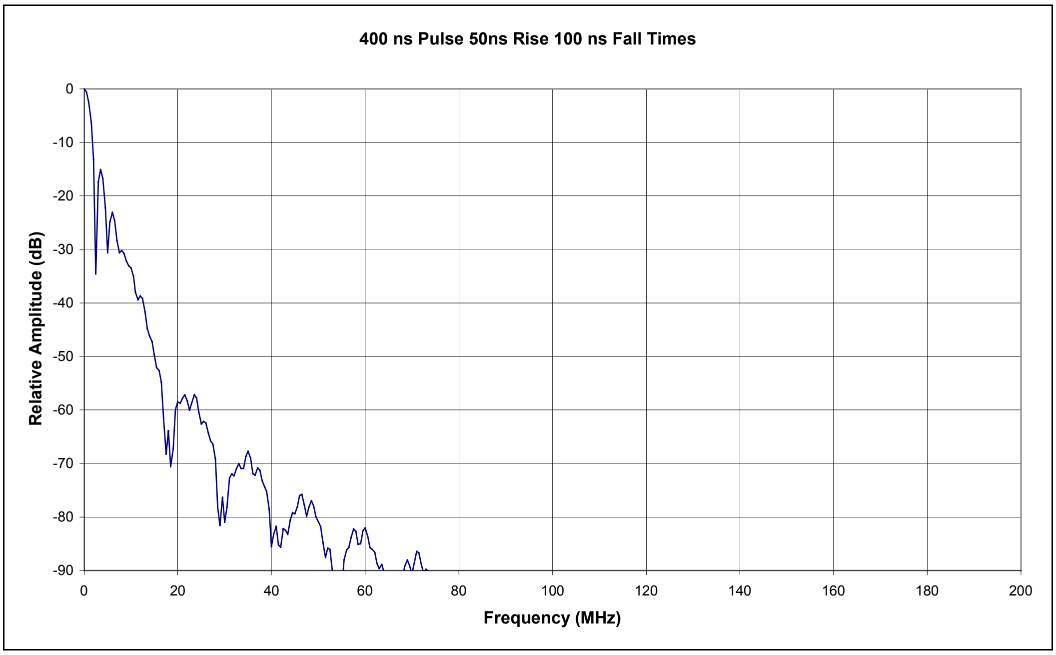


Figure 3.2.3-12 Spectrum of a Pulse with a 50ns Risetime and 100ns Falltime



3.2.3.4.4 Spectrum of Gaussian pulse

In theory it can be shown that the spectrum of a Gaussian amplitude pulse has no side-lobes in the frequency domain and has an interval between the -20, -40 & -60 dB points much less than that for a rectangular or trapezoidal pulse (see Figure 3.2.3-14). It is more efficient in spectral use; however the use of a Gaussian amplitude pulse has many practical problems that make it effectively useless as a primary radar pulse. It does however have applications in Distance Measuring Equipment (DME) or navaids where much lower peak and mean powers are used.

The Gaussian amplitude pulse is particularly inefficient in delivering energy (it is the energy on the target that defines the detectability) to a target. For a given peak power the Gaussian pulse requires approximately 2.4 times the pulse length (defined as 6σ) than that required for an equivalent rectangular pulse.

This would give problems with range discrimination, minimum range, PRR limitation or radar dwell time (occupancy) depending on the type or radar and radar mission.

Alternatively, pulses greater in amplitude would have to be used to compensate for this inefficiency.

As well as requiring a longer pulse to produce the same energy as a rectangular pulse, what is probably more important is that, there are practical problems associated with the generation of these types of shaped pulses at the peak power required for use with radars:

- In radars utilising a high power oscillator valve it is not possible to control the shape of the rise and fall-times to generate this type of pulse.
- In driven (coherent transmitters) the use of Gaussian amplitude pulses necessitates the use of linear amplifiers.

Some of the problems associated with linear high power amplifiers are:

- Very low efficiency of conversion of prime power to RF. This is critical in solid-state or active array transmitters where the ability to dissipate wild heat (heat generated in the transmitting device that must be removed by cooling using air, liquid or conduction) is severely limited and transistor junction temperatures are critical to the operation of the radar.
- Distortion (phase and amplitude) of the pulse produced by the amplifier is much more severe in linear amplifiers as opposed to those operating under limiting conditions. This could distort the "perfect" transmitted Gaussian spectrum and result in errors when the pulse is compressed on receive.
- In linear amplifiers the pulse to pulse coherence is not as good as in some types of limiting amplifiers. This is due to the amplitude variation that can occur in linear amplifiers. This would degrade the sub-clutter visibility that could be achieved. Solid-state linear amplifiers would tend to lose coherence much more than limiting amplifiers on a pulse to pulse basis as device junction temperature changes during the pulse.
- Due to the high small signal gain, problems can be experienced with "within-pulse" noise being generated by the transmitter.
- Due to the variation in small signal gain (particularly in solid-state amplifiers and TWTs) it is difficult to design a system which could operate linearly at the power levels required and over a wide agile or instantaneous bandwidth (greater than 20%).
- In active arrays, where the transmitted power is combined in space, individual amplifiers are required to have phase and amplitude matching in order to preserve transmitted side-lobes. Currently, linear amplifiers cannot achieve the required matching in amplitude. In a wide band solid-state amplifier chain, typical devices could show up to a 10 dB variation over the radar band.

Long pulses, rectangular or otherwise, require the use of pulse compression to achieve the required range discrimination. Wide band driven systems make use of pulse compression techniques. It is not clear whether a pulse compression waveform could be devised based on the Gaussian amplitude shape. If it could be, it is not obvious how such modulation would modify the spectrum of the pulse, or what effects the expected distortion would have on such a pulse. It is considered likely that the distortion could affect the compressed pulse fidelity and produce range sidelobes.

The radar dynamic range is also an issue with using amplitude shaping. The dynamic range of received signals which the radar must process may easily be of the order of 150 dB and distortion of the pulse can occur on receive. It is also the dynamic range that prevents the use of amplitude weighting on the Tx signal (the receiver would not handle the wide dynamic range of the radar echos added to that of the pulse weighting) for use with pulse compression.

Figure 3.2.3-13 shows a Gaussian pulse which will have the Gaussian spectrum shown in Figure 3.2.3-14, this has very good spectrum efficiency. This pulse is also 400ns to the half power point but in order to achieve the compact spectrum, the transmit period must be several times the nominal pulse length.

Figure 3.2.3-13 400ns Gaussian Pulse

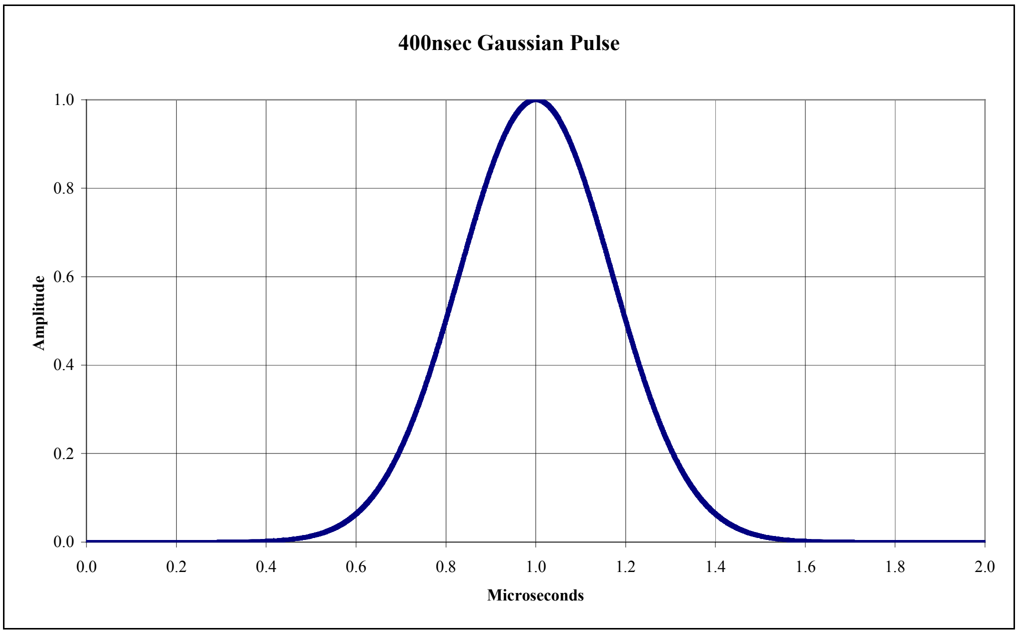
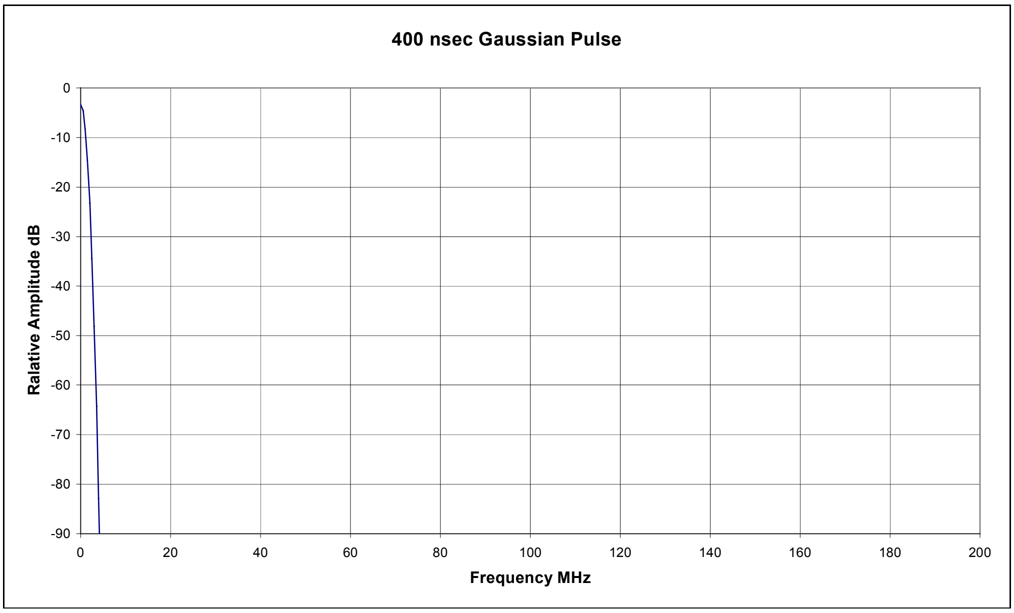


Figure 3.2.3-14 Spectrum of a 400ns Gaussian Pulse

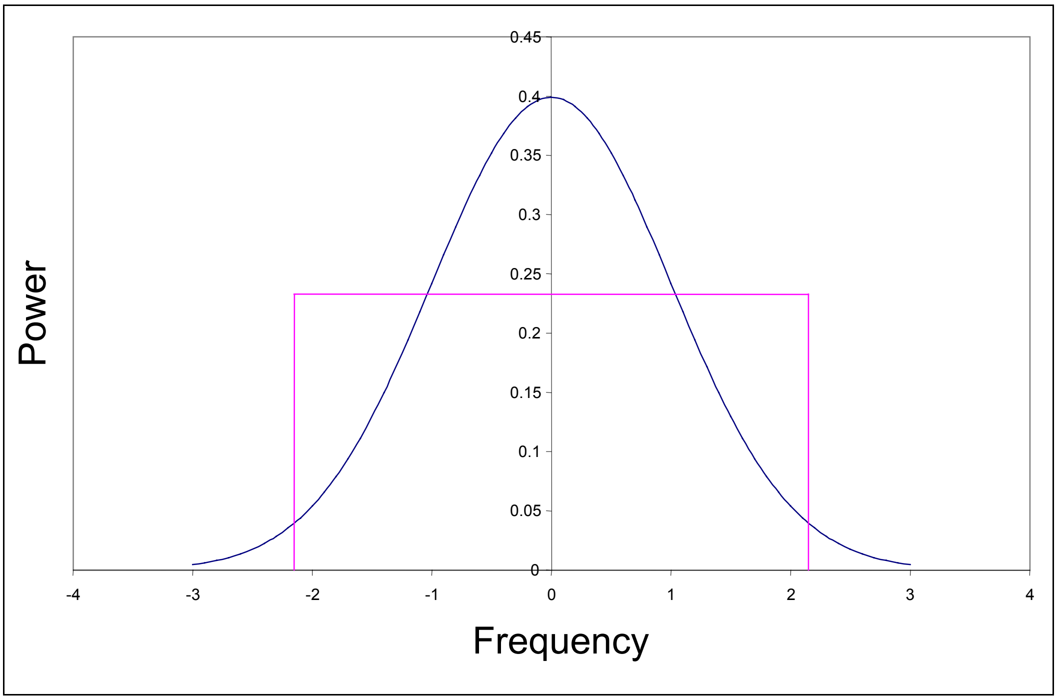


Although a Gaussian pulse has narrow spectrum it has the following characteristics which make it unsuitable for use in radar systems.

It needs a linear transmitter power amplifier which is inefficient for high power.

The mean power transmitted determines the detection performance of a radar. The mean power of a Gaussian pulse is less than the mean power of a rectangular pulse with the same peak amplitude. So the peak power of a Gaussian pulse must be increased to achieve the same mean power. This is shown diagrammatically in Figure 3.2.3-15, which shows a Gaussian pulse and a rectangular pulse of the same mean power. Note that the Gaussian pulse has a peak value almost double that of the rectangular pulse. This increase in peak power would necessitate a large increase in the transmitter size and cost and would increase the stresses on the microwave components resulting in a decrease in reliability and lifetime.

Figure 3.2.3-15 Rectangular and Gaussian pulses of equal Mean Power



A Gaussian transmitter output pulse could be produced by filtering a rectangular pulse. This would only be suitable for single fixed frequency radars. It would need a very narrow band filter, and any change of frequency would require a new filter. The filter would have to dissipate the significant amount of energy that it rejected. It would also reduce the efficiency of the radar and the detection range. However, most air traffic control and air defence radars use two or more frequencies to give improved performance by using frequency diversity operation. This would not permit filtering of the output.

In the case of radars using two transmitters, filtering is applied to separate the two channels; but these filters are relatively wide band and therefore not suitable for spectrum shaping.

3.2.3.4.4.1 The Use of Gaussian Pulses

Navaids equipment, such as DME, operate in the congested allocations around 1 GHz, and these use Gaussian pulses in order to restrict the bandwidth so that many channels can be allocated. Because this is a transponder based system, where the only requirement is to trigger a threshold response in a receiver, the power in the pulse is very low, thus the limitations described above do not apply.

There are some military applications where Gaussian pulses have been proposed. In these applications the key parameter is the frequency band to be used. Relative low frequency applications where the penetrating properties of the EM waves are required is one such application. In this particular case, due to the very limited availability of spectrum and the need to operate in a band allocated to communications or broadcasting, a Gaussian pulse has been used. The radar however has to suffer all the problems described; in such specialist cases the radar performance is sacrificed for the need to use the required frequency.

No civil use of Gaussian pulses in non-transponder based systems has been identified or is likely to be considered acceptable.

3.2.3.5 Spectra of Frequency Coded Pulses

The pulse compression that can be obtained in a radar receiver is controlled by the product of the pulse length and the sweep bandwidth. The sweep laws for three ATC radars are compared below. Table 3.2.3-1 summarises the frequencies at which the -20dB, -40dB, -60dB and -80dB points occur for each type. It can be seen that the radar with the longest pulse and narrow sweep bandwidth has the quickest roll off of the spectrum. The following paragraphs show the spectra for three S-Band ATC radars operating at 2.8MHz.

Travelling Wave Tube ATC Radar (Type A)

For radar Type A (S-Band TWT) with a non-linear FM frequency sweep:

Transmitted pulse length	= 20 µs
Pulse sweep Bandwidth(Chirp)	= 2.5 MHz
Time Bandwidth product	= 50

Therefore the 20µs pulse can be compressed to 0.4 µs, giving a 60 metre range cell size.

Figure 3.2.3-16 shows the sweep law for this radar and Figure 3.2.3-17 shows the generated spectrum.

Figure 3.2.3-16 Radar Type A Sweep Law

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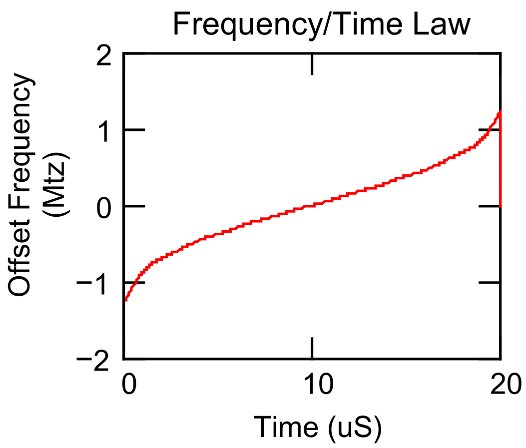
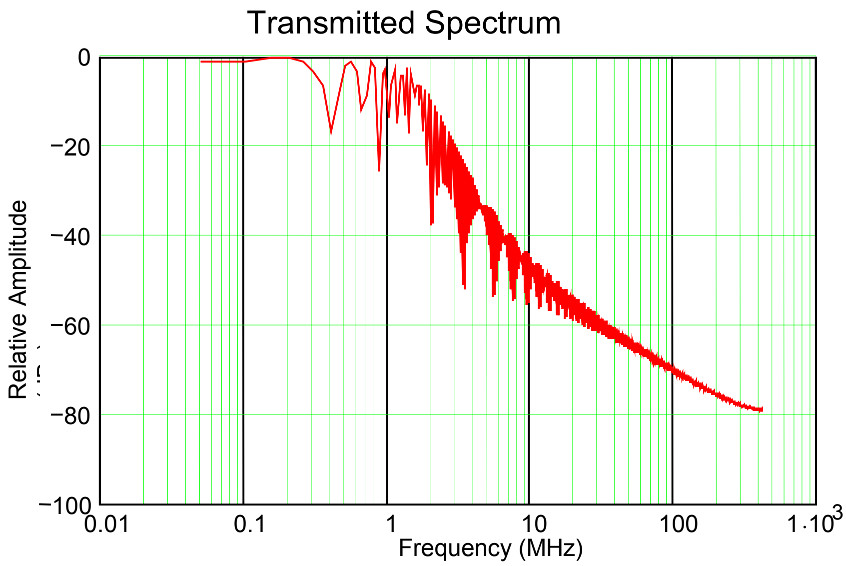


Figure 3.2.3-17 Radar Type A Spectrum



Solid-state Transmitter ATC Radar (Type B)

For radar Type B (S-Band Solid-state) with a non-linear FM frequency sweep:

Transmitted pulse length	= 73.5 µs
Pulse sweep Bandwidth	= 2.03 MHz
Time Bandwidth product	= 149

Therefore the 73.5 µs pulse can be compressed to 0.5 µs, giving a 75 metre range cell size.

Figure 3.2.3-18 shows the sweep law for this radar and Figure 3.2.3-19 shows the generated spectrum.

Figure 3.2.3-18 Radar Type B Sweep Law

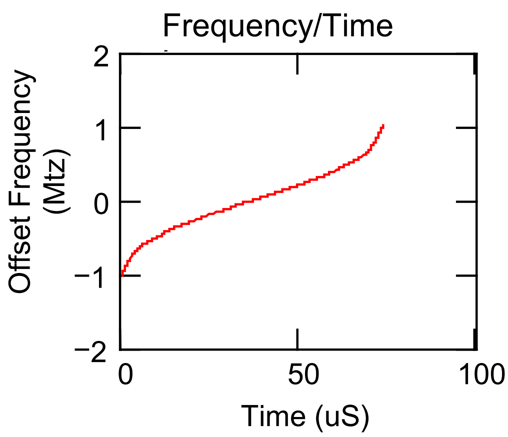


Figure 3.2.3-19 Radar Type B Spectrum

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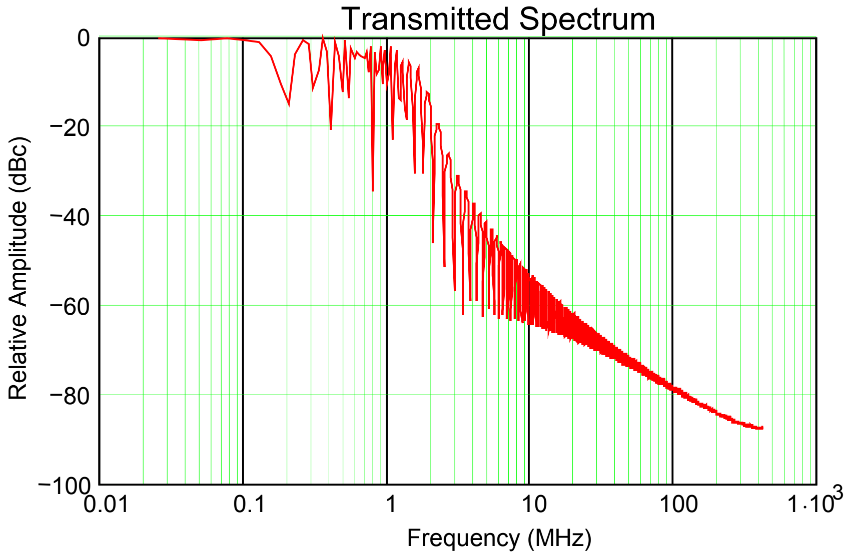

Solid-state Transmitter ATC Radar (Type C)

For radar Type C (S-Band solid-state) with a non-linear 1 MHz FM frequency sweep:

Transmitted pulse length	= 100 μs
Pulse sweep Bandwidth	= 1 MHz
Time Bandwidth product	= 100

Therefore the 100 μs pulse can be compressed to 1.0 μs, giving a 150 metre range cell size.

Figure 3.2.3-20 shows the sweep law for this radar and Figure 3.2.3-21 shows the generated spectrum.

Figure 3.2.3-20 Radar Type C Sweep Law

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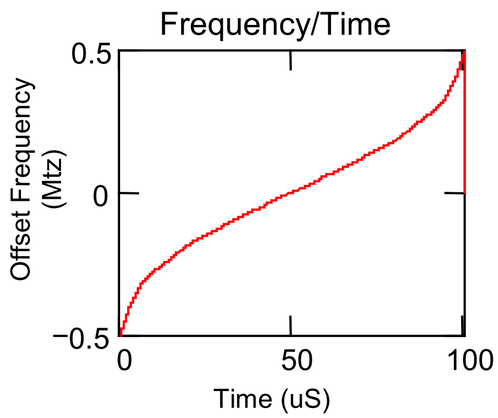

Figure 3.2.3-21 Radar Type C Spectrum.

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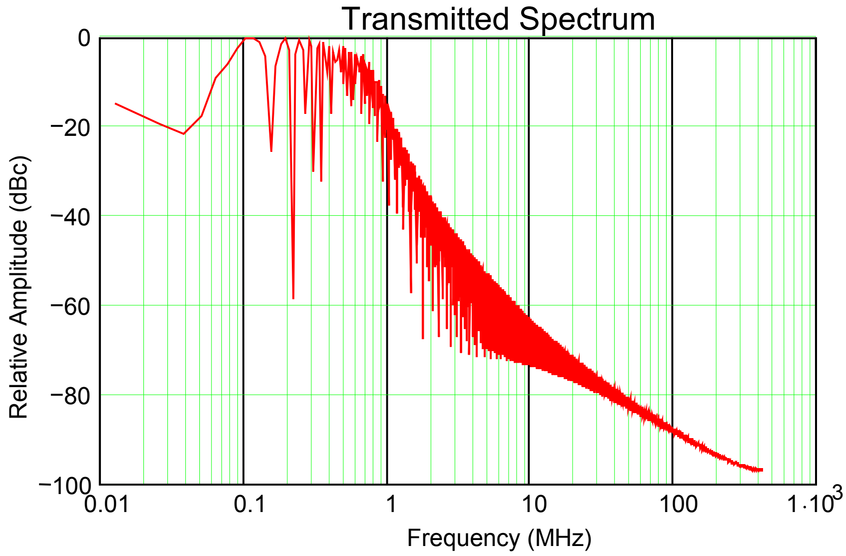


The spectra of the 3 types of transmitter, at 100 MHz from the fundamental frequency, show that the longer pulses with a narrower bandwidth fall off at a faster rate.

Spectrum level at 2.9 GHz

Radar Type A	-59 dBc
Radar Type B	-65 dBc
Radar Type C	-70 dBc

For comparison purposes the following two pairs of figures show the spectra for radar Type C with an alternative non-linear FM and with a linear FM.

For radar Type C (S-Band solid-state) with a non-linear 2 MHz FM frequency sweep:

Transmitted pulse length	= 100 μs
Pulse sweep Bandwidth	= 2 MHz
Time Bandwidth product	= 200

Therefore the 100μs pulse can be compressed to 0.5μs, giving a 75 metre range cell size.

Figure 3.2.3-22 shows the sweep law for this radar and Figure 3.2.3-23 shows the generated spectrum.

Figure 3.2.3-22 Radar Type C (with non-linear FM) Sweep Law

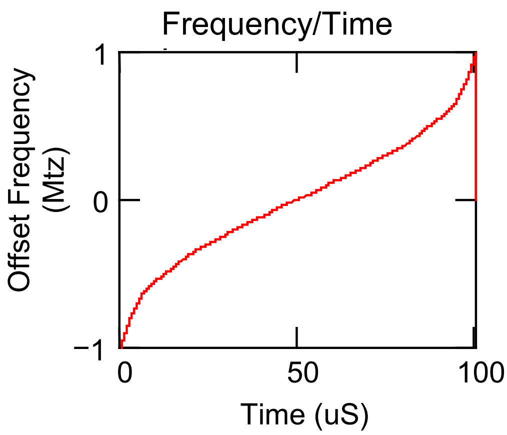
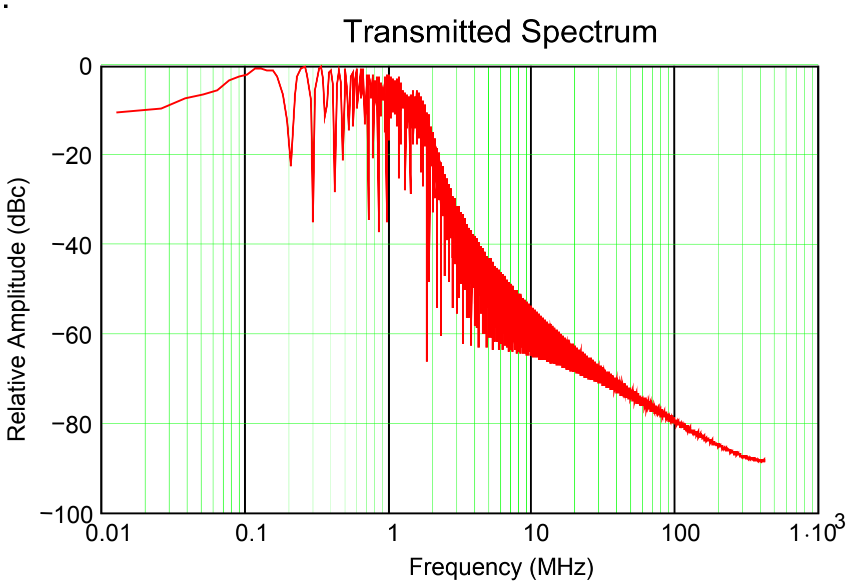


Figure 3.2.3-23 Radar Type C (with non-linear FM) Spectrum.



For radar Type C (S-Band solid-state) with a linear 1 MHz FM frequency sweep:

Transmitted pulse length = 100 μs

Pulse sweep Bandwidth = 1 MHz

Time Bandwidth product = 100

Therefore the 100μs pulse can be compressed to 1.0μs, giving a 150 metre range cell size.

Figure 3.2.3-24 shows the sweep law for this radar and Figure 3.2.3-25 shows the generated spectrum.

Figure 3.2.3-24 Radar Type C (with linear FM) Sweep Law

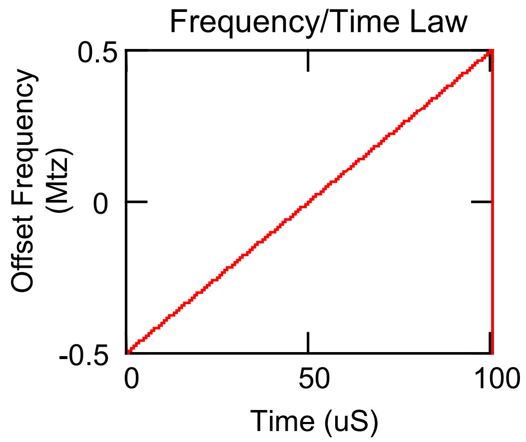


Figure 3.2.3-25 Radar Type C (with linear FM) Spectrum.

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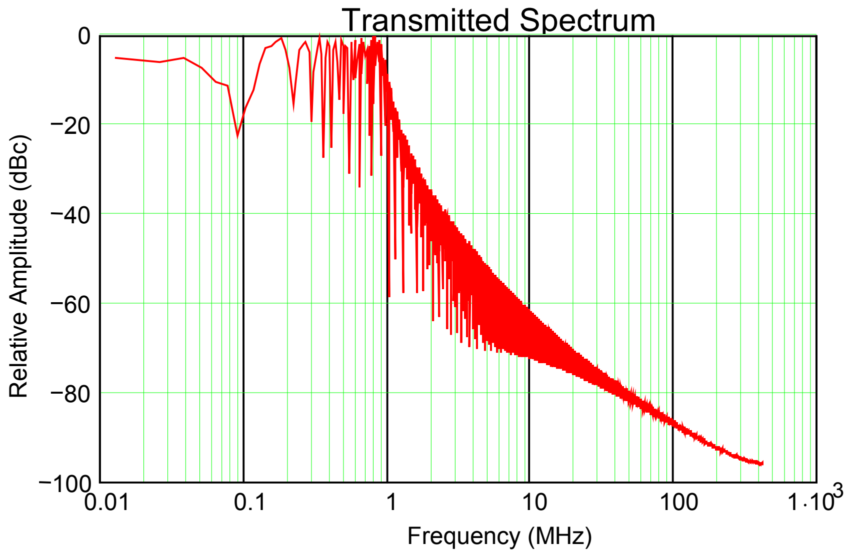


The wider 2 MHz sweep raises the 2.9 GHz spectrum level by 2 dB to -68 dB, and the 1MHz linear sweep produces a result similar to that of the non-linear 1 MHz FM.

Table 3.2.3-1 -20dB, -40dB, -60dB and -80dB Frequencies for each Radar type.

Radar Type	Spectrum	-20 dB	-40 dB	-60 dB	-80 dB
Type A	20 μs pulse 2.5 MHz non-linear sweep	2.975 MHz	7.387 MHz	35.91 MHz	-
Type B	73.5 μs pulse 2.03 MHz non-linear sweep	2.278 MHz	4.48 MHz	16.87 MHz	122.52 MHz
Type C	100 μs pulse 1.0 MHz non-linear sweep	1.114 MHz	2.394 MHz	7.987 MHz	43.738 MHz
Type C with non-linear FM	100 μs pulse 2.0 MHz non-linear sweep	2.214 MHz	4.211 MHz	15.296 MHz	109.85 MHz
Type C with linear FM	100 μs pulse 1.0 MHz linear sweep	1.216 MHz	2.534 MHz	8.666 MHz	49.19 MHz

The various bandwidths of the spectra are compared in Table 3.2.3-2 below

Table 3.2.3-2 Comparisons of Various Bandwidths of Compressed Pulse Spectra

Type	Chirp 3dB Bw	Pulse Width T	T x Bw	20dB Bw	20dB /3dB	40dB Bw	40dB /3dB	60 dB Bw	60dB /3dB	80 dB Bw	80dB /3dB	40dB /20dB	60dB /20dB	80dB /20dB
	MHz	μs	Product	MHz	Ratio	MHz	Ratio	MHz	Ratio	MHz	Ratio	Ratio	Ratio	Ratio
NL	2.50	20.00	50.00	2.98	1.19	7.39	2.95	35.91	14.36			2.48	12.07	
NL	2.03	73.50	149.21	2.28	1.12	4.48	2.21	16.87	8.31	122.52	60.35	1.97	7.41	53.78
NL	1.00	100.00	100.00	1.11	1.11	2.39	2.39	7.99	7.99	43.74	43.74	2.15	7.17	39.26
NL	2.00	100.00	200.00	2.21	1.11	4.21	2.11	15.30	7.65	109.85	54.93	1.90	6.91	49.62
L	1.00	100.00	100.00	1.22	1.22	2.53	2.53	8.67	8.67	49.19	49.19	2.08	7.13	40.45

The longer the time bandwidth product, the more "rectangular" is the spectrum based on the ratio of the chirp to the 20, 40 & 60 dB bandwidths and the ratios of the 40 and 60 dB bandwidths to the 20 dB bandwidth. There is an indication that the non-linear chirp is better, however it is not quite comparing 'like with like' as the compression ratio is not exactly equivalent for the same chirp bandwidth.

If this data is compared to un-modulated pulses of similar bandwidth:

An un-modulated pulse has a 3 dB bandwidth of approximately 1/t

B_N approximately B_{-20} bandwidth is given from below:

$$B_N = \frac{1.79}{\sqrt{t \cdot t_r}} \text{ or } \frac{6.36}{t}$$ Equation 3.2.3-1

The 20 to 3 dB ratio is 6.36:1, compared to < 1.2:1 for the chirped pulses.

For non-FM pulse radars, including spread spectrum or coded pulse radars, the B_{-40} bandwidth is the lesser of:

$$B_{-40} = \frac{K}{\sqrt{t \cdot t_r}} \text{ or } \frac{64}{t}$$ Equation 3.2.3-2

where the coefficient *K* is 6.2 for radars with output power greater than 100 kW and 7.6 for lower-power radars and radars operating in the radionavigation service in the 2 900-3 100 MHz band.

For trapezoidal pulses, the B_{-20} and B_{-40} bandwidths depend on the pulse rise time but comparing these two bandwidths gives a ratio between 3.5:1 for $K = 6.2$ to 4.2 :1 for $K=7.6$. This compares to approximately 2:1 for the chirped pulses.

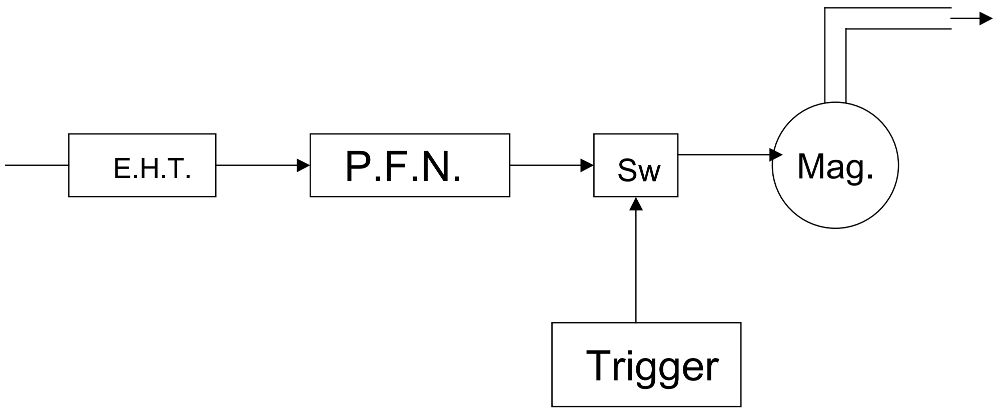
In all cases the spectra of chirped pulses are considerably narrower than those of unmodulated pulses with the same range resolution, whose 3dB beamwidth is approximately 1/t.

The longer pulses have a better spectrum utilisation, but this is at the expense of a longer blind range while the radar is transmitting which has to be covered by a short range fill in pulse. This has to be on a different frequency to the main pulse to keep the radar echoes from the two pulses separate. In the limit, a long range radar with a solid-state transmitter may need to transmit a long pulse, whose short range eclipsed region is covered by a shorter pulse, which in turn has its eclipsed region covered by a further, shorter pulse to provide detection coverage down to the minimum range.

3.2.4 Magnetron Transmitters

Magnetron tubes have been used in radar transmitters for 60 years. They readily produce high peak power, from a device that is basically simple and low cost. They produce pulses of fixed duration at a fixed frequency, but with a random starting phase. Figure 3.2.4-1 shows the block diagram of a magnetron transmitter. To ensure that a magnetron starts in the correct mode, it must have the correct rate of rise of the cathode voltage; too fast a rise rate and the magnetron will not start to oscillate, too slow a rise rate and a lower current mode may be excited. This limits the pulse shaping that can be applied for the purposes of minimising the emitted spectrum.

Figure 3.2.4-1 Magnetron Transmitter Block Diagram



Magnetrons will also produce a noise output following the wanted output pulse if the rate of fall of the modulating pulse is too slow, or if the pulse does not drop cleanly to zero volts.

As well as the desired output, magnetrons produce significant amount of spurious noise. However the resonant cavities in a magnetron suppress the noise that is not near the operating frequency, except for the harmonics.

Magnetrons also radiate significant energy in the VHF and UHF bands from the cathode stem. This does not couple into the waveguide antenna feed, and will be contained if the transmitter is suitably shielded.

The magnetron frequency will drift with changes in the ambient temperature, and with changes in the anode current. Control of the cooling and a stabilised modulator will minimise the frequency drift when the magnetron is operating.

When a Magnetron is first switched on, it will be at ambient temperature and a heater current will be applied to heat the cathode to cause electrons to be emitted to start operation, but the anode will initially remain at or near the ambient temperature. However, when the anode current is applied, the magnetron starts to oscillate and produce the RF output. Once fully operating, the anode will have heated up and cooling (either water or air) will be applied to the magnetron to maintain it at its operational temperature. Back bombardment occurs during operation and heater power is reduced as a function of the duty cycle to prevent overheating of the cathode.

As the anode heats up it expands and the resonant cavities enlarge reducing the resonant frequency. The maximum drift is within the first few minutes and then slowly approaches equilibrium over a period of 10 to 30 minutes depending on the magnetron type. This drift will occur not only at startup but also when the pulse duration, PRR or duty cycle is changed.

The time from switch-on to thermal equilibrium varies widely with magnetron type, due to their different sizes and thermal mass. Typical temperature sensitivities for a number of magnetron types are shown in Table 3.2.4-1. The physical size of the resonators in a magnetron is fixed by the frequency and limits the anode and cathode sizes. This limits the heat dissipation and power output capabilities of the magnetron.

Table 3.2.4-1 Magnetron temperature sensitivity

Frequency	Model	Temperature sensitivity
L-Band	M586	-0.035 MHz/°C
S-Band	M5162	-0.07 MHz/°C
S-Band	M5170	-0.07 MHz/°C
X-Band	M5149	-0.25 MHz/°C
X-Band	M5592	-0.25 MHz/°C

Using the information contained in Table 3.2.4-1, it can be calculated that an S-Band pulse magnetron heating up from an ambient of 15°C to an operating temperature of 80°C will have a change in frequency of -4.55 MHz.

Other factors that may affect the output frequency of a magnetron are the VSWR load on it and the anode voltage level.

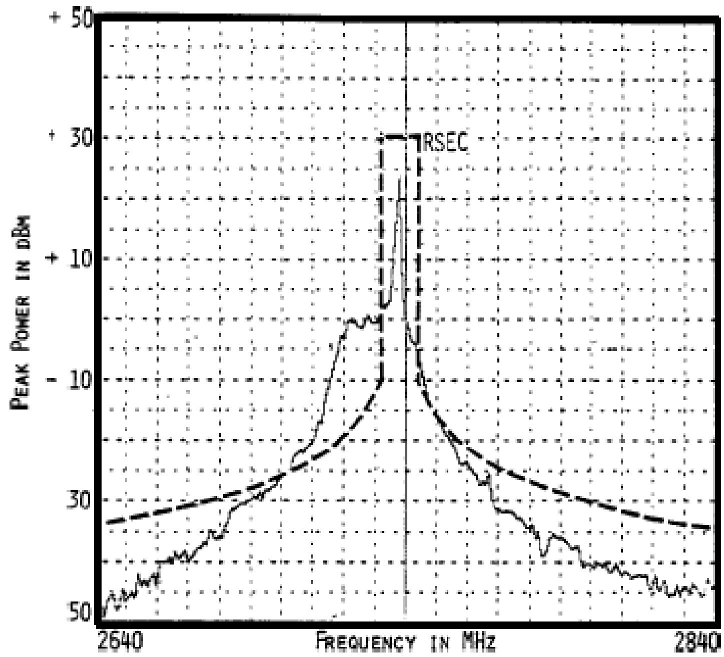
To minimise the variation in magnetron output the modulator must provide the required high voltage pulse shape. Most magnetron transmitters employ a line type modulator, consisting of a charging circuit, Pulse Forming Network (PFN) and a switch. The L and C passive elements of the PFN determine the shape and duration of the pulse. Magnetrons present a non-linear load to the PFN and therefore additional circuits for de-spiking and damping are required.

The peak charging voltage in the PFN must be closely controlled because a 1 percent change in the peak charging voltage will produce a 2 percent increase in the power delivered to the magnetron. For this reason clipper circuits are added to the modulator to control the energy stored in the PFN, despite variations in the charging voltage or the pulse repetition rate.

Some radar transmitters, such as those used on ships, require a number of pulse lengths, short ones for short range high range resolution use, and longer pulses for long range use, where higher energy is needed to achieve detection at the longer ranges. This is achieved by the switching sections of the PFN in or out of circuit.

The design of the modulator must minimise any droop in the pulse to prevent intra-pulse frequency change. Similarly any ripple on the high voltage power supply will cause inter-pulse frequency modulation.

Figure 3.2.4-2 Conventional Magnetron Spectrum With Porch [6]



The spectra of conventional magnetrons show a "porch". This is a plateau region before the peak of the main pulse spectra. Figure 3.2.4-2 shows the spectrum of a FPS-90 radar which uses a conventional magnetron[7]. It is caused by the anode-cathode voltage which "pushes" the frequency as the current rises; it is also less stable than the main pulse showing a pulse to pulse variation of up to 10 dB. Starting a magnetron in the proper mode requires the proper rate of rise of the magnetron anode-cathode voltage. The limits on this depend on the tube starting time and the closeness of other modes. Too fast a rate of rise may even result in failure to start at all. Starting time is approximately $4Q_L/f_o$, where Q_L is the loaded Q of the magnetron. This indicates that it is difficult to use high power low frequency magnetrons for short pulse lengths. The risetime is chosen to minimise the porch while ensuring that the magnetron starts in the correct mode each time.

Magnetrons for radar use are available from a range of manufacturers with a wide range of parameters. Typical parameter ranges are given in Table 3.2.4-2

Table 3.2.4-2 Magnetrons

Band	Peak Power	Pulse Length	Duty Cycle
L	40 kW– 2.2 MW	0.5 – 4.5 μs	0.0005 – 0.002
S	500 kW – 1.0 MW	0.5 – 6 μs	0.0005 – 0.002
C	200 kW– 300 kW	0.2 – 2.5 μs	0.0006 – 0.001
X	1 kW – 225 kW	0.4 – 4.0μs	0.0001 – 0.0033

[6] RSEC = Radio Spectrum Engineering Criteria, see Chapter 5 "Spectrum Standards", NTIA Manual of Regulations & Procedures for Federal Radio Frequency Management (January 2000 with May/September 2000 revisions)

[7] NTIA Report 82-92

3.2.4.1 Magnetron Ageing

Magnetron oscillators depend on the physical nature of the cavity to control the RF emissions and in particular the frequency of the fundamental oscillation, unwanted emissions and the Π_{-1} mode. The Π_{-1} mode is a short-lived spurious oscillation that occurs at a frequency above the fundamental oscillation.

In use, the cavity undergoes changes leading to the phenomena of ageing. The fundamental output frequency drifts and the spectrum deteriorates leading to increased unwanted emissions, particular an increase in Π_{-1} emissions.

The effect that the ageing has on the system depends on the specific type of radar. How much ageing can be tolerated depends on how sensitive the system is to the effects and, to some extent, how closely the performance of the system is monitored. In some systems the gradual deterioration can go unnoticed until the tube fails catastrophically.

During the 1990's, the UK Met Office noticed inconsistencies between radars in their weather radar network which was caused by the ageing of the conventional magnetrons originally fitted[8]. In an attempt to improve the situation, the Met Office modified their systems by introducing coaxial magnetrons.

Figure 3.2.4-3 shows measurements made by the UK Met Office of a conventional magnetron at installation and after 3 months. The frequency shows a drift of 0.5 MHz and the spectrum has deteriorated.

Figure 3.2.4-3 Conventional Magnetron before and after 3 months [8]

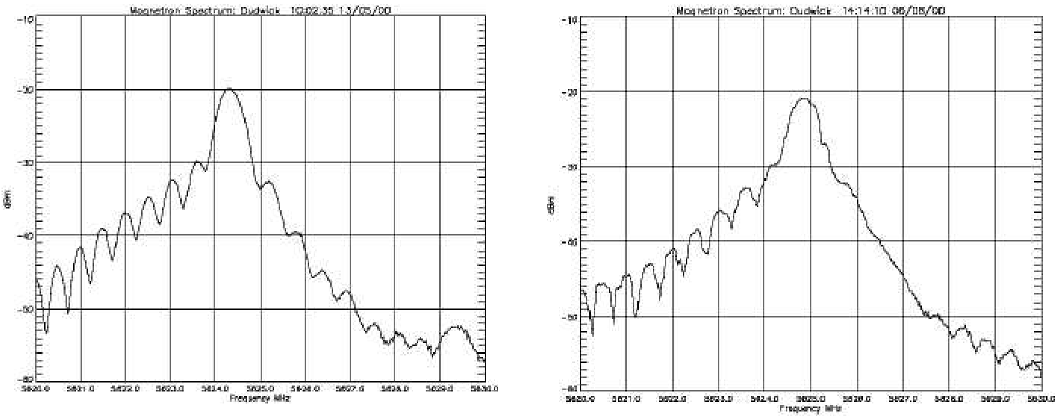
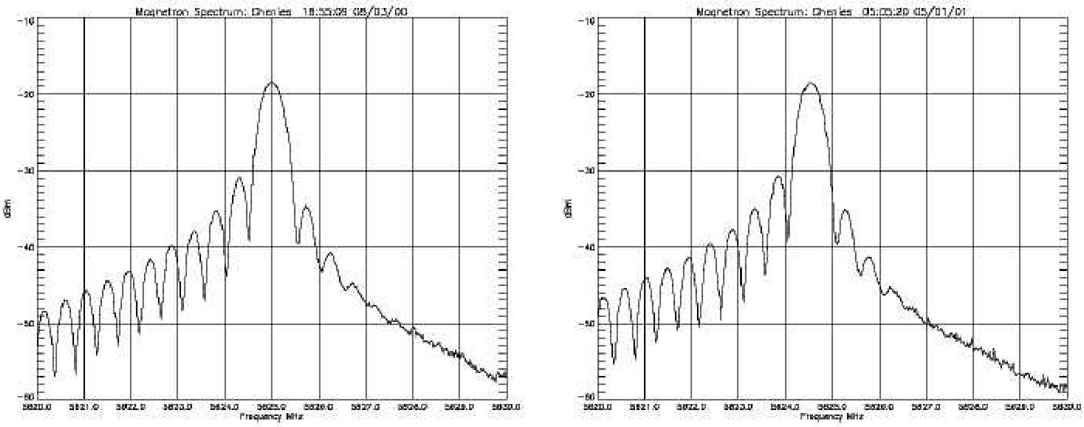


Figure 3.2.4-4 shows measurements made by the UK Met Office of a coaxial magnetron after 9 months, this shows there is still some frequency drift but the spectrum has been maintained.

8 Transmitter Issues in the UK Weather Radar Network: AMS 61st Annual Meeting, Workshop on Radar Calibration.

Figure 3.2.4-4 Coaxial Magnetron before and after 9 Months [8]



As well as changing to coaxial magnetrons, the UK Met Office also instigated a comprehensive monitoring system.

It is important to know the actual magnetron drift as allowance for it must be made in the frequency planning of the radar.

3.2.4.2 Coaxial Magnetrons

Coaxial magnetrons have a resonant stabilising cavity with a high Q surrounding the anode and coupling the anode to the output port. In a coaxial magnetron the major proportion of the energy (~ 80%) is stored in this resonator instead of in the anode cavities. This reduces the stress on the anode and cathode giving a longer life and higher reliability. The high Q of the cavity controls the frequency and provides a more stable output with an improved spectrum and reduced spurious emissions.

Coaxial magnetrons are not suitable for producing very short pulses (less than 0.2μs) due to the high Q of the resonant cavity and the energy stored in it. They are generally available for C-Band and above as stabilisation with a cavity of acceptable size is more practical at these frequencies. It is also of more importance because the effects of pushing and pulling are more significant at these higher frequencies. Coaxial magnetrons do not have the porch of conventional magnetrons, but they do show a noise "hump" about 100MHz above the fundamental frequency; this may exceed the spectrum mask level.

Figure 3.2.4-5 WSR-74C Radar, Coaxial Magnetron [9]

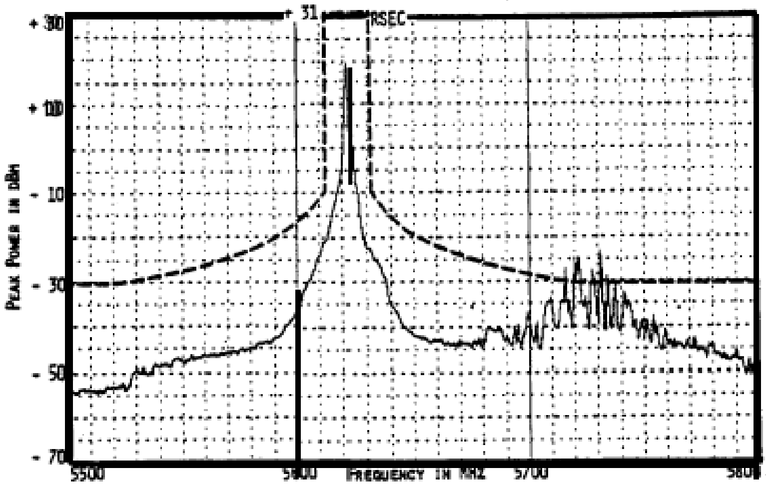


Figure 3.2.4-5 shows the spectrum of a coaxial magnetron in a C-Band weather radar. This shows the "hump" about 100MHz above the fundamental frequency.

Table 3.2.4-3 Coaxial Magnetrons

Band	Peak Power	Pulse Length	Duty Cycle
C	250 kW & 1000 kW	0.2 – 3.0 µs	0.001
X	3.3 kW – 350 kW	0.25 – 2.0µs	0.0002 – 0.001

[9] RSEC = Radio Spectrum Engineering Criteria.

3.2.5 Driven Tube Transmitters

There are three main types of amplifier tubes

- Cross-Field Amplifiers (CFAs)
- Klystrons
- Travelling Wave Tubes (TWTs)

The choice of output tubes for a particular radar is a complex issue, and in many cases good spectral qualities may be outweighed by other features which conflict with the requirements for that radar.

The peak power capabilities of RF tubes have progressed to a state where the limitation has become the breakdown and arcing in the waveguide system, even when pressurised by dry air or an insulating gas. Radars have therefore used an increase in the duty cycle to achieve higher average power without any increase in the peak power. Pulse compression of a coded transmitted waveform is used to achieve good range resolution.

3.2.5.1 Cross-Field Amplifiers

These have high efficiency, small size and use a relatively low voltage. They also have relatively low gain, and so are usually driven by a medium power TWT. Such use of two tubes in cascade offers advantages in efficiency, operating voltage, size and weight. In addition, for low power operation the CFA may be turned off; it then becomes transparent to the drive signal, giving a choice of two levels of output power. Typical parameters for some CFAs are listed in Table 3.2.5-1.

Table 3.2.5-1 Cross Field Amplifiers

Frequency Band	Peak Power (kW)	Duty Cycle	Pulse Width µs	Spurious Noise dB below pulse peak output level
L	100	0.032	40	-40
L	1250	0.004	5.0	-35
S	60	0.028	36.0	-35
S	660	0.015	0.015	-40
S	2200	0.0056	28.0	-30
C	500	0.02	45.0	-40
X	300	0.004	1.5	-35
X	500	0.0011	2.0	-35

To prevent the CFA from transmitting noise before and after the wanted transmit pulse the RF drive must be applied so that it straddles the modulator voltage pulse. This will cause the output pulse to sit on a pedestal due to the feed-through of the wider RF drive pulse. This transparency of the CFA is used in some radar systems to provide a low or high power transmitted pulse by switching the CFA on and off. An amplifier chain with a TWT followed by two CFAs will allow three levels of transmitted power. This transmit power level switching is used in some 3D radars where long range is required at low elevation angles, but only short ranges at high elevation scan angles.

CFAs share a number of the problems associated with magnetrons and the same preventive measures apply. However, because the RF drive pulse is present during the modulator voltage rise, there is little starting delay in the desired mode, and the pi-mode will produce little energy if the voltage rise passes quickly enough through the starting voltage range for this mode.

The pi-mode is a mode of oscillation in a magnetron (where it is wanted) and is unwanted in a CFA. In the pi-mode, the alternate segments between the resonant cavities are assumed to be at the same potential at the same instant, and an AC field is assumed to exist across each individual cavity. This mode is called the pi-mode, since adjacent segments of the anode have a phase difference of 180 degrees or one-pi radians. Whereas this mode is the most commonly used in a magnetron as it has a greater power output than other modes, the CFA is an amplifier and therefore any tendency to oscillate must be avoided or suppressed.

3.2.5.2 Klystrons

Klystrons are used where high gain and high power are required. Unless carefully tuned, klystrons can produce significant harmonic power output. The bandwidth of a klystron increases as the RF power level being generated increases because the stronger beam provides heavier loading of the cavities in the klystron. Figure 3.2.5-1 shows the block diagram of a klystron transmitter. Typical parameters for some klystrons are listed in Table 3.2.5-2.

Figure 3.2.5-1 Klystron Transmitter Block Diagram

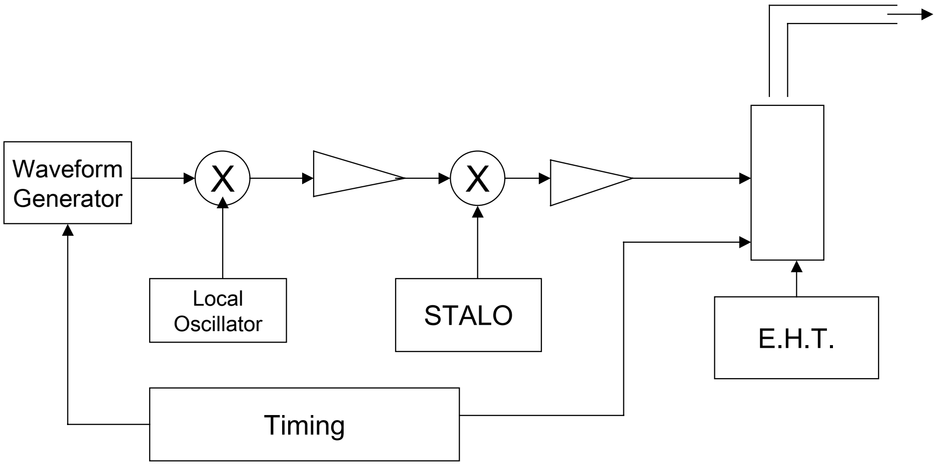


Table 3.2.5-2 Klystrons

Frequency Band	Peak Power (kW)	Average Power (kW)	Max. Pulse Length (μs)
L	3500	6	8
L	4000	8.5	8
S	1500	1.5 – 2.7	3 - 5
C	1000	NA	NA
C	250	NA	NA
X	120	NA	NA
X	50	NA	NA

One manufacturer has developed the Twystron, a combined TWT and klystron which has greater efficiency and wider bandwidth than the broadband S-Band TWT on which it is based.

Klystrons with broadband clustered cavities have output bandwidths of up to 20 percent. Although more complex and expensive than a normal klystron, the clustered cavity klystron is less complex and less costly than a comparable TWT or Twystron.

Klystrons operate at approximately twice the voltage of CFAs for the same output power; this has cost implications.

3.2.5.3 Travelling Wave Tubes (TWTs)

Travelling wave tubes are used in transmitters where wide bandwidth is required and where the very high power of a klystron is not required. TWTs are often used as the driver stage of a high power klystron transmitter. Figure 3.2.5-2 shows the block diagram of a TWT transmitter.

Slow wave helix TWTs permit bandwidths in excess of 100% but are limited in output power to a few kilowatts. Higher power tubes have narrower bandwidths and may have band edge oscillation problems.

Figure 3.2.5-2 TWT Transmitter Block Diagram

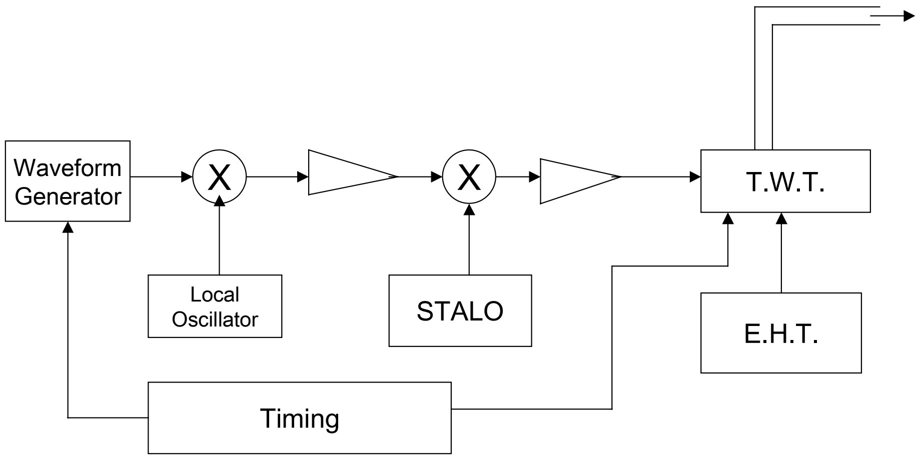


Table 3.2.5-3 Travelling Wave Tubes.

Frequency Band	Peak Power (kW)	Average Power (kW)	Duty cycle (max.)
L	140	6.0	0.036
S	58	1.3	0.025
S	170	2.4	0.014
C	8	2.4	0.03
X	30	0.25	0.0084
X	6	0.12	0.02

Slow wave structures in high power TWTs fall into two categories:

- Helix derived versions and
- Coupled cavity versions

Ring bar circuits derived from the helix version are used below 100 kW having broad bandwidth and better efficiency than coupled cavity TWTs which predominate above 200kW.

Coupled cavity TWTs that are cathode modulated will pass through a region during the rise and fall-times of the beam voltage where the beam becomes synchronous with the pi-mode of the TWT and it can oscillate. These oscillations occur at the leading and trailing edges of the RF output pulse. They are difficult to eradicate completely, but can be avoided by grid pulsing when the high voltage is above the oscillation range.

3.2.6 Solid-State Transmitters

The development of high power Solid-State (SS) devices capable of operating at microwave frequencies has led to the replacement of the output tube in a range of radar transmitters, particularly in ATC, airborne and defence radars. Solid-state transmitters fall into two categories:

- Replacement of the high power tube in a radar by a set of SS modules whose outputs are combined to feed the antenna (Corporate-combined). Figure 3.2.6-1.
- Active phased array radars where the each transmit module feeds an antenna element in the array face (Space-combined). Figure 3.2.6-2.

Figure 3.2.6-1 Corporate-Combined Solid-state Transmitter Block Diagram

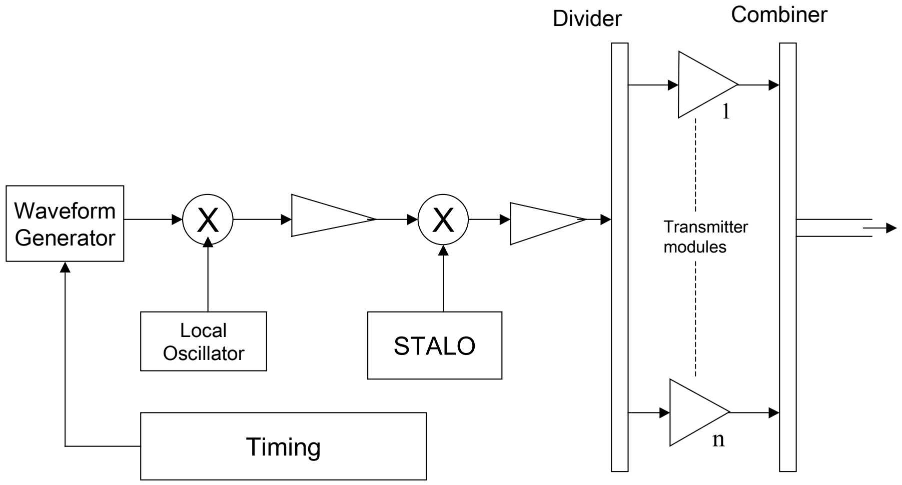
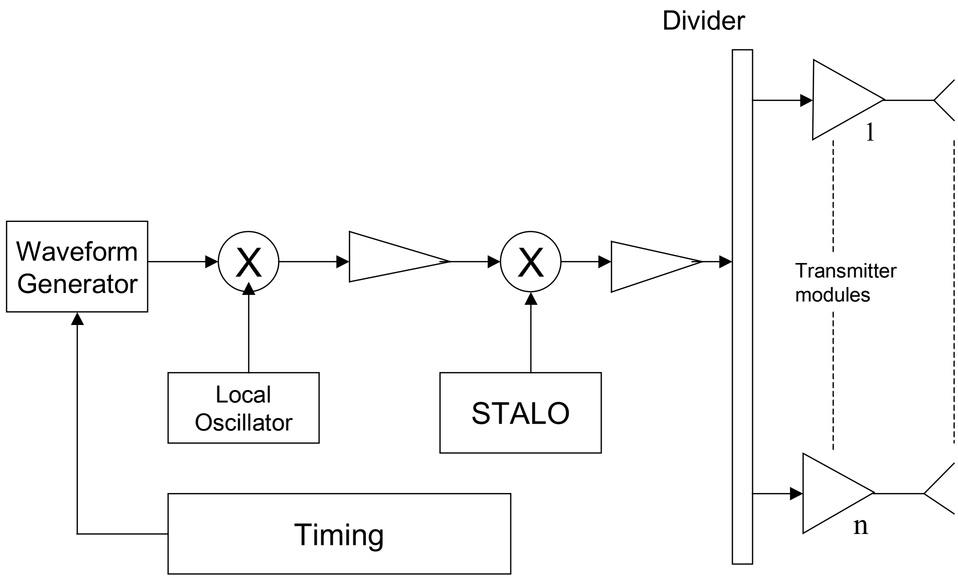


Figure 3.2.6-2 Space-Combined Solid-state Transmitter Block Diagram



Hybrids of the two categories are also in use where corporate-combined modules feed the rows of a space-combined array.

The advent of solid-state transmitters has necessitated a change in the operating characteristics of radar. Solid-state modules are average power limited devices while tubes are typically peak power limited devices. The short pulse lengths and high peak powers of tube transmitters cannot be directly replaced by solid-state transmitters that can provide a lower peak power at a higher duty cycle. To achieve the same mean power, system designers now choose as high a duty cycle as possible to reduce the peak power requirement.

To maintain the required range resolution the transmitted pulses are coded by a swept frequency. In the receiver these long pulses are compressed to achieve the range resolution; a typical radar transmits 100μs long pulses which are compressed down to 1μs. This compression also increases the signal to noise ratio. The radar cannot receive while it is transmitting so is blind for the first 100μs (15 km). To cover this close in region the transmitter also transmits a short pulse of 1 to 5μs interleaved with the long pulses. To prevent interference between these two sets of pulses, they are transmitted on two different frequencies.

However this does not increase the frequency allocation requirements in every case because ATC magnetron radars often have dual transmitters to meet the Mean Time Between Failures (MTBF) and reliability requirements. Comparable SS radars have a single transmitter with multiple modules providing graceful degradation coupled with higher reliability.

In an active phased array each antenna element is combined with a transmit/receive module. The modules include phase shifters, which are used to steer the combined antenna beam by up to a maximum of 60 deg off the axis of the antenna face. Land and sea based phased array radars are so far confined to the military, due to their cost.

The transistors used in the modules operate in class-C mode and are not suitable for amplitude shaping of the output pulses to improve the spectrum. Solid-state amplifiers typically have rise and fall-times in the order of 120 to 200ns. This slower risetime, compared with magnetrons and driven tubes, will improve the spectrum occupancy.

However, the modules could also be turned on and off in a sequence to produce the required output pulse rise and fall-times. This is applicable in the case of the corporate fed transmitter, but in the case of a phased array radar the required beam-shape and its associated sidelobes are not formed until the majority of the modules are transmitting.

3.2.7 Mitigation Options Available to Antennas

3.2.7.1 Introduction

This section discusses the suppression of unwanted emissions in the spatial dimension.

The radar antenna is used to couple energy from the transmitter into free space and thus it directly controls the spatial distribution of the transmitted signal. The antenna can concentrate the energy in the wanted direction and suppress the energy in unwanted directions. In antenna terms the wanted direction is normally referred to as the main beam, and the unwanted direction the secondary or sidelobes. One area of secondary lobes that are sometimes forgotten is that of cross-polarised radiation.

The antenna main beam characteristics, in terms of beamwidth and gain, is generally set by the radar system's detection and resolution requirements and is a given requirement. Thus interference caused by the main beam will not be discussed in this section. Section 3.3.2.1.2 (Main Beam Sector Blanking) discusses some issues associated with main beam coupling. Notwithstanding this it is generally the case that the reduction of main beam interference in a direction the radar is required to operate can only be achieved at the expense of loss of radar performance. This is not the case in the directions of unwanted radiation as by definition the radar requires no performance in these directions and the ability to detect targets in unwanted directions is a positive disadvantage. Thus the suppression of radiation into secondary directions is a benefit from both the interference and the radar performance viewpoints.

Scanning radars, either electronically or mechanically scanned, need to point their beams in a given direction. The processing generally assumes that detection produced by the system comes from a target that is essentially within the main lobe of the antenna and hence its azimuth position can be related to the electrical pointing direction of the antenna. This may or may not be related to any mechanical reference but providing the system has knowledge of any differences this is not an issue. The width of the main lobe and any subsequent bearing uncertainties are a system issue and outside the scope of this section. The problem occurs when a detection is made coming from a direction not associated with the main lobe of the radiation. In this case the processing assumes the reply is coincident with the pointing direction of the main beam and ascribes that azimuth to the detection.

This problem is best illustrated by the phenomena known as "ring around". This occurs when radars are operating in the presence of very large reflections such as cliffs or very large ships. In this case the echo is so large that the gain of the antenna even in the unwanted direction is large enough to allow the target to exceed the detection threshold. The result is that the target presents on the display as a continuous ring; the antenna not being capable of providing sufficient spatial discrimination. Whilst there are techniques within the receiver and processing that can mitigate the effect the primary solution is to reduce the antennas secondary lobes.

Thus, to the radar designer, the reduction in unwanted radiation is a key part of the antenna specification.

3.2.7.2 Azimuth Sidelobes

Sidelobes are caused by the radiation from a finite aperture and are related to the size of the aperture vs. the beamwidth of the radiation required from that aperture.

A uniformly illuminated rectangular aperture is analogous to a rectangular pulse in time and it produces a Sinx/x distribution in space as the pulse does in frequency. The uniformly illuminated aperture gives the narrowest beam width and hence the highest gain. It does however, like the rectangular pulse, produce high sidelobes. A rectangular aperture has a far-field pattern with its first sidelobe at -13 dB below the main lobe peak. A uniformly distributed circular aperture has slightly lower first sidelobes at around -17 dB but has consequentially a wider beam.

Generally for most radar applications, certainly on receive, much lower sidelobes are required to prevent problems such are ring around and associated false detection incidents. However it needs to be noted that the radar system operates on a two-way transmission and to some extent poor transmitted sidelobe can be compensated for by very good receiver sidelobe. An example of this is a phased array radar where all the elements are fully energised on transmit, giving a beam with a certain level of sidelobes. On reception an amplitude weighting is applied across the phased array aperture giving lower sidelobes at the expense of a broader receive beam. The lower receive sidelobes reduce the effect of any interference received through the sidelobes. The radar performance is governed by the combined transmit and receive antenna patterns.

Active arrays tend to make use of this fact because of the difficulty of controlling sidelobes produced by an array of modules operating in Class C (saturation).

The reduction in sidelobes may be accomplished by providing a taper on the aperture illumination function. In reflectors this is accomplished by a combination of feed design and geometry, and in arrays by so-called beamforming networks.

The antenna designer trades off the level of the sidelobes against the desired beamwidth and its consequential gain. The rule is generally that the lower the sidelobes that are required from a given aperture size then the wider the beamwidth that results and the lower the gain that is achieved for a given elevation coverage requirement.

However errors in the application of the taper can give rise to sidelobes well above the design level. Systematic errors due to beamforming manufacturing errors or periodic or systematic reflector distortions can give rise to specific sidelobes in defined directions. Truly random manufacturing errors generate "noise"-like sidelobes that effectively set the limit on how low in practice the sidelobes can go.

In the limit it is possible to design a distribution that has "no" secondary lobe, The Gaussian is the best known, but it has a very wide beamwidth for the given aperture. It would need to be truncated if the aperture is not to become excessively large and this truncation produces some sidelobes.

Gaussian beams do not generally find an application in radar antennas, however, they are used in Quasi-optical antenna systems where the size of the antenna and feed are very large in electrical terms; such as large satellite ground stations or radio telescopes etc. However as radar moves into the mm wavebands the application of Gaussian beams may be possible.

3.2.7.3 Reflector Antennas

In a reflector antenna the azimuth sidelobes are produced by a series of sources:

The antenna taper:

The feed horn design and the geometry of the reflector set the basic beamwidth and close in sidelobes[10]. Any distortion of the reflecting surface away from the ideal will cause unwanted lobes to occur.

This is not the case in Cassegrain or other multi-reflector systems however these designs are rare in civil applications.[11]

[10] This can be seriously affected by feed blockage but it assumed that all the current antennas are off set designs that avoid this problem.

[11] The AMS WF 3 system used a Cassegrain design with a spinning sub-reflector but the use of these systems in the UK has ceased.

Feed radiation:

Direct radiation from the feed adds to the radiation coming off the reflector. Due to the difference in gain between the two this has only a little effect in the forward direction but can dominate at angles approaching and greater than 90° from the boresight.

Scatter:

Scatter tends to dominate in the rearward direction where the feed radiation is blocked by the reflector, this principally scatters from the edge of the reflector and its level is related to edge taper. Poor mechanical design can also contribute to scatter in other directions.

Reflector Porosity:

Many systems use reflectors made of mesh. This is generally done to reduce the weight of the antenna and is a big issue in tactical systems.

Depending on the pitch, the mesh allows a finite amount of energy to pass through and hence to radiate backwards. In some antennas this can dominate in the back-lobe region.

The control of the sidelobes is thus dependent upon the initial design, followed by control of the manufacturing tolerances. In the period covered by radars presently in service great strides have been made in the ability to model reflectors electro-magnetically. The ability to design and control the sidelobe performance of reflectors is now such that very few manufacturers build prototype antennas. Improvements in manufacturing and use of carbon fibre as a reflector medium have resulted in much more repeatable designs.

It can now be said that for modern reflector antennas the secondary radiation is now "wanted" in so much as it is predictable and can be accurately specified. However, when deciding on the level of such radiation and how much it should be reduced by the design, the radar system requirements are still the design drivers and these may differ in the future regarding interference suppression requirements.

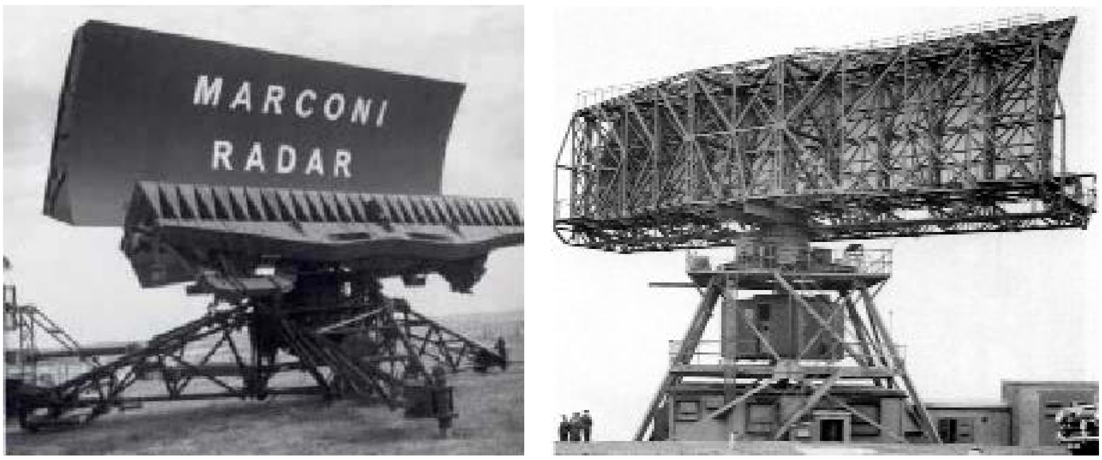
Historically doubly curved reflectors for ATC roles achieved sidelobes below the main lobe of 20 to 23 dB close to the main beam falling to 30 to 45 dB in the far-out regions.

Modern designs can achieve sidelobes below the main lobe approaching 30 dB close in, falling to 45 dB in the far-out regions. Figure 3.2.7-1 shows a modern low sidelobe reflector used for ATC purposes.

Figure 3.2.7-1 Watchman S ATC Radar

There is an option that has been used in military systems for many years to further reduce the unwanted radiation particularly in the rearward direction. This is the use of the cylindrical reflector. In this design, the reflector is fed by a linear array to form the azimuth pattern and is shaped in the vertical plane only to produce the required elevation coverage. These antennas can achieve extremely low far-out sidelobes. Designs have been demonstrated using solid reflectors with back lobes in excess of -60 dB relative to the main lobe.

Figure 3.2.7-2 Examples of Singly Curved Reflectors



Due to the complicated nature of the feed, these antennas are more expensive than double curved designs, in the order of 1.5 to 2 times. Whilst they can be made to operate in fixed Circular Polarisation (CP), it is difficult to produce a switchable polarised antenna that gives good CP.

3.2.7.4 Phased arrays

In a Phased array antenna the azimuth sidelobes are produced by a series of sources:

The aperture taper:

This is achieved by using a beamforming network to feed the array elements. Any error in the beamforming network or the flatness of the antenna face will cause unwanted lobes to occur.

Scatter:

The truncation of the array at the edges can set up currents that can radiate from the edge of the array. This effect is seen most in electrically small antennas and linear arrays. Radomes can also lead to scatter and the formation of flash lobes in mechanically scanning systems. These are due to double reflections in the radome producing antenna lobes momentarily in unwanted directions.

Array Porosity:

Some types of arrays are porous and do not use a continuous ground plane. This is generally done to reduce the weight and wind loads on the antenna. The LVA antennas used for SSR are examples of this type (as shown in Figure 3.2.7-1).

The ground plane allows a finite amount of energy to pass through and hence to radiate backwards. In some antennas this can dominate in the back-lobe region.

In civil systems, array antennas are traditionally used in the following applications:

- maritime surveillance,
- VTS,
- airborne weather,
- X-Band ASDE,
- PAR.

The extension of array technology into applications currently fulfilled by reflectors (i.e. ATC, Ku-Band ASDE, Ground weather) is generally considered to be too expensive unless there is a definite need generated by the radar system design, that can not be accommodated in other ways. The adoption of array technology in order to reduce the unwanted emissions is as yet not considered a cost-effective approach. In large planar arrays currently used by the military, close in sidelobes of less than 30 dB can be achieved falling below 50 dB in the far-out region.

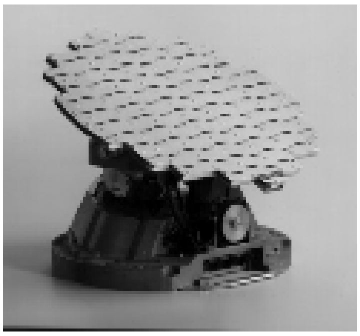
The smaller linear open array systems used by marine, VTS and ASDE, cannot achieve the low level far-out sidelobes, fundamentally due to a lack of aperture. Some techniques do exist such as dielectric lenses, flares & chokes, however whilst these give some control of the elevation beamwidth they do not substantially reduce the back-lobe. Table 3.2.7-1 below gives a list of the published performance of a set of open array scanners.

Table 3.2.7-1 Open Array Scanner Sidelobe Levels

Width	**Frequency**	**Azimuth**	**Elevation**	**Sidelobes at <+/- 10 deg**	**Sidelobes[12] at > +/- 10 deg**
Feet	Band	BW deg	BW deg	dB	dB
2[13]	X	3.9	25	22	22
4	X	1.85	25	22	22
6	X	1.15	25	25	25
6.5	X	1.23	25	24	30
6.5	X	1.23	20	28	32
8	X	0.95	20	28	32
10	X	0.75	20	26	30
12	S	1.9	25	25	30

The planar array scanners used in airborne radar can potentially achieve a better front to back ratio. The larger versions used in military radar can give very low sidelobes. The level of sidelobes that can be achieved in commercial systems falls as the antenna size reduces. Weather radar handbooks quote figures of 25 dB for small commercial sets. Figure 3.2.7-3 shows a weather radar antenna, and mount designed for general aviation use.

Figure 3.2.7-3 Airborne Weather Radar



These systems can however suffer distortion from the radome. The following quote is from a weather radar user guide[14]:

> *"Also note that there are small lobes of the gain characteristic at fairly large angles. These are called sidelobes. Generally these are not important since the gain value for these lobes is 25 or more dB from the peak. However a band radome can increase these sidelobes to a point that they cause a constant radar reflection from the ground . This is referred to as an "altitude ring" because the display will show a concentric ring at a distance equal to the slant range of the sidelobe to the ground."*

This is the airborne equivalent of ring-around and results from an increase in radiation towards the ground resulting in the potential for interference with ground systems

[12] For the smaller antennas usually only one number is given

[13] Radome scanner with patch array

[14] RDR 2100 Pilot's Guide Rev 1 Allied Signal

The problem of back lobe suppression is very significant on SSR systems. In civil use these systems use either a "hog-trough" antennas or LVAs. 14 foot & 28 foot hog-troughs are in use as are the 8m open arrays see Figure 3.2.7-4 and Figure 3.2.7-5 below.

Figure 3.2.7-4 ATC Radar Fitted with Hogtrough SSR Antenna

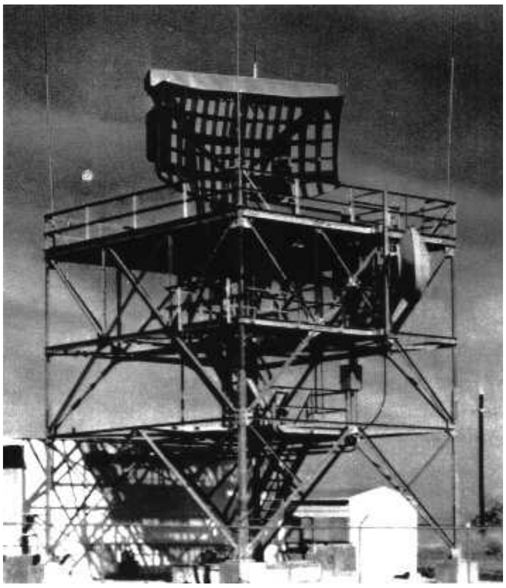


Figure 3.2.7-5 SSR LVA open array antenna

The hog-troughs suffer the same problems as the marine slotted waveguide antennas in that they have very little vertical aperture and thus they tend to produce large back-lobes. This is a particular problem for SSR because it is a transponder based system. The signal loss between the aircraft and the SSR antennas only falls off as $1/R^2$, unlike the $1/R^4$ in primary radars; SRR systems are thus much more likely to receive replies initiated by sidelobe interrogations.

In order to make the system less susceptible to this, an extra "control " pulse is added to the interrogation protocol. This control, or P2 pulse, is transmitted on a separate antenna[15] which has a approximately omni-directional pattern and whose gain is greater than the sidelobes but much less than the main beam of the interrogator antenna. The aircraft receives both pulses, compares their amplitude and only replies if it judges that it has

[15] In Figure 3.2.7-4 the auxiliary antenna can be seen as a white pole protruding vertically from the hog-trough.

received a main lobe interrogation. This system, which is called Integrator Side Lobe Suppression (ISLS), allows the system to operate with relatively poor antenna sidelobes.

Some 20 years ago problems with target tracking lead to the replacement of many of the civil hog-troughs with what are called LVA antennas. These have a much larger elevation aperture and are designed to reduce the illumination seen by the ground that was degrading the system. However in order to reduce the wind load on the antenna the open structure has been adopted. Figure 3.2.7-5 shows the close-up of such a system and it can be seen that the antenna is very porous, giving rise to high back lobes.

Hence in terms of reducing unwanted radiation, the SSR system is very poor. To date however this generally has not been an issue as the transmitters use very low duty cycle. The maximum duty cycle of an SSR interrogator is 0.1% with one third being fed to the control beam and two thirds to the interrogation beam; an interrogation consists of a set of 3 pulses where the 1st and 3rd are fed to the interrogation beam and the 2nd to the control beam. The peak powers used are around 2 kW giving a mean power of 2 watts.

However there is a new form of SSR coming into service. This is known as mode S. In the mode S system the transmitted duty cycle on the interrogation beam could eventually rise to 10% on average and in some small sectors, such as air-lanes, could reach 60%. This will give rise to a massive increase in unwanted emissions. The duty cycle on the control beam will also double but this is insignificant compared to the interrogation beam.

3.2.7.5 Elevation Pattern

The elevation pattern of the antenna is generally used to define the coverage of the system and to suppress ground reflections that could give rise to multi-path effects. It also has a role in suppressing back lobe radiation and defining the front to back ratio. In linear arrays the back lobe is an image of the array factor in the rearward direction. If the radiators that make up the array were omni-directional then the back lobe would have the same gain as the main lobe.

In an actual antenna, the radiators do however has some directivity by the nature of the structure so the back-lobe is suppressed by a factor related to the azimuth beamwidth of the array elements. However the elevation pattern also contributes to the suppression of the back lobe. A narrow elevation pattern will also add to the level of back-lobe that is achieved. In crude terms, the azimuth pattern of the element suppresses signals going around the sides of the antenna, whilst the elevation pattern suppresses signals going around the top and bottom. Antennas with larger elevation apertures have lower back lobes. If the antenna is porous however the situation is a little more complicated.

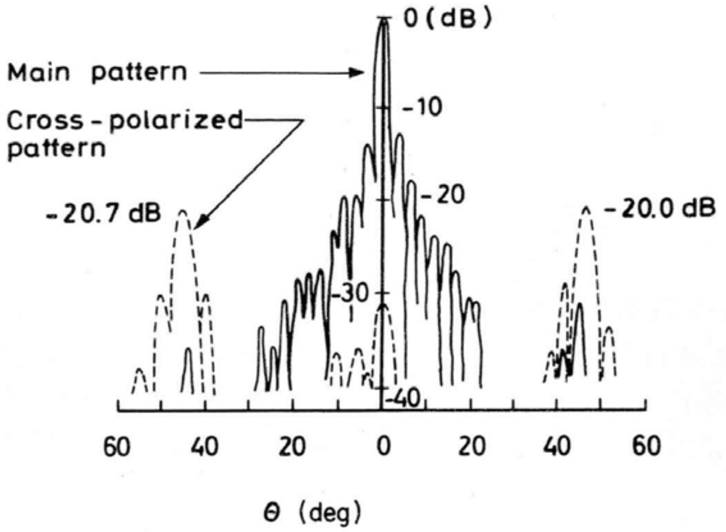
In order to reduce unwanted emissions in array antennas the array needs to be made bigger and less porous. Both these mitigation options would lead to larger and heavier antennas. Alternatively, the antenna could be protected by a radome. The topic of radomes are discussed below in section 3.2.7.7.

3.2.7.6 Cross Polarisation

All antennas generate cross-polarised energy which generally comes from imperfections in the feed structure or radiating elements. Normally it is at a low level and does not prove a problem in radar except when the property of polarisation is being used either to reduce interference or to aid clutter rejection.

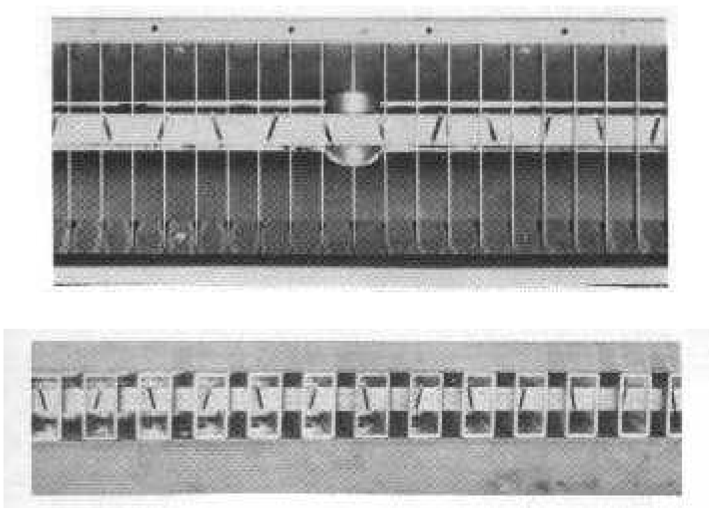
Some antennas however naturally generate high levels of cross-polar energy as part of their design. In order to radiate, narrow wall slotted waveguide antennas have to use slots that are inclined to the vertical if they are to radiate at all. Such slots naturally generate both co and cross-polar signals. The larger the slot incline, the more cross-polar content is produced. Generally slots are alternate left and right angled and this has the effect of cancelling out the cross-polar radiation on boresight. It does however cause the energy to add at approximately ± 45° in the azimuth plane. This can generate high levels of cross-polar sidelobes. Figure 3.2.7-6 illustrates this effect.

Figure 3.2.7-6 Generation of Cross Polar Side-lobes[16]



In order to suppress this cross polar pattern, grids or cavities can be added, Figure 3.2.7-7 shows two such structures.

Figure 3.2.7-7 Cross Polar Suppression Structures



3.2.7.7 Radomes

Antennas are sometimes covered by radomes particularly in areas where bad weather is likely. Radomes can distort antenna patterns and scatter energy.

Early radomes used metal space-frame designs which consisted of a metal framework with a thin fabric stretched over the structure. The metal structure was random in construction in order to break up any correlation and radiate the scattered energy isotropically. These radomes were very poor and led to tracking errors in monopulse systems. Later on dielectric space-frame radomes, where the metal struts were replaced by dielectric joints were developed. This improved the situation but still suffered from strut scattering.

The state of the art are the sandwich radomes, which are made up of panels that have strength in their own right and are joined by impedance matched joints. The radome is self-supporting and requires no space-frame.

[16] From 'Advances in Microwaves', published by Academic Press 1971

Water on the radome can add to the scattering and in order to reduce such effects, a hydrophobic coating is required to aid the shedding of water.

3.2.7.8 Structural Scattering

Figure 3.2.7-4 shows a typical ATC installation, the antenna is surrounded by support structures, safety rails, lightning rods, radio antennas etc. If they intersect the beam, these items will scatter the energy in all directions. In order to mitigate this, these items need to be removed from within the radar beam.

As an example of the level of scattering Table 3.2.7-2 shows the range at which scatterers of differing sizes have to be placed to isotropically scatter energy at the same level as the antenna side-lobes. The Radar Cross Section (RCS) shown in Table 3.2.7-2 is the bistatic RCS in the direction of scatter when illuminated by the radar.

Table 3.2.7-2 Range for equivalent scattered energy level

	Radar Cross Section		
Side-lobe	**1 m²**	**10 m²**	**100 m²**
dB	m	m	m
-30	9	28	89
-40	28	89	282
-50	89	282	892
-60	282	892	2820

3.2.7.9 Harmonic Radiation

At frequencies well above the operating frequency of the antenna the transmission characteristics of the antenna become undefined. Beams of arbitrary gain at arbitrary angles and polarisation can be produced. The best way to mitigate these effects is to prevent the transmission of these frequencies into the antenna, possibly by the use of a low-pass filter.

3.2.7.10 Beam Squint/Fill Time

Some types of antenna designs squint with frequency, this issue is covered in section 3.1.1.

Squinting antennas are generally made up from travelling wave feeds, antennas using these components or serpentines or slow wave structures can also suffer from "fill-time". This effect generally only occurs on antennas that are electrically very long, hence it takes a finite time for all the radiators to be energised, i.e. for the antenna to "fill-up". This has the effect of slowing the risetime of an incident pulse as the phase front builds. In the limit, this can set a fundamental limit on the narrowest pulse that can be used. Generally however the effect is only seen on large military types of antennas.

However, a 28ft Open Array would have a fill time of 20ns which may affect the short pulses used.

3.2.7.11 Antenna design Example

The advent of computer antenna design and modelling software has led to a significant improvement in the performance of radar antenna systems over the last quarter century.

A comparison of two antennas available for ATC radars illustrates this. The metal mesh reflector antenna is shown in Figure 3.2.7-8 and its associated beam shape in Figure 3.2.7-9. The alternative of a carbon fibre composite reflector antenna is shown in Figure 3.2.7-10 and its associated beam shape in Figure 3.2.7-11.

Table 3.2.7.3 compares the parameters of the two antennas and shows the significant reduction of 20 to 25 dB in the side and back lobes. This significantly reduces the level of interference, both generated and received, outside of the main lobe of the antenna.

Table 3.2.7-3 Comparison of Metal Mesh/Carbon Fibre Reflectors

Parameter	Metal Mesh Reflector	Carbon fibre composite reflector
Main beam gain	33.1dB	33.4 dB
Azimuth beamwidth	1.5 deg	1.5 deg
Elevation coverage	30 deg Cosec²	40 deg Cosec²
Main sidelobe	-25 dB max	-30 dB max
Other sidelobes within ±6 deg	-28 dB max	-46 dB max
Sidelobes outside ±6 deg	-30 dB max	-55 dB max

Figure 3.2.7-8 Metal Mesh Reflector (with co-mounted SSR)

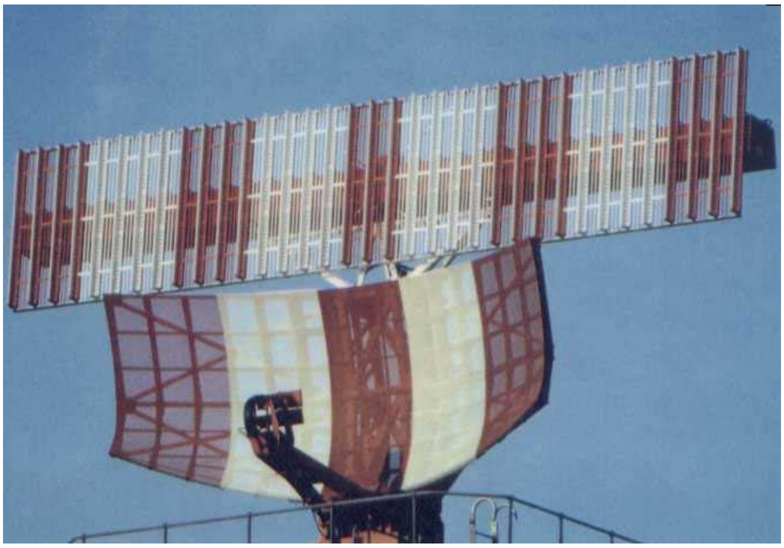


Figure 3.2.7-9 Metal Mesh Reflector Beam Shape

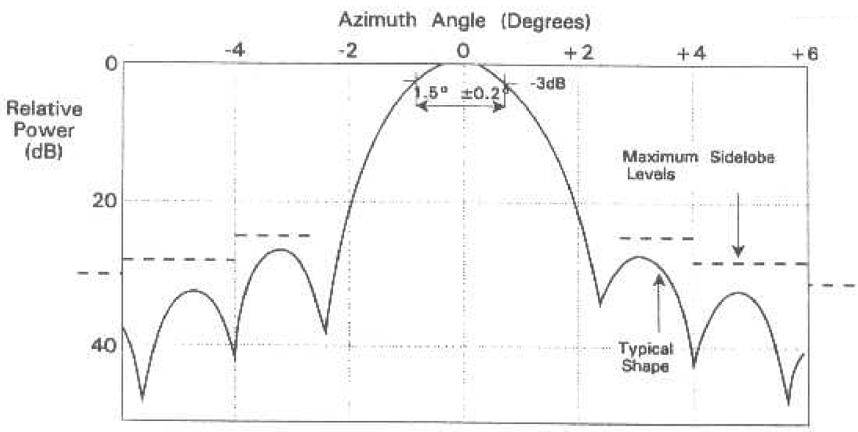
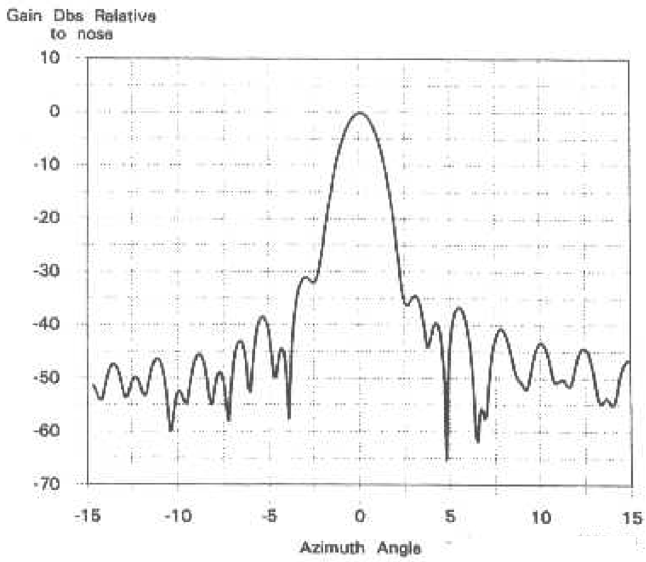


Figure 3.2.7-10 Carbon Fibre Reflector

Figure 3.2.7-11 Carbon Fibre Reflector Beam shape showing Gain in dBs relative to the main beam



3.2.7.12 Summary

In order to constrain the emissions to the wanted directions the following mitigation options can be pursued.

- The design of reflector antennas could be improved, and in the limit, cylindrical reflector antennas could be used.
- Array antennas could use a larger aperture.
- Elevation patterns should be designed to minimise surface and structural reflections. This may require the use of stabilised mounts on naval systems

- Larger antennas may require the use of radomes, preferably these should be sandwich design with matched joints. Water shedding surfaces must be used.
- All obstructions should be removed from illumination by the main beam.

3.2.8 Frequency Selective Surfaces

Frequency Selective Surfaces (FSS) are made from sheets of thin dielectric with a periodic array of small copper elements on the surface of the sheet. An electro-magnetic wave (EM), incident on the surface of the FSS, will experience almost total reflection from the surface at a particular frequency F_r where the elements of the FSS resonate and with virtually no transmission through the sheet. To an incident EM wave, it behaves like a continuous sheet and not at all like the dielectric sheet with a small amount of conductor on it.

At frequencies away from this resonant frequency the FSS will reflect almost none of the incident EM wave and the majority of the power will be transmitted through the sheet. In the case of a horn fed reflector antenna this will pass through the FSS and the support structure will then be illuminated by these frequencies and a random radiation pattern generated to the rear of the antenna.

A broader bandwidth antenna can be produced by using multiple layers of FSS sheets, each tuned to slightly different frequencies. However a single sheet will have a loss in the region of 0.5 dB, and multiple layers will have progressively increased losses due to the two way passage through the upper layers. As the antenna is used on both transmit and receive this loss will be doubled to 1 dB. Therefore to maintain the same performance as before either the receiver must be 1 dB more sensitive or the transmitter increase its output power by 1 dB, a 25% increase. This would increase a transmitter cost significantly, as most transmitters are operated at or near their rated output power.

The properties of a FSS make it ideal for use as a plane wave filter, and it is used in transmission systems either as a selective band-pass filter or a band-stop filter at centimetre and millimetre wavelengths.

The above discussion relates to a plane wave incident on a plane surface. However, many antennas use curved reflectors, either a single curvature reflector with a line feed, or a double curvature horn fed reflector. In both cases the wave front is no longer normal to the reflector surface but will have an angle of incidence that varies across the reflector. To maintain a constant resonant frequency the dimensions of the resonant patches will change across the surface. This would be a complex design process and would result in an antenna that is only optimum at a single frequency. The design of a multilayer surface would be even more complex.

The increased cost and fixed frequency do not make the use of FSSs for radar antenna reflectors an attractive proposition.

FSSs are used in radomes to make them transparent over a small band of frequencies, and could be used in the radomes for small radars (X-Band and above). This would allow only the wanted frequency to radiate, and the unwanted harmonics and spurious emissions to be trapped inside the radome, where they can be dissipated; but placing a filter in the waveguide between the transmitter and antenna would achieve the same result at a lower cost.

3.2.9 Low Probability of Intercept (LPI) Waveforms

Low Probability of Intercept (LPI) radars have been developed primarily for naval use, and are used for ship borne surveillance and navigation applications. LPI radars are designed to minimise their detection by electronic surveillance equipment or by radar warning receivers. The LPI radars transmit a modulated low power Continuous Wave (CW) waveform so that the range of detected targets can be determined. Modulation methods used are either FM or noise like.

FMCW waveforms are also used in LPI radar altimeters, harbour docking radars and vehicle collision avoidance systems.

The modulation may be Frequency Modulated CW (FMCW), random, or pseudo-random, noise like modulation. The target range is found by correlating the transmitted waveform with the received echo signal and measuring the time difference; this is directly related to the range of the target.

A typical LPI radar has a switchable power output of up to 1 Watt compared to equivalent conventional pulsed radar with a 10 kW output pulse power. Both have similar detection ranges on targets, while the lower power of the LPI radar reduces the range at which an ESM system can detect the radar. Similarly the low transmit power reduces the potential for causing interference in other equipment.

The relevant parameters for a typical LPI radar (PILOT) are shown in Table 3.2.9-1.

Table 3.2.9-1 LPI radar

Radar Output Power	Radar Detection Range (km)		ESM Intercept Range (km)
	100 m² RCS Target	1 m² RCS Target	Typical ESM system
LPI Radar			
1.0 W	28	8.8	2.5
0.1 W	16	5	0.8
10 mW	9	2.8	0.25
1.0 mW	5	1.5	0
Conventional Pulsed Radar			
10 kW	25	7.9	250

However, LPI radars are limited to short range applications. This is due to their dynamic range limitation. LPI radars typically have separate transmit and receive antennas that are co-mounted; it is difficult to achieve better than 60dB electrical isolation between the two antennas. The other limitation is the simultaneous presence of echoes from close in clutter and from distant targets.

Target echoes reduce with the fourth power of the range. A target at a range of 100 km will be a factor of 10 further away than one at 10 km; but the return signal power will be a factor of 10^{-4} of that returned from the target at 10 km. Therefore the ratio of minimum to maximum range has to be limited in LPI radars to avoid an excessive dynamic range requirement.

3.2.10 Passive Radar

3.2.10.1 Passive Tracking Systems

One way to reduce interference from a radar is not to transmit but to rely on other sources to provide the received signal. It is possible to track targets by detecting their emissions and by comparing the time of arrival at several stations to calculate and track their positions. Such systems were first developed in the 1960's but today's modern computers make the implementation much more cost effective. These systems are generally referred to as passive tracking systems. They rely on existing transmissions from aircraft, vessels or vehicles, or third party transmissions from TV, Radio or cellular mobile phone transmitters.

There are several types of passive tracking systems that can be considered and they generally fall into one of two types:

- Transponder Based (Beacon Systems).
- Passive radars using transmitters of Opportunity.

3.2.10.1.1 Transponder Based (Beacon Systems)

Targets can be fitted with a beacon that transmits signals at regular intervals, or use can be made of the on-board SSR system. Alternatively, the beacon can be stimulated to transmit by low level interrogations. As an alternative to multi-lateration the target can transmit its GPS position. These systems however require the use of co-operating targets.

A network of receivers at fixed locations can be used to receive transmissions from the targets. Multi-lateration using time of arrival from a minimum of 3 sensors can be used to calculate the position of the aircraft in 2 dimensions; to find the position in 3 dimensions requires the addition of a fourth receive station.

Aircraft respond to SSR interrogations by transmitting a response with a known format. The time of arrival of an SSR response pulse can be measured at each of the sensors and this information relayed to a central station where the position of the target is calculated. The position of the target is determined by cross-correlating the signals received at each of the receiver sensors and calculating the difference in times of arrival. This information together with the position of the sensors is then used to triangulate the position.

This method relies on accurate measurement of time at each sensor, and also on the sensors being in synchronism.

The accuracy of measurement of a multilateral system depends on:

- The geometry of the sensors; an equilateral triangle is the optimum arrangement .
- The position of the target relative to the sensors.
- How accurately the sensors are synchronised
- How accurately the sensors can measure the Time Of Arrival (TOA).

3.2.10.1.2 Transmitters of Opportunity (Passive Radar)

There are two forms that may be used.

- In the first form of this type of passive radar, a network of receive stations looks for the reflections by a target of RF signals from a third party transmitter. The third party transmitter may be, for example, a TV transmitter, radio station or cellular phone transmitter. The sensors operate as bistatic radars to form a multi-static radar system. The TOA difference between the reference signal received directly from the transmitter and the indirect signal reflected from the aircraft gives the difference in path lengths between the direct transmitter to receiver and that from transmitter to receiver via the target aircraft. This defines an ellipse around the transmitter-receiver baseline of the possible target positions. Using two or more receivers in different locations gives an array of ellipses; where they cross defines the target position.

- The second form of this type of passive radar uses a single receive station and multiple transmitters. One version of this type of passive radar is the Lockheed Martin Silent Sentry™ radar which uses the reflections from FM radio transmissions to track aircraft and provide coverage similar to that of a primary radar.

In the Silent Sentry™, reference signal antennas receive the direct line of sight reference signals from a number of broadcast transmitters operating in the VHF or UHF bands. The main passive receive antenna receives the indirect signals reflected by the aircraft. This covers a quadrant, and four antennas are used for the full 360 degree coverage. The system uses high gain linear phased array antennas and wide dynamic range receivers coupled with high speed processors that use Passive Coherent Location (PCL) technology to determine the time of arrival and the Doppler for each target. Triangulation using three or more transmitters gives the position for each target.

Silent Sentry™ systems are available for mounting on buildings or fixed structures, or containerised for rapid relocation. The system is based on Commercial Off The Shelf (COTS) products and range in cost from $3 million to $5 million. The range performance is quoted as 220 km on a target with 10 m^2 radar cross section.

Roke Manor Research have developed a passive radar system, CELLDAR™. This uses the transmissions from mobile phone base stations as the transmitters. These are widely distributed in most populated regions.

The disadvantage of passive radar systems is the lack of control over the transmitters being used, and there is no guarantee of their availability. This is an important factor where safety of life is concerned.

3.2.11 The use of Filters for the control of Unwanted Emissions

A traditional way to control the unwanted emission from transmitters is by the use of filters. The choice of the class and type of filter depends on the exact nature of the emissions to be suppressed and those to be transmitted. Transmission factors include factors such as, bandwidth, loss and phase distortion. Suppression factors include the required attenuation and the frequency separation between the pass and stop bands.

Filters come in several classes:

- Band-pass;
- Low-pass;
- Band-stop;
- High-pass.

Of these classes the first three are most appropriate for reducing unwanted emissions.

3.2.11.1 Band-pass Class

Band-pass filters transmit a specific set of wanted frequencies and reject others. The amount of rejection provided by the filter depends on:

- The type of filter,
- The width and centre frequency of the "pass" band,
- The number of sections in the filter.

The loss incurred from such a filter depends on the following factors:

The Loaded Q	=	Ql
The Unloaded Q	=	Qu
A factor relating to the type of filter and the number of elements	=	Σg_i

The unloaded Q is the natural Q of the resonant circuits used to construct the filter. Band-pass filters used on the output of radar transmitters are generally built using cavities of one type or another.

These cavities provide the low loss required coupled with a high power handling capacity. One of the most common types used is a direct coupled waveguide $\lambda/2$ cavity filter.

This consists of a series of half wavelength cavities coupled by shunt inductive components, formed either from irises or posts. See Figure 3.2.11-1 and Figure 3.2.11-2 below.

Figure 3.2.11-1 Inductive Iris in Waveguide

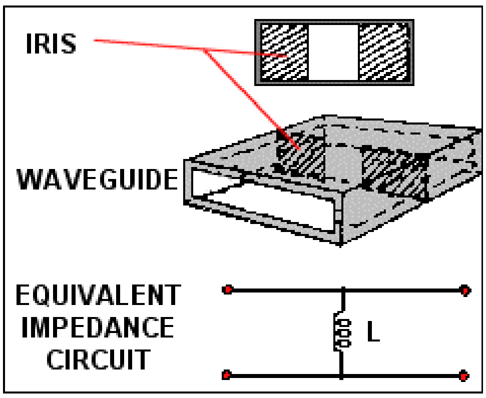
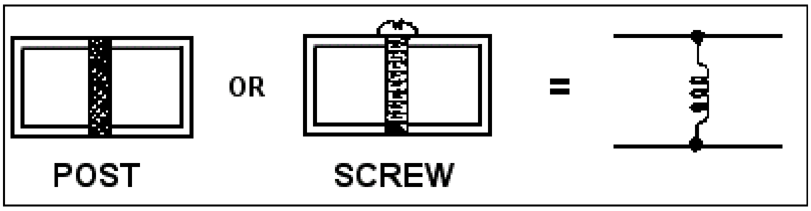


Figure 3.2.11-2 Inductive Post in Waveguide



If these elements are spaced at $\lambda_g/2$ then the intervening waveguide sections form a resonant cavity see Figure 3.2.11-3. Depending on the power handling and the exact electrical and mechanical design of the filter either posts or irises are used.

If a lower transmission loss is required then it is possible to use a filter made up of directly coupled cylindrical cavities see Figure 3.2.11-4.

Figure 3.2.11-3 Two-Cavity Iris Coupled Waveguide Band-pass Filter

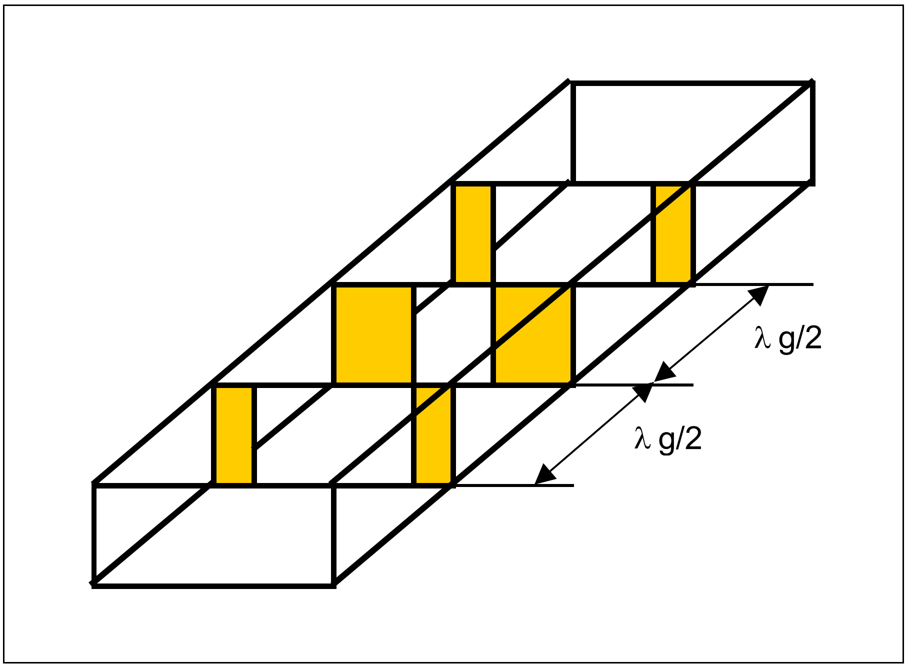
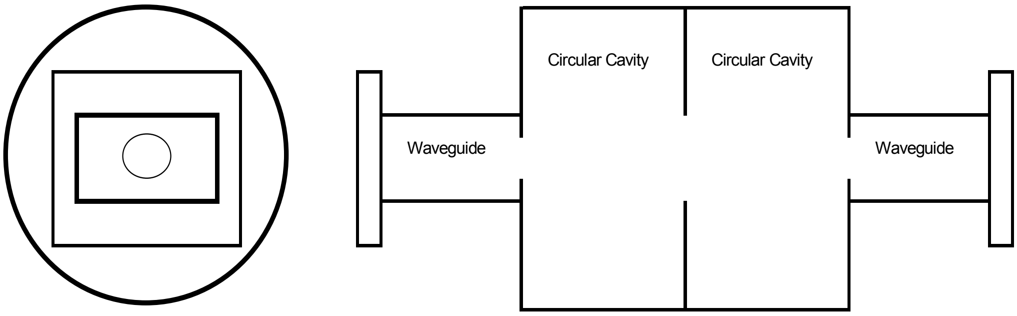
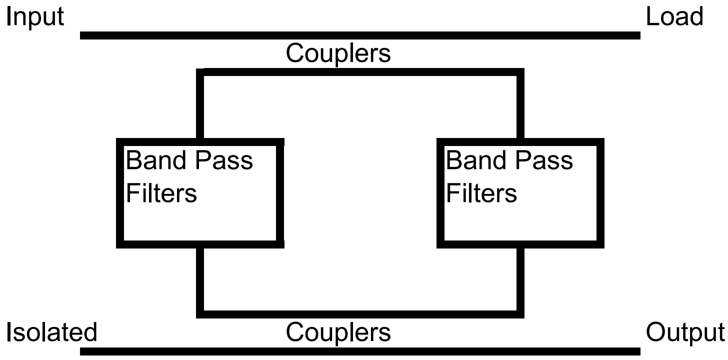


Figure 3.2.11-4 Direct Coupled Two Section Circular Waveguide Cavity Band-pass Filter



Band-pass Filters present a highly mismatched reactive load to any signals outside the pass band and if not protected by a circulator, this can cause problems with the transmitting valve. A solution is to use a constant impedance filter (sometimes referred to a "Lorenz Ring") this is a combination of Band-pass filters and 3 dB couplers. The same functionality can be achieved with two Band-stop filters, however, in this implementation the Load and Output ports are interchanged. See Figure 3.2.11-5 below.

Figure 3.2.11-5 Constant Impedance Filter



As an alternative to the ring structures, a "Travelling Wave Directional Filter" see Figure 3.2.11-6, can be used. In this filter a circular cavity is excited with two orthogonal modes which provides a directional property similar to the Lorenz Ring.

At lower powers, coaxial cavities can be used. These do not have the peak power handling capacity of waveguide designs and generally have lower unloaded Q's resulting in lower insertion losses. They do however provide a solution in lower power transmitters.

3.2.11.1.1 Insertion Loss

The insertion loss of a Band-pass filter is given by the following equation:

$$L = 4.34 \times \frac{Ql}{Qu} \sum_1^n g_i \quad \text{Equation 3.2.11-1}$$

Where n = number of filter elements.

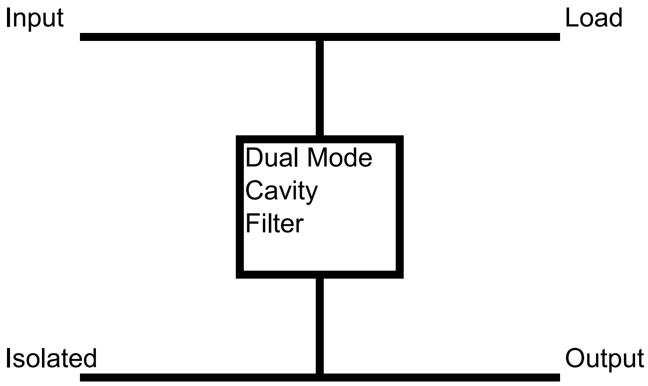
The loaded Q, Ql is the ratio of the pass band to the centre frequency i.e.

$$Ql = Bw / f_o$$

The unloaded Q, Qu is the natural Q of the cavity used. This is a function of the size of the cavity, the operating frequency and resonant mode, and the ohmic loss. The ohmic loss is a function of the conductivity of the cavity walls. In order to maximise the Qu, the cavity is either silver plated or made of Oxygen Free High Conductivity (OFHC) Copper. Depending on the temperature stability required of the cavity the whole filter may be constructed of copper or some more stable material such a Invar. If Invar is used then it will be silver plated.

The term $\sum_1^n g_i$ is the sum of the low-pass prototype *g* values, these depend on the type of filter (i.e. Tchvbyshev or Butterworth) and the pass band ripple. There is one *g* value associated with each cavity and one each for the input and output coupling. The longer the filter the more g values and the greater the loss.

Figure 3.2.11-6 Travelling Wave Directional Filters



For relatively narrow band filters suitable for radars operating on one or two closely spaced frequencies, band-pass filters can be used to provide significant attenuation over the OOB region and at the boundary of the SE region. Such filters have up to four sections and can be designed with insertion losses of less than 0.5 dB. However if the pass band has to be wide enough to cover a complete radar band, then to achieve significant attenuation at the SE boundary for the band edge frequencies the filter becomes too long (approximately 9 elements) which results in an unacceptable insertion loss.

Band-pass filters operate well in the OOB region and the close SE region, however at frequencies approaching the harmonics, Band-pass filters tend to have spurious pass bands either related to the geometry of the cavities or caused by the presence of higher order modes within the structure.

Band-pass filters operate well at frequencies below the fundamental frequency achieving high levels of attenuation below the "cut-off" frequency of the waveguide cavities.

3.2.11.2 Low-pass Class

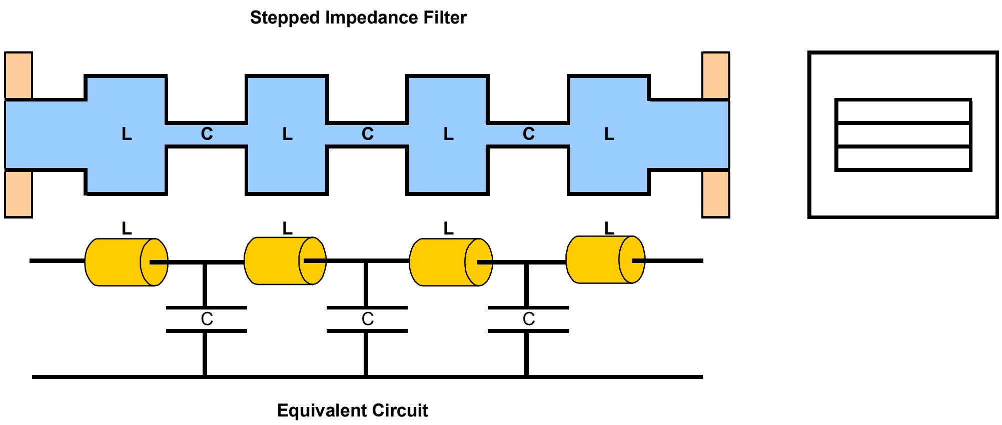
These are generally used for the suppression of frequencies in the SE region. They have wide pass bands and are particularly useful where radars have very wide operating bandwidths. Because they have essentially a low Q they can be fabricated with low insertion loss. For high power systems Low-pass filters can be fabricated in a waveguide, whilst lower power systems can be fabricated in a coaxial medium.

3.2.11.2.1 Stepped Impedance Filters

The simplest form of high power, low-pass filter, is the "stepped impedance" waveguide filter. Consecutive stages of low and high impedance produce a version of a classical LC ladder filter. The more LC sections there are, the faster will be the roll-off. Figure 3.2.11-7 shows the implementation of the stepped impedance filter in waveguide and its equivalent circuit. These filters however do have finite extent to their stop bands. This is due to two problems:

- In order to approximate to the lumped equivalent circuit the ratio of the two impedance sections needs to be as high as possible, and this ratio is limited by the voltage breakdown criteria in the low impedance (capacitive) sections.
- The presence of TM modes can cause the filter to exhibit spurious responses. If this is a problem then a "Waffel Iron Filter" can be used

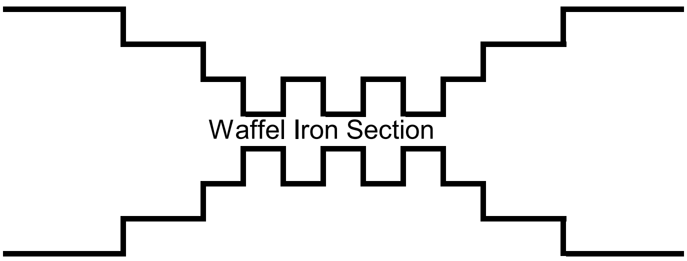
Figure 3.2.11-7 Stepped Impedance Filter



3.2.11.2.2 Waffel Iron Filters

These type of filters provide very wide stop bands and do not suffer from the re-entrant or over moding properties of the stepped impedance types, see Figure 3.2.11-8.

Figure 3.2.11-8 Waffel Iron Structure

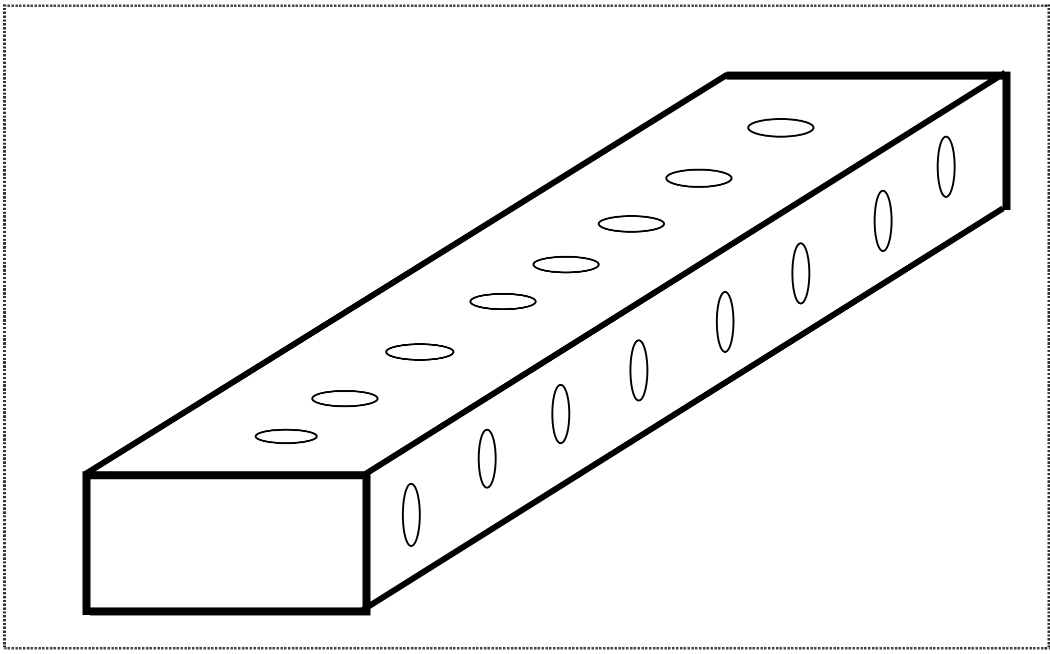


If constant impedance is required, then the Lorenz Ring technique can be applied with the Band-pass filters replaced with Low-pass. However, a better approach is to use a "Leaky Wave" filter.

3.2.11.2.3 Leaky Wave filters

These filters are very good at suppressing harmonic radiation however they have very low Q values and are not effective in the OOB or non-harmonic SE boundary regions. They operate by having a "Leaky Waveguide" structure. This is a waveguide that has small coupling apertures cut through its walls, designed to cut off at the fundamental frequency so they do not couple energy out of the waveguide. At harmonic frequencies, the coupling holes become transparent and the energy is extracted from the waveguide. Holes can be positioned so as to couple to both TE and TM modes, see Figure 3.2.11-9. The result is a structure with constant impedance that reduces the amount of harmonic radiation. The harmonic energy is coupled into a cavity line with absorbent material where it is dissipated as heat. Experience has shown in practice, that a well designed Leaky Wave Filter will reduce all significant harmonics to an acceptable level. These filters, because they are very low Q and only effectively "turn-on" at the harmonic frequencies, have very good power handling characteristics and can be used with systems that are operating at a significant percentage of the rated peak power of the waveguide. In some cases the "leaky wave" filter is the only practical solution.

Figure 3.2.11-9 Leaky Wave Structure



3.2.11.3 Band-stop Class

The Band-stop filter operates by suppressing a selected band of frequencies and transmitting all others. The classic example of the Band-stop filter is the tuned coaxial stub shown in Figure 3.2.11-10 and Figure 3.2.11-11 below. In this filter a short circuited piece of coaxial line is connected in shunt with the main line. At the frequency when the short circuit line is equal to $\lambda/2$ the short circuit is reflected onto the main line and a band-stop characteristic is formed. The width of the stop band or "notch" depends on how closely coupled the resonator is to the main line, in this case it depends on the characteristic impedance of the stub. The higher the impedance the narrower the stop band or "notch"; the depth of the notch being a function of the size and conductivity of the stub. These simple notches however are still closely coupled even with high impedance line and tend to have very wide notches. They also exhibit band-pass characteristics at odd multiples of $\lambda/4$ where the short circuit is transformed into a shunt open circuit.

Figure 3.2.11-10 Direct Coupled Coaxial Notch

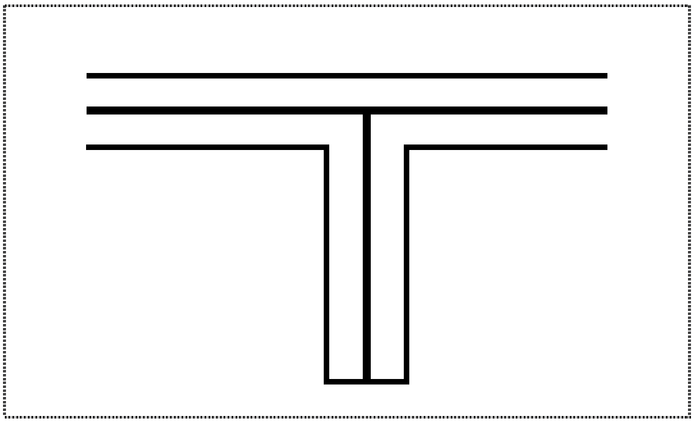
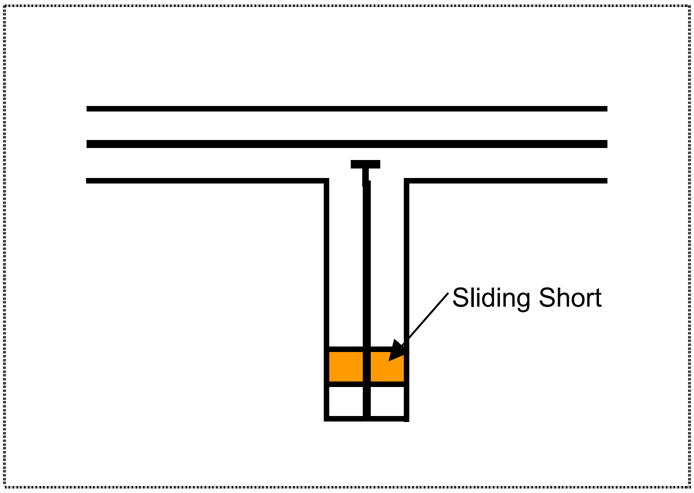
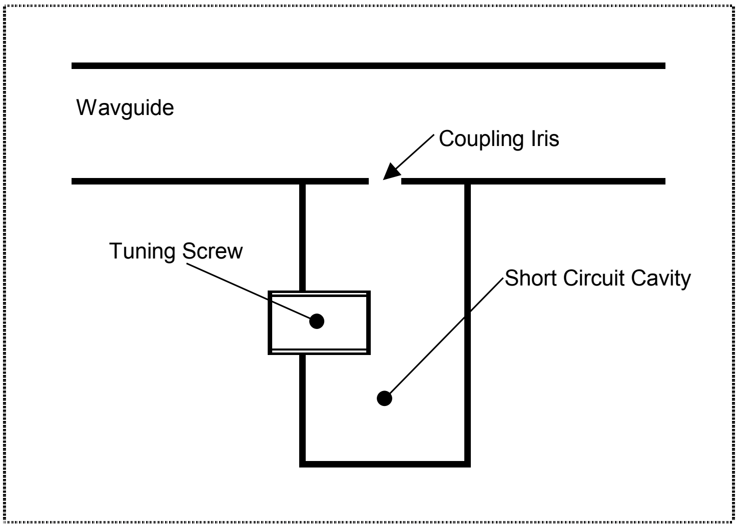


Figure 3.2.11-11 Capacitively Coupled Band-stop Filter



In order to reduce the coupling and narrow the stop band a series stub can be used, this element is $\lambda/4$ short circuited line, the short circuit can be made adjustable for tuning. Multiples of these elements can be provided either tuned to individual frequencies or synchronously tuned to provide wider stop bands. Figure 3.2.11-12 shows the waveguide version of such a band-pass element.

Figure 3.2.11-12 Waveguide Band-stop Filter Element



Band-stop filters are very good at power handling, this is mainly due to the fact that the wanted high power signal is generally confined to the lower Q parts of the circuit. This is particularly true if the stop bands are well separated in frequency from the wanted pass bands.

Band-stop filters are particularly useful if individual frequency components are required to be suppressed.

Care needs to be taken however when designing filters at harmonic frequencies that due account is taken of the waveguide modes present in the feed.

3.2.11.4 Cascaded Filters

One way to avoid the problems of spurious pass band is to use cascaded filter types, such that one type of filter suppresses the spurious pass band of the other.

The classical case for this is a Band-pass/Low-pass filter combination, although Low-pass/Band-stop and Band-pass/Band-stop are also used.

In the Band-pass/Low-pass arrangement the Band-pass section provides the attenuation required in the OOB region with the low-pass suppressing the SE region. This arrangement works particularly well as the low Q design of the Low-pass filter adds very little to the insertion loss of the Band-pass section.

3.2.11.5 Filters For Active Arrays

The ability to filter the output of active arrays is severely limited by the close coupling between the output of the transmitter module and the radiating element. In order to reduce the losses the output of the Power Amplifier (PA) is kept as close as possible to the radiator and, in many cases, the radiator is integral with the Transmit/Receive module. Any loss after the PA gives rise to two problems, it contributes directly to a loss of Equivalent Isotropically Radiated Power (EIRP) and secondly it generates extra "wild" heat at the array face.

If the loss of EIRP is not acceptable then extra modules must be added to compensate These modules, as well as adding cost, also require all the antenna infrastructure required to power, control and cool them.

It is generally not considered good design practice to have excessive losses after the PA stage.

An example is a 3 metre diameter phased array radar using elements producing 10 Watts peak power output which would have the following parameters:

Diameter	=	3 m
Area	=	7.07 m^2
Wavelength, λ	=	0.1 m

The element spacing for a square lattice arrangement of the elements is 0.536λ [17] giving an area per element of $0.287\lambda^2$.

This gives 2463 transmit elements in the array.

Total peak power	=	24.63 kW

A 0.5 dB loss in each element will reduce the output power by 10 %

Reduced output power	=	22.17 kW
Loss in Tx Power	=	2.46 kW

More modules will be required to compensate for the reduction in output power. Each module contributes twice to the radar performance, once to the total power radiated, and

[17] "Radar Handbook", 2nd Edition, M Skolnik. P7.21

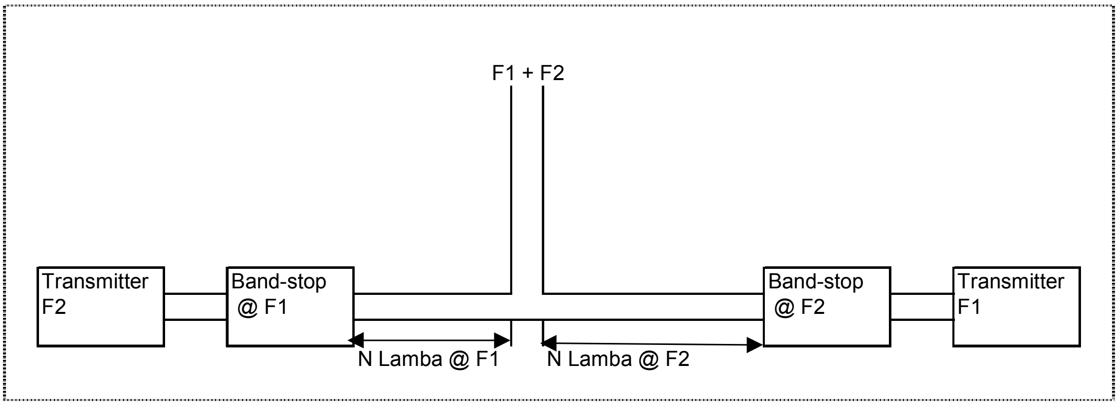
once to the antenna gain (The additional modules increase the array area and therefore the gain). This indicates that 123 additional modules would be required, and the array would need to be enlarged to house the additional modules. Adding such additional elements to an array would significantly increase the cost.

Given these design constraints, the size and type of filter is limited and only low Q designs are possible. It is likely that a filter that modifies the OOB region would not be possible, filters that suppress harmonic radiation are however possible. A further problem with the compact nature of these filters is the isolation that can be achieved. The filter reaches an insertion loss limit related to the signal break through, a function of the transmission line technology being used. Other components in the transmit chain however could provide some low levels of attenuation in the OOB region.

3.2.11.6 Diplexers

When combining two transmitters of different frequencies, it is necessary to make use of filters in the diplexer. The choice of the type of filter used can have a large impact on the output spectrum of the system. The simplest form of diplexer is the "star-point" combiner. This is illustrated in Figure 3.2.11-13 below.

Figure 3.2.11-13 Band-stop Star Point Combiner

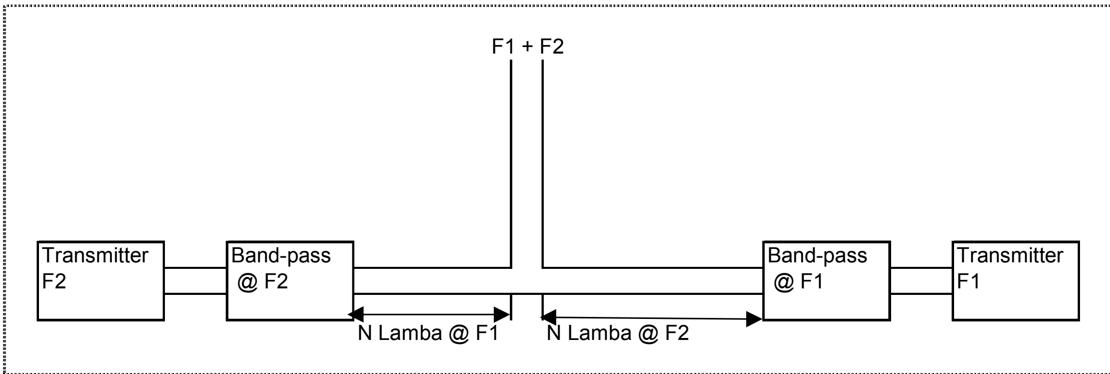


In this device the two transmitters are connected by the use of a transmission line "T". Each arm of the "T" is provided with a Band-stop filter tuned to the frequency of the opposite transmitter. This prevents the output of one transmitter coupling into the second. The spacing between the filter and the "T" junction is adjusted such that the reflection from the Band-stop filter appears as an open circuit at the junction thus causing the "T" to be matched. In this arrangement, as the Band-stop filter is "narrow" band, OOB and SE signals are radiated. Being essentially a low Q broad band structure the insertion loss to the spurious signals is low.

This can be remedied at the expense of complexity and some extra loss by the use of a Band-pass Star Point Combiner. See Figure 3.2.11-14.

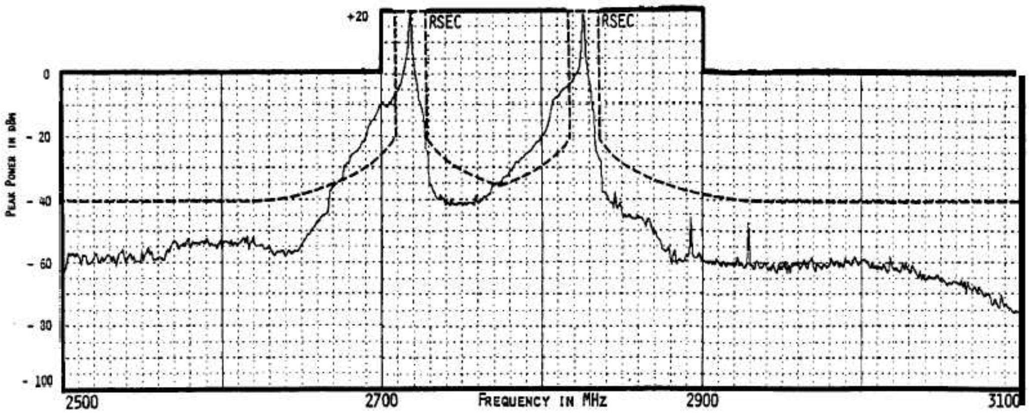
In this device the Band-stop filters are replaced by Band-pass filters which then provide filtering into the OOB and SE regions.

Figure 3.2.11-14 Band-pass Star Point Combiner



The difference in the two types are shown in Figure 3.2.11-15 and Figure 3.2.11-16 below.[18] These show the output spectra of two transmitters using essentially the same output magnetron, the difference being only the type of diplexer used.

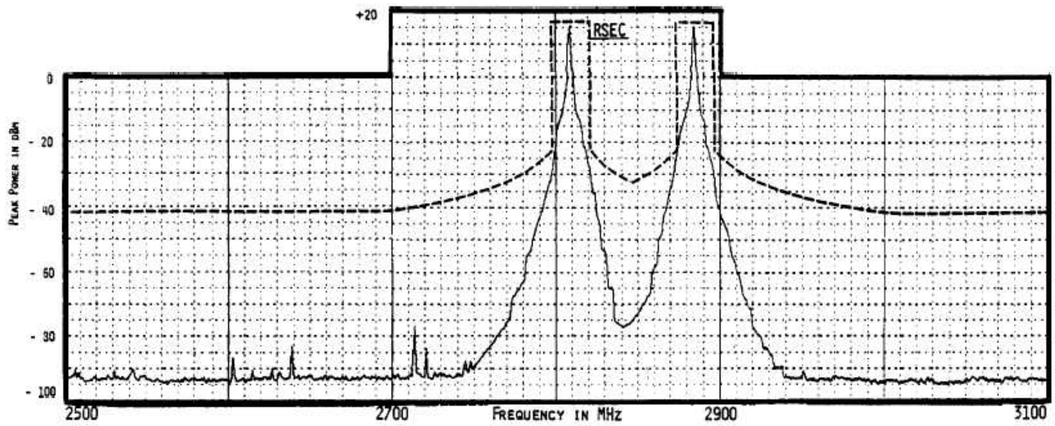
Figure 3.2.11-15 TPN-19 Band-stop Diplexer



b. TPN-19, conventional magnetron.

[18] NITIA Report 82-92

Figure 3.2.11-16 GPN-20 Band-pass Diplexer [19]



a. GPN-20, conventional magnetron, diplexer filtered.

It is obvious that the diplexer using the Band-pass characteristic has much the cleaner spectrum.

The use of Band-pass filters is not of course limited to use in diplexers; the same effect can be achieved on single frequency radars by adding a simple Band-pass filter to the output.

3.2.11.7 Sample Filter Designs

This section presents two filter designs to illustrate what can be practically achieved. One filter is the type that would be associated with a single channel radar the other is the type of filter that could be used to suppress radiation at the edge of a dedicated radar band. The designs however must be taken as representative only of what can be achieved, and should not be taken as a fully optimised design example.

3.2.11.7.1 Single Channel Filter

If we consider a radar operating at 2800 MHz with a 1µs pulse and a 15ns risetime, this is typical of an ATC radar. This pulse has a 3dB bandwidth of 1 MHz. In order to prevent distortion of the signal the pass band of the filter will be made equal to the necessary bandwidth of the signal.

The necessary bandwidth of the signal is approximately equal to the 20 dB bandwidth of the spectrum. For this pulse shape the BW_{-20dB} is given[20] by the lesser of the following:

$$Bw_{-20dB} = \frac{1.79}{\sqrt{t \times t_r}} = 14.6MHz, \qquad \frac{6.4}{t} = 6.4MHz$$ Equation 3.2.11-2

If we wish to attenuate the signal at the OOB/SE boundary by 40 dB then it is necessary to calculate the normalised frequency variable, this depends on the pass band and the frequency at which the 40dB rejection is required.

The OOB/SE boundary occurs at a frequency excursion equal to 10 times the Bw_{-40dB} point, where the Bw_{-40dB} point occurs at the lesser of[21] ;

[19] RSEC = Radar Spectrum Engineering Criteria

[20] ITU-R Recommendation SM.1541, Annex 8

[21] 7.6 is the appropriate value for ARNS radars.

$$Bw_{-40dB} = \frac{7.6}{\sqrt{t \times t_r}} = 62MHz, \qquad \frac{64}{t} = 64MHz$$ Equation 3.2.11-3

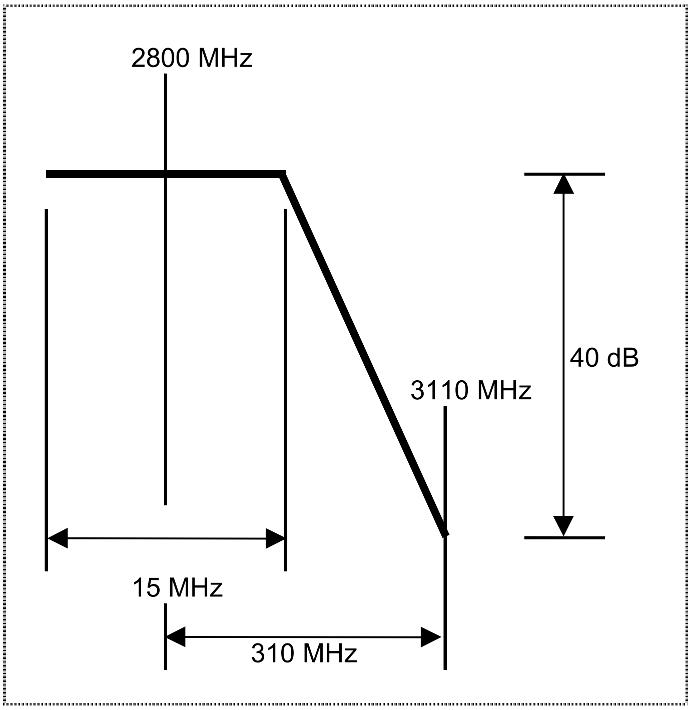
If we wish to give a design margin on loss and group delay[22], for the sake of this example the filter equal ripple bandwidth will be set to the larger (worst case) 14.6 MHz value. The boundary occurs at an excursion of :

$$\frac{62 \times 10}{2} = 310MHz$$

This puts the rejection point at 2800+310 =3110 MHz.

To allow for design implementation and temperature drift the pass band should be slightly wider than the necessary bandwidth, if we set the filter pass band to 15 MHz then Figure 3.2.11-17 shows the design mask for the filter:

Figure 3.2.11-17 Design Mask for Single Channel Filter



To maintain a good match in the pass band a 0.01 dB ripple Tchebyshev design has been selected. The insertion loss A, in the stop band of such a filter is calculated from:

$$A = 10\log_{10}\left[1 + \left(10^{\frac{A_m}{10}} - 1\right)\cosh^2\left(n\cosh^{-1}\{\omega'\}\right)\right]$$ Equation 3.2.11-4

[22] In a practical design the filter parameters would be further optimised to trade-off bandwidth against insertion loss rejection, number of elements etc. The final pass band width would be somewhere between 6.4 and 15 MHz. However for this example the pass band width will be set to 15 MHz.

Where : ω' = normalised frequency variable

A_m = Pass band ripple = 0.01 dB

n = number of sections

Bw = Pass Band width = 15 MHz

Fc = Centre Frequency = 2800 MHz

Fo = Rejection Frequency = 3110 MHz

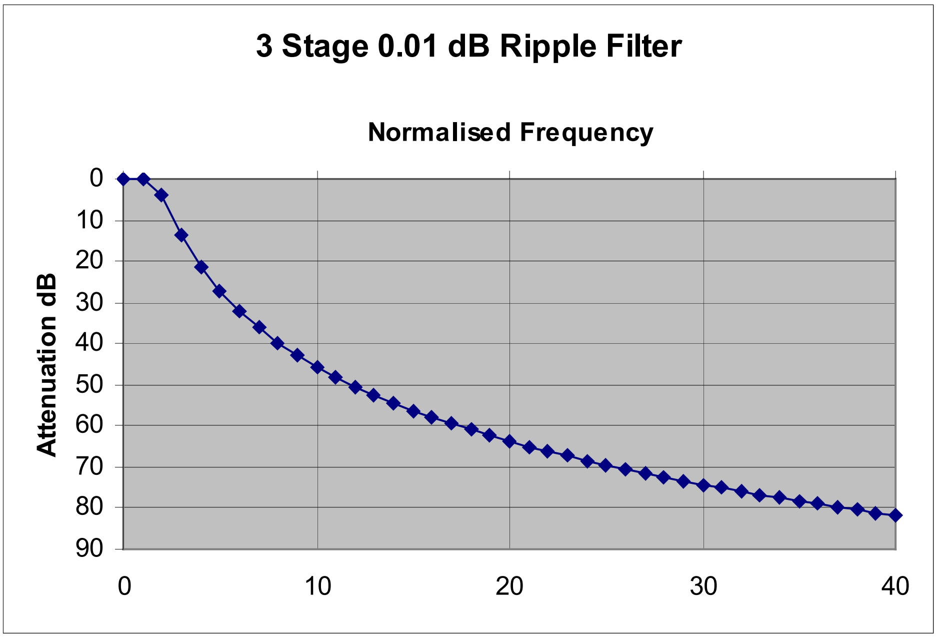
The normalised frequency variable is calculated from:

$$\omega' = \frac{Fc}{Bw}\left(\frac{Fo}{Fc} - \frac{Fc}{Fo}\right) = \frac{2800}{15}\left(\frac{3110}{2800} - \frac{2800}{3110}\right) = 39.3$$

At a normalised frequency variable of 39.3 a two section filter would give 43 dB of loss at Fo. To allow for a design margin it was decided to adopt a 3 section design[23].

The predicted performance of a 3 section filter is given in Figure 3.2.11-18.

Figure 3.2.11-18 Predicted Filter Response



This shows a predicted attenuation in excess of 80 dB at the desired frequency.

It is now necessary to estimate the insertion loss of such a device.

If the filter were implemented in WG10 using half wave resonators, the unloaded Q would be 9400 for a filter made in copper.

This would result in a loss for a three section filter, where $\Sigma g_i = 2.22$, of:

$$L = 4.34 \times \frac{Ql}{Qu}\Sigma_1^n g_i = 4.34 \times \frac{\left(\frac{2800}{15}\right)}{9400} \times 2.22 \approx 0.2dB \qquad \text{Equation 3.2.11-5}$$

[23] This type of filter is slightly easier to implement with an odd number of sections

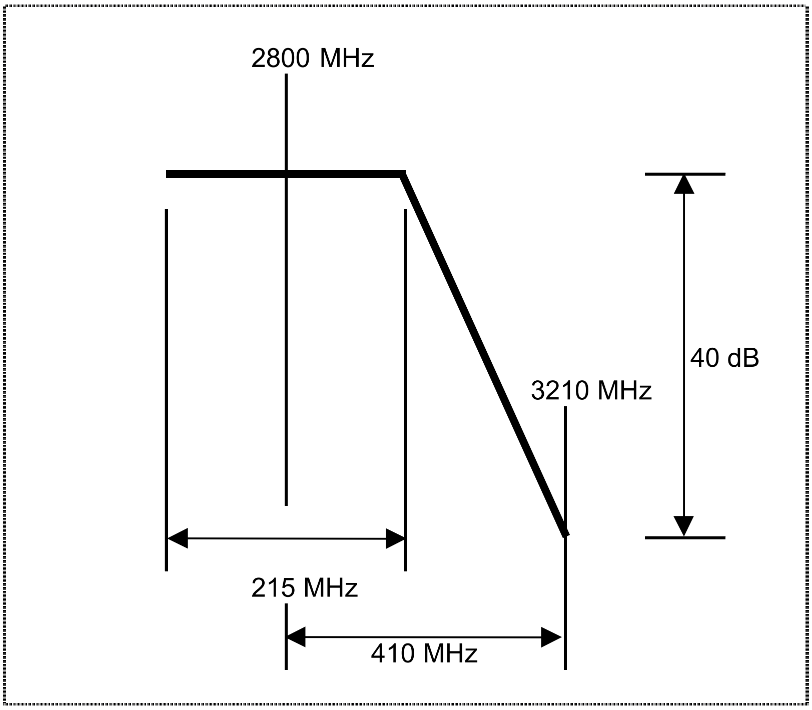
This design has not been optimised and it is likely that further design trade-offs could reduce the loss by trading some of the extra rejection however it demonstrates that such a filter is feasible.

If the radar operated on more than one frequency then the single channel filter approach is generally not feasible. A filter would be required that tracked the radar output frequency. Whilst such filters can be designed for low power (YIG filter), or for slow time (Electrically driven mechanically tuned filters) neither of these can operate at the tuning rate and at the power level required by a multi-frequency radar.

3.2.11.11.2 Multichannel Filter

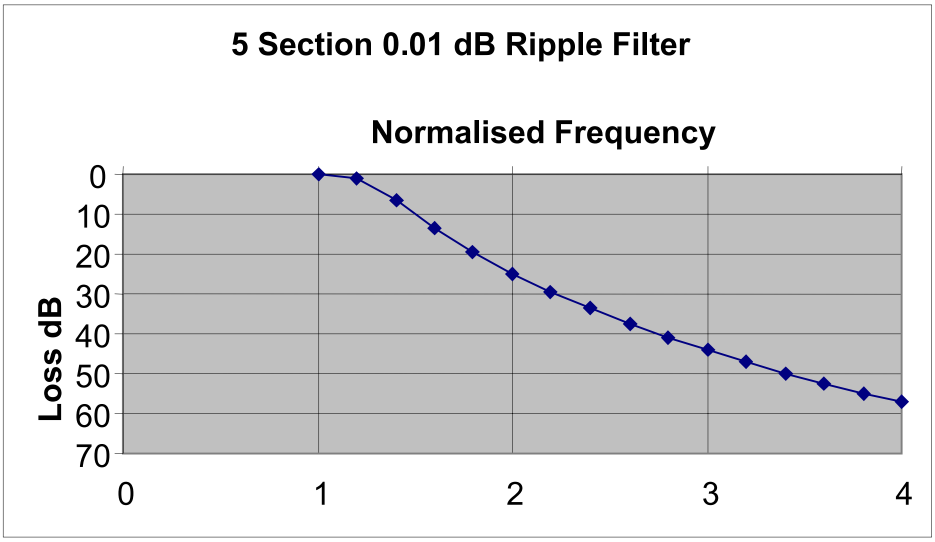
If the use of filters is to be extended to radars operating on more than one frequency in the band then the pass band must be widened enough to cover all the frequencies used, however the rejection point must be maintained relative to the channels at the band edges. Figure 3.2.11-19 shows the design mask for the ARNS band of 2700 to 2900 Mhz.

Figure 3.2.11-19 Design Mask for a Multi-channel Filter



This filter has a normalised frequency variable at the F_o point of 3.6, to achieve the 40dB this would require 5 sections. The response of such a filter is given below in Figure 3.2.11-20.

Figure 3.2.11-20 Five Section Filter



The loss of such a filter is lower than the previous filter being calculated at $<$ 0.1 dB. The filter has become longer, potentially increasing the loss, but the widening of the pass band has lowered the loaded Q by more than enough to compensate for this.

To summarise, in the scenario chosen it has been shown that it looks practical to use a band-pass filter to reduce the emissions from a single channel radar at the OOB/SE boundary by greater than 40 dB without incurring too much extra loss. It also looks possible to provide a filter to carry out the same function at the end of the band whilst maintaining a 200 MHz pass band.

These are two specific applications and should not be taken as representative of all cases. The filter design will become more demanding if:

- Higher Frequency Bands are Used
- The NB of the radar is increased
- The SE/OOB boundary is moved closer to the Bw_{-40dB} point.

If the filter were implemented in X-Band, the single channel filter loss would increase to approximately 1.2 dB and the multi channel filter loss would increase to approximately 0.2 dB. This is a function of the lowering of the unloaded Q and an increase of the loaded Q. The loss of the single channel filter could possibly be reduced by trading off some of the attenuation and increasing the width of the pass band. This would lower the loaded Q and reduce the losses.

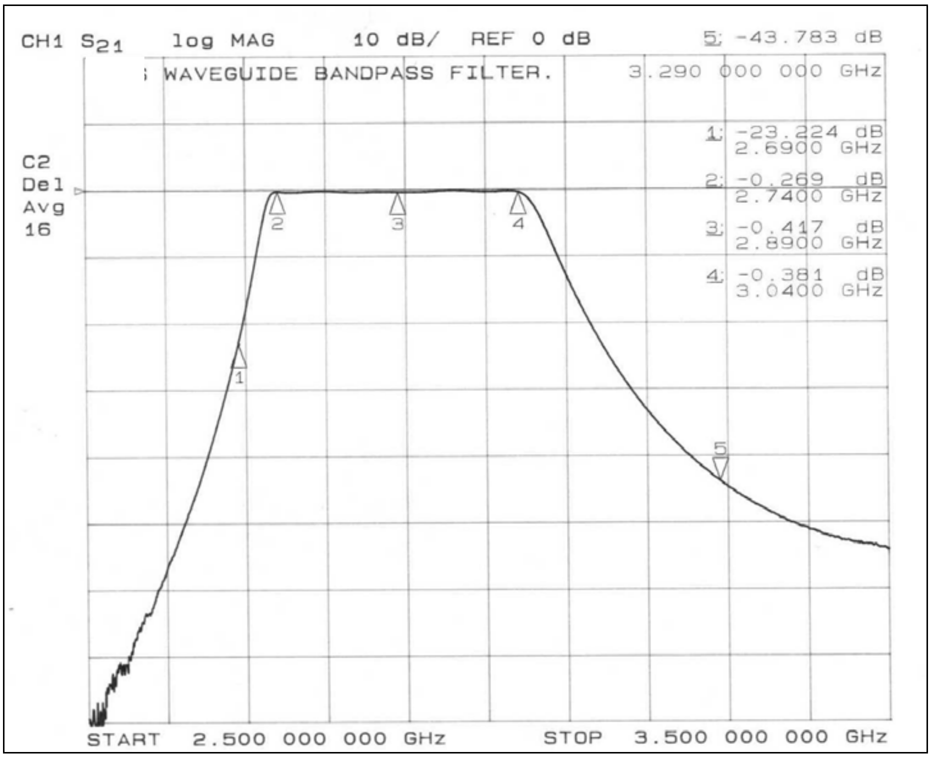
The last point above is critical as this controls the rate of roll-off outside the pass band and it is this value that sets the number of sections required for the filter. As the number of sections increase, the loss increases and it becomes no longer possible to compensate by widening the pass band to lower the loaded Q.

3.2.11.7.2 Practical Example

Figure 3.2.11-21 shows the measured result of a 7 segment filter designed to reduce emissions in the OOB region. The filter is designed to pass signals in the band 2.75 to 3.05 GHz and to have 40 dB rejection at 3.29 GHz.

This filter has a loss of less than 0.2 dB over the pass band.

Figure 3.2.11-21 Measured Filter Response



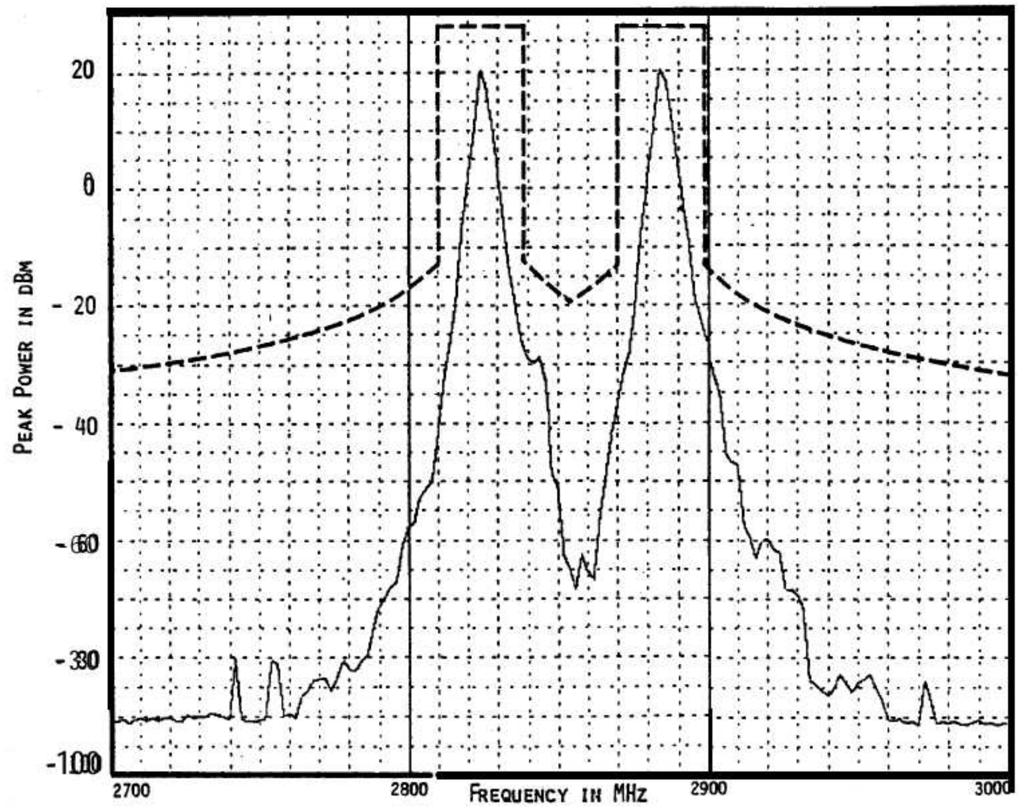
Note that the steep roll-off below the pass band is a function of waveguide filters and is related to the waveguide cut-off.

3.2.11.8 Summary of the use of Filters

To summarise; in conventional radars the use of filters is feasible to control emissions around or about the OOB/SE boundary in some cases. It has been shown that filters can be used for radars operating on single channels in S-Band. This may be extended to multi-channel systems in this band to control radars operating near the band edge. Extensions to wider pass bands, higher frequencies, and particularly to faster roll off requirements need to be considered on a case by case basis. What can be said with confidence however, is that in the region of the harmonic frequencies for conventional radars, filters can provide suppression without incurring excess losses. The use of filters in active array radars is more problematic.

Figure 3.2.11-22 shows an example of what can be achieved by the combination of a high Q tube associated with a band-pass filter. This is an ASR8 transmitter which uses two fixed tuned Klystron amplifiers each filtered by a Band-pass diplexer.

Figure 3.2.11-22 ASR8 Output Spectrum



3.2.12 The Effects of Filtering on Radar Pulses

In order to transmit a pulse without any distortion it is necessary in theory to have an infinite bandwidth, in practice however systems do have to limit the bandwidth. In this section some consideration is given to what level of bandwidth limiting is acceptable for radar pulses.

Considering a simple rectangular pulse of 1μs width with an 18 ns rise and fall time. The spectrum of this 1μs pulse is given in Figure 3.2.12-1, the time response of this spectrum is given in Figure 3.2.12-2.

Figure 3.2.12-1 Spectrum of 1μs pulse

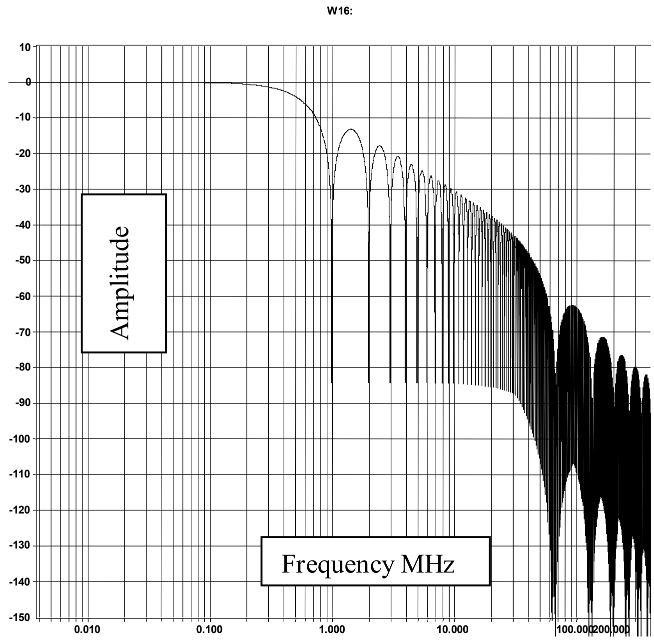


Figure 3.2.12-2 Time Response 1 μs Pulse

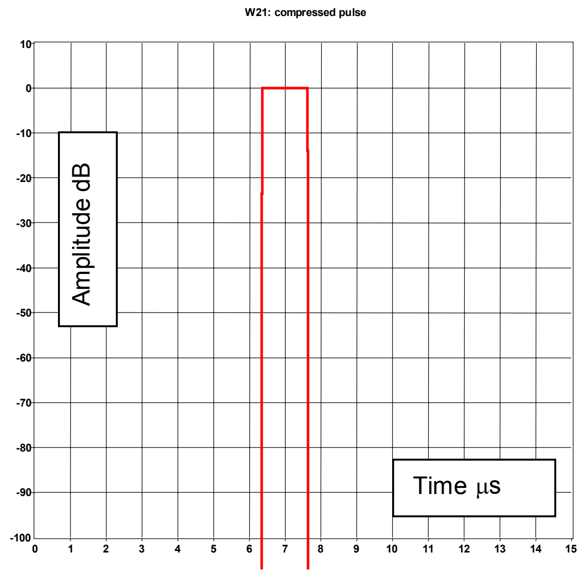
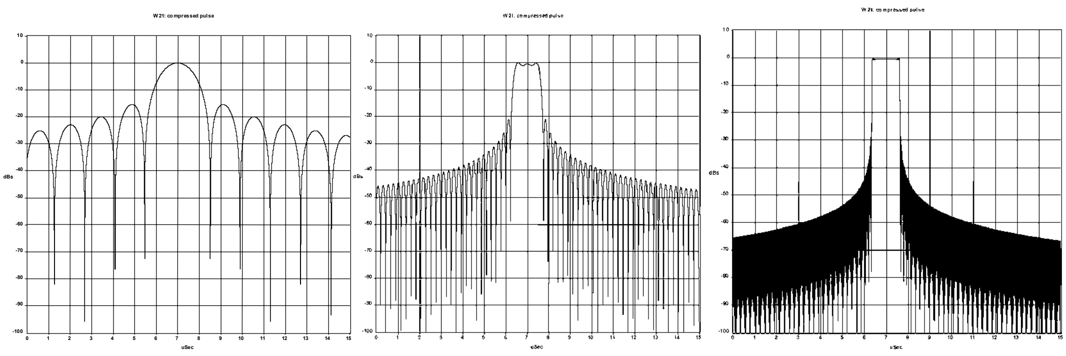


Figure 3.2.12-3 shows the time responses achieved if the pulse is filtered using a rectangular window for filtering at the -3, -20 & -40 dB points. The -3 dB filter gives rise to a time pulse which is much wider and distorted in shape, with time sidelobes of -15 dB. The -20 dB width filter preserves the basic width of the pulse better but has a high level of ripple

and -20 dB sidelobes. The -40dB filter recovers the full shape of the pulse but the band limiting effect does lead to some low-level time sidelobes below -30 dB.

Figure 3.2.12-3 Filtered Time Response



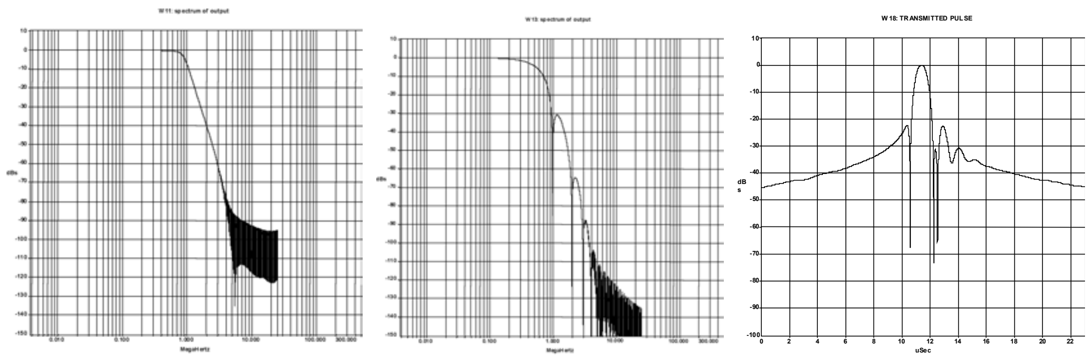
3 dB Filter **20 dB Filter** **40 dB Filter**

It can be seen in Figure 3.2.12-3 that as the spectrum is progressively filtered with narrower window widths the distortion of the time response increases. The effect of the filter is to progressively increase the level of the sidelobes and distortion of the main-lobe pulse shape. Once the rectangular filter is narrower than the main-lobe width of the spectrum, then the time response tends to the form of a Sin(x)/(x) shape, it now being the Fourier transform of a rectangular spectrum. In the limit the level of filtering that can be applied depends on the radar application and the level of distortion that can be tolerated. At first consideration the 3 dB filter is unacceptable, the 20 dB is marginal and the 40 dB is acceptable.

The results in Figure 3.2.12-3 were generated using a rectangular filter window, the distortion of the time response also depends on the rate of filter roll-off as well as the bandwidth.

Considering a filter with a finite roll-off. Figure 3.2.12-4 shows the time response achieved using a Butterworth filter of 2 MHz. The results show the filter shape applied to a spectrum as shown in Figure 3.2.12-1, the resulting filtered spectrum, and the time response of the filtered pulse.

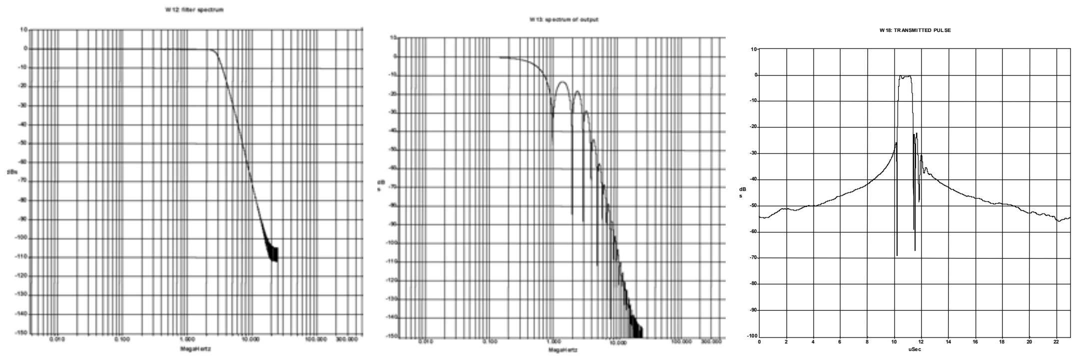
Figure 3.2.12-4 13 Section Butterworth Filter 10 dB BW = 2 MHz



Filter Shape **Spectrum** **Time Response**

This is equivalent to filtering the pulse with a pass bandwidth equal to the pulse main lobe width. This results in a highly distorted pulse response with high sidelobes. The spectrum is suppressed outside the 3dB spectral width.

Figure 3.2.12-5 13 Section Butterworth Filter 10 dB BW = 7 MHz



Filter Shape **Spectrum** **Time Response**

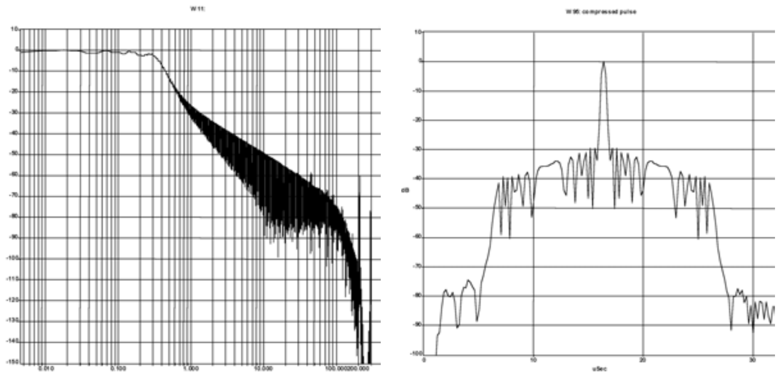
Figure 3.2.12-5 shows the pulse now filtered with a 7 MHz filter this is equivalent to filtering the pulse at the -20 dB spectral bandwidth which is equivalent to filtering at the necessary bandwidth.

This results in a time response that is much better preserved when compared to the -3 dB filter, however time sidelobes are still apparent and this may not be acceptable. The filter used is quite long, and in practice it may be preferable for insertion loss reasons, to use a shorter filter, this could improve the time response at the expense of less suppression of the spectrum.

The pulses considered above are for uncompressed pulses, it is now required to look at the effect on compressed pulses. If we consider a chirped signal of 1 MHz, this will have the same compressed bandwidth as the uncompressed 1μs signal considered above, these two pulses would have very similar range resolution characteristics.

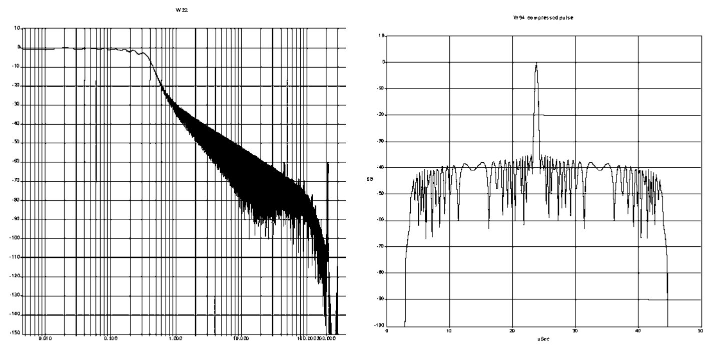
Two pulse lengths have been chosen 40 and 80 μs both of these are typical of what would be used in ATC radars. Figure 3.2.12-6 shows the spectrum and time response of the 40 μs pulse. Figure 3.2.12-7 shows the spectrum and pulse response of the 80 μs pulse.

Figure 3.2.12-6 Spectrum and time response of a 1 MHz x 40μs Pulse



Spectrum **Time Response**

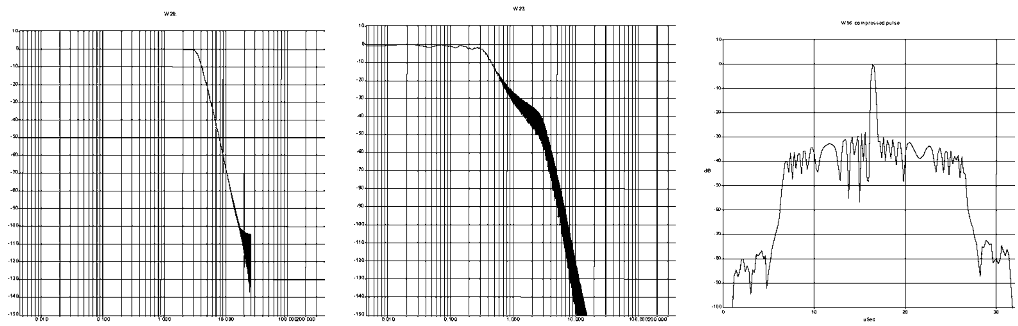
Figure 3.2.12-7 Spectrum and time response of a 1 MHz x 80μs Pulse



Spectrum **Time Response**

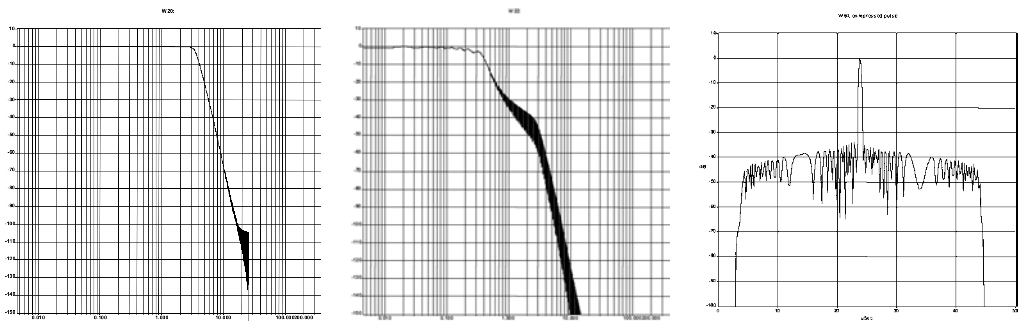
Applying a similar filter of 6 MHz to the two chirped pulses the following results are achieved for the two pulse lengths. This is equivalent to filtering the spectrum at the necessary bandwidth. Figures 3.2.12-8 and 3.2.12-9 show the filter shape applied, the resulting spectrum and time response[24].

Figure 3.2.12-8 Filtered Chirped Pulse 40μs



Filter Shape **Spectrum** **Time Response**

Figure 3.2.12-9 Filtered Chirped Pulse 80μs



Filter Shape **Spectrum** **Time Response**

The filter has much less of an effect on the chirped pulses than the uncompressed pulse and in both cases, the time response is acceptable. This is because the compressed pulse spectrum is much more contained than the uncompressed pulse spectrum and hence is

[24] The time response is at the output of the pulse compressor

less effected by the filtering. The effect of the filter is marginally less on the 80 µs pulse than on the 40 µs pulse, again this is because the larger time bandwidth product of the longer pulse leads to a more rectangular constrained spectrum.

This work indicates that it is possible to filter a spectrum using a band pass filter of between the -20 and -40 dB bandwidth of the spectrum. A filter set at the -40 dB bandwidth can be used to constrain the roll-off in the OOB region in line with the new design aims, this should enable the current specified 20dB/dec roll-off to be increased.

This work shows that filters of around the necessary bandwidth could also be used to constrain the spectrum in the region between the -20 and -40 dB bandwidth regions this could be used to reduce the 40 dB bandwidth. The exact width of the filter that can be used depends on the acceptable distortion and the roll-off required outside the pass band.

Results from the US have shown how it is possible to produce very narrow spectra by the use of filters.

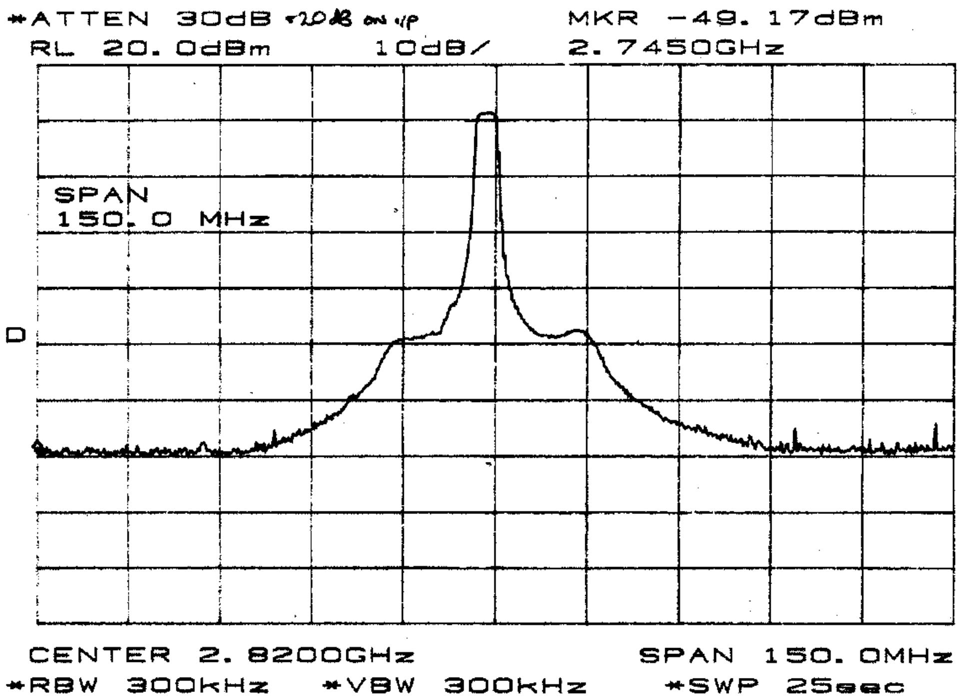
It must be remembered however that the type of filtering considered in this section only applies to single frequency radars, the types of filtering discussed are not appropriate to multi-frequency radars.

3.2.13 Design of Up-Conversion

As well as the shape of the drive pulse, other features in the transmit chain can introduce unwanted emissions. Non-linearity in the system can give rise to spurious mixing products of the fundamental and other signals in the system. Also, insufficient attention being paid to oscillator and filter design can lead to noise side-bands being produced. The class C amplifier has a high gain to small signals and can amplify the phase noise of the amplifier. Because the main pulse is in limit, it is not amplified to the same extent as the small signals. This results in the phase noise amplitude increasing with respect to the main pulse. This is shown in Figure 3.2.13-1 where the sideband shoulders of the TWT output are only 40 dB below the main pulse.

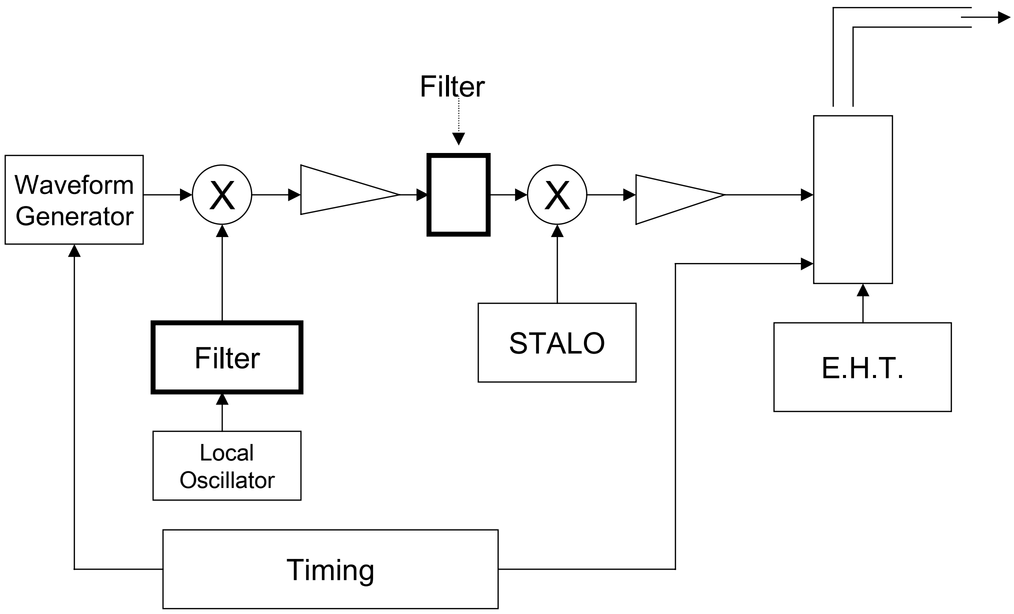
Figure 3.2.13-2 shows a TWT transmitter with filters on the 1st local oscillator and mixer outputs. Narrow band filters cannot be fitted to the Stalo or final mixer outputs because of the frequency agility of this type of transmitter.

Figure 3.2.13-1 TWT Transmitter Spectrum[25]



[25] The noise floor is limited by the Spectrum Analyser's instrumentation noise.

Figure 3.2.13-2 TWT Transmitter Block Diagram



3.2.14 Signal-to-Noise Degradation due to Interference

The detection performance of a radar is dependent on the ratio of the received signal to the noise in the receiver. The sources of this noise are the thermal noise from the sky and the internally generated noise in the receiver and antenna. Any noise-like interference will add to this noise and cause a reduction in the S/N and the detection range of the radar. The following equation shows the relationship between the reduction in S/N and the Interference level.

$$\Delta(S/N) = \frac{(S/N)}{(S/(N+I))} = \frac{N+I}{N} = 1+\frac{I}{N} \qquad \text{Equation 3.2.14-1}$$

where -

S = Signal power

N = Noise power

I = Interference power

Table 3.2.14-1 and Figure 3.2.14-1 shows the reduction in S/N as a function of the interference from –20 dB up to 5 dB with respect to the noise level. At the current ITU-R Recommendation M.1464[26] recommendation of I/N = -6 dB, there is a 1 dB reduction in the S/N, which will cause a 3 to 10% reduction in Pd which would compromise the safety-of-life standards. Even an I/N of –9 dB would cause a ½ dB reduction in S/N; this is still a significant reduction.

Figure 3.2.14-2 shows the S/N plotted against Pd for a Swerling 1 target and a single radar pulse. Figure 3.2.14-3 shows the effect of a 1 dB reduction in the S/N. At the most sensitive area around the 40% Pd region, there is an 8% loss in Pd. Further explanations regarding the effect of a reduction in S/N on Pd are given in section 3.3.

The loss in performance could be recovered by increasing the signal level 'S'; but this requires an increase in the transmitter power or pulse length. Increasing the transmitter power may require a new, more powerful transmitter at significant expense as transmitters do not have spare capacity built-in. Increasing the pulse length also requires an increase in the mean power, and degrades the range resolution in radars that do not use pulse compression.

[26] ITU-R Recommendation M.1464 — Characteristics of and protection criteria for radionavigation and meteorological radars operating in the frequency band 2 700-2900 MHz

Table 3.2.14-1 Reduction in S/N due to Interference

Interference level relative to noise (dB)	Signal to noise ratio degradation (dB)
-20	0.04
-19	0.05
-18	0.07
-17	0.09
-16	0.11
-15	0.14
-14	0.17
-13	0.21
-12	0.27
-11	0.33
-10	0.41
-9	0.51
-8	0.64
-7	0.79
-6	0.97
-5	1.19
-4	1.46
-3	1.76
-2	2.12
-1	2.54
0	3.01
1	3.54
2	4.12
3	4.76
4	5.46
5	6.19

Figure 3.2.14-1 S/N reduction due to Interference

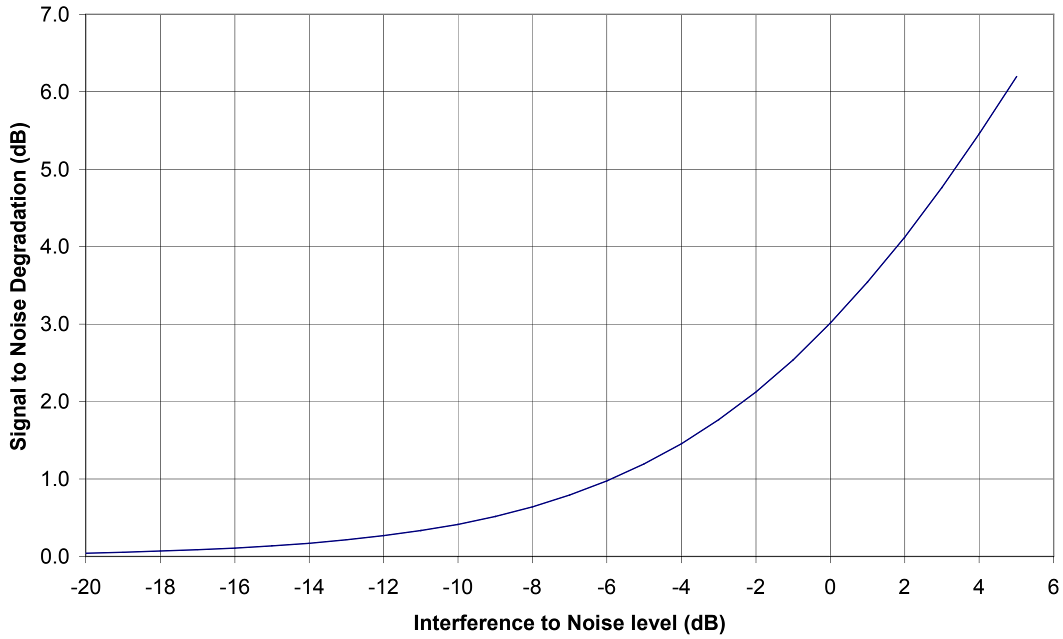


Figure 3.2.14-2 Probability of Detection v. Signal/Noise for a Swerling 1 target

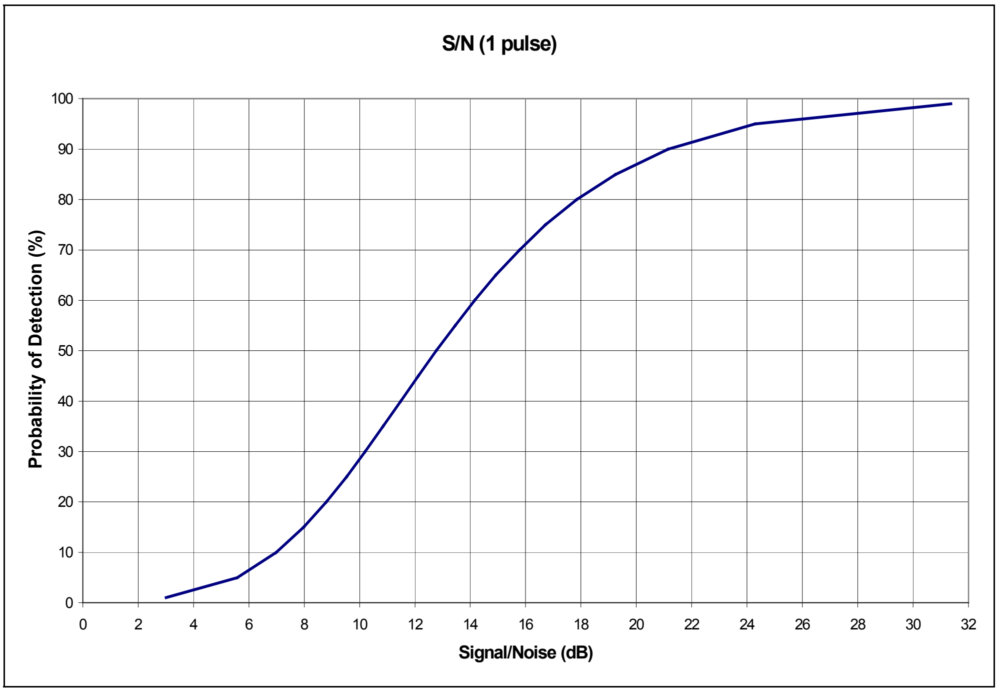
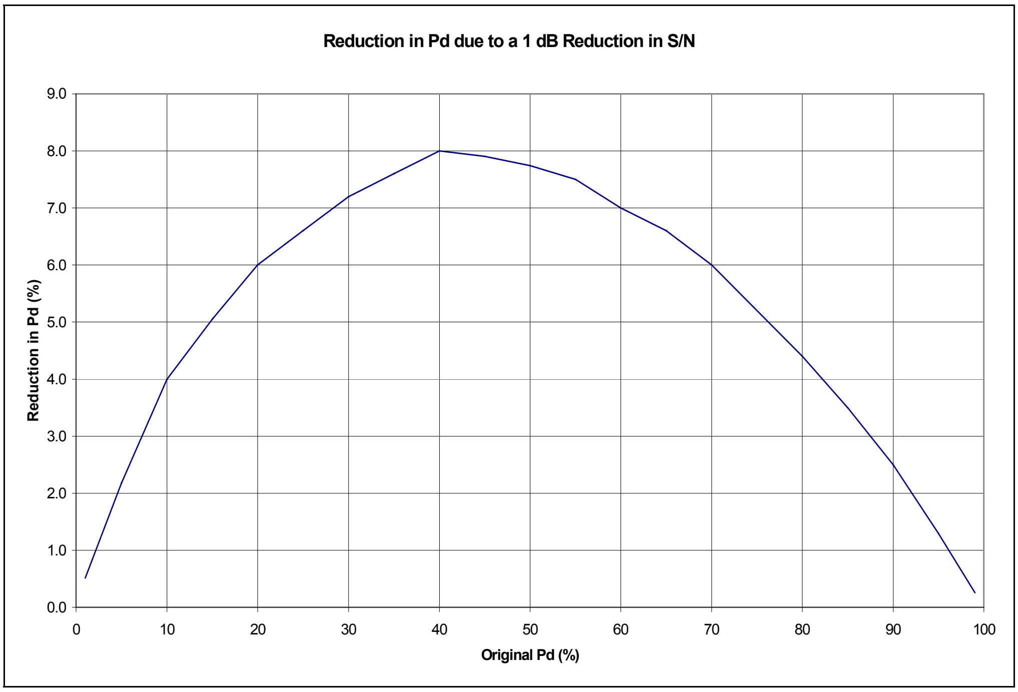


Figure 3.2.14-3 Reduction in Pd due to a 1dB reduction in S/N



3.2.15 Reduction of the Necessary Bandwidth

So far the mitigation options discussed have concentrated on constraining the transmitted energy as closely as possible to the Necessary Bandwidth defined by the range resolution requirements. This requirement comes from the simple relationship that Resolution $\propto$ 1/Bandwidth.

The mechanism of this is that a radar transmitting a long pulse will have a greater detection range than if it were transmitting a short pulse of the same peak power, because the detection is a direct function of the transmitted energy (power x pulse length). The bandwidth is narrower and a matched receive filter will have less noise and will therefore detect a smaller signal.

However there are drawbacks to using longer pulses. The range cell size, and therefore the range resolution, is a function of the pulse length; objects close together in range can only be separately resolved by short pulses. Large range cells also have the problem of reflecting larger clutter echoes from land, sea or rain. If the range cell size is doubled, the clutter echo will also double, while the target will not (assuming that the target is less than a range cell and the clutter is homogeneous in range). This will reduce a radar's ability to detect targets that are obscured by clutter. Table 3.2.15-1 shows the relationship between pulse length, bandwidth and range cell size.

Table 3.2.15-1 Pulse Length

Pulse Length (μs)	3 dB Bandwidth (MHz)	Range Cell (metres)
10.0	0.1	1500
5.0	0.2	750
2.0	0.5	300
1.0	1.0	150
0.5	2.0	75
0.4	2.5	60
0.2	5.0	30
0.1	10.0	15
0.05	20.0	7.5
0.04	25.0	6.0

3.2.16 High Range Resolution

High Range Resolution techniques are used in the research, space and military fields for resolving targets that are close together and for imaging processes.

The use of High Range Resolution in radars offers the means of improving the performance and extracting information about the target, or for resolving two or more closely spaced targets. If the range resolution is sufficiently fine, then an image of the target's reflector locations can be generated. This data, together with the amplitudes of the individual scatterers, can then be used for target identification.

However, to obtain high range resolution generally requires either a very short pulse length or a very wide within-pulse swept bandwidth that can be compressed on receive to form a narrow receive pulse. Stepped frequencies may be used instead to synthesise a swept frequency. But all these methods require the radar to use a wide frequency spectrum.

Techniques for resolving targets that are closely spaced in range without using a wide bandwidth are also being investigated. These involve identifying the strongest target return in a combined target echo and subtracting from the combined echo a profile of the system response, thus removing that target and its sidelobes. The process is then repeated on the remaining radar echo to identify other individual targets. These profiles can be in the frequency or time domains[27]. However the process requires a high S/N ratio (in excess of 20 dB), a large dynamic range (up to 60 dB) and it is computationally complex requiring a very significant increase in the signal processing power of a radar.

To provide a higher S/N ratio at long range in a radar would require a significant increase in the transmitter output power level; for example to provide an extra 5 dB of S/N, a solid state ATC radar with a 15 kW transmitter would need a transmitter power of 48 kW. As well as involving a major transmitter change, the circulator, T/R cell, rotating joint and antenna feed would all require uprating to handle the increased power level. While possibly saving bandwidth this would be at the expense of becoming a bigger interference source and increasing the system cost.

Alternatively the range of the radar could be reduced to 75% of its previous value. At this reduced range, the S/N ratio will be 5dB above the previous maximum range value. The area of radar cover will also be reduced to 56% of its previous coverage.

Also the presence of clutter, such as echoes from land, sea, and weather, adds further responses to the combined echo and restricts the use of these HRR processes in some situations. As the civil uses of radar involve the detection of targets in clutter, this limits the usefulness of these methods of achieving high range resolution.

[27] "Techniques to Improve the CLEAN Deconvolution Algorithm", A Freedman, R Bose & B D Steinberg, Journal of the Franklin Institute Vol.332B No.5 1995.

3.2.17 Frequency Diversity

Frequency diversity is used in radar systems to improve the Probability of Detection; it is particularly used in ATC and defence radars.

Driven transmitters use two or more bursts of pulses on different frequencies in a single beamwidth as the beam scans across a target. Magnetron radars may use two transmitters on different frequencies for reliability and for the improved detection; in this case there is also a doubling of the transmitter power, with a further 3 dB improvement in the performance.

Radar Targets are generally classified according to their RCS fluctuation properties; a non-fluctuating model and four fluctuating models which have been classified into four Swerling types (the non fluctuating model is often referred to as “Swerling 0“):

Swerling 0	No fluctuation	steady target with constant RCS
Swerling 1	Slow fluctuation	multiple scattering points
Swerling 2	Fast fluctuation	multiple scattering points
Swerling 3	Slow fluctuation	one major scattering point
Swerling 4	Fast fluctuation	one major scattering point

Swerling 0 targets are steady targets that do not fluctuate with time or aspect angle; objects approaching a spherical shape represent this class. Aluminium spheres used as radar test targets are examples of this class of radar targets.

Swerling 1 targets consist of multiple scattering elements and whose RCS is virtually constant from one pulse to the next, but are statistically independent from scan to scan, typically a jet aircraft.

Swerling 2 targets consist of multiple scattering elements and whose RCS has a fast fluctuation and is statistically independent from pulse to pulse, typically a propeller aircraft, or an aircraft illuminated by pulses whose frequency is changing.

Swerling 3 targets consist of one major scattering element and a number of minor scatterers, and whose RCS is virtually constant from one pulse to the next, but are statistically independent from scan to scan, typically a missile.

Swerling 4 targets consist of one major scattering element and a number of minor scatterers, and whose RCS has a fast fluctuation and is statistically independent from pulse to pulse, typically a missile illuminated by pulses whose frequency is changing.

The use of two frequencies in a single “look” decorrelates a target and moves it from a Swerling Type 1 towards a Swerling Type 2 (“mixed” Swerling case).

The improved S/N for a given probability of detection is given by[28]:

$$S/N_O = S/N(n_{sw1}) + S/N(F_{sw2}) - S/N(F_{sw1}) \qquad \text{Equation 3.2.17-1}$$

Where

S/N_O = Effective Signal to Noise

n = total number of pulses

F = number of frequencies

$SW_{\#}$ = Swerling case

[28] "Recent Developments in Target Models for Radar Dection Analysis" P Swerling, AGARD Conference Proceeding No 66 on Advanced Radar Systems 1970.

For a typical ATC radar with 18 “hits” (target returns) in a beamwidth the single pulse S/N required for a Pd of 80% and a Pfa of 10^-6 is:

S/N_0 = 8.5 dB when one frequency is used (a Swerling 1 target).

But when two frequencies are used (9 pulses on each frequency) the required S/N for the same Pd and Pfa becomes:

S/N_0 = 5.94 dB

This is an improvement of 2.56 dB, a significant performance improvement. A single frequency transmitter would have to increase its output power by 80% to achieve the same performance as one operating on two frequencies.

3.2.18 Options for Mitigation

3.2.18.1 Magnetron Transmitters

The Necessary Bandwidth of a magnetron transmitter is determined by the pulse length and the pulse rise and fall-times. The detection range and range resolution requirements determine the pulse length while the risetime is constrained to a narrow band if stable operation of the magnetron is to be achieved, typically 15 to 60ns depending on the frequency band and magnetron type. This leaves little scope for a change in these parameters. If the Spurious Emissions of a magnetron transmitter must be reduced, a filter after the magnetron can be fitted; See Section 3.2.11 for a description of the filter types and their effect.

Coaxial magnetrons have a better spectrum close to the centre frequency completely eliminating the low side “porch” and are more stable exhibiting less frequency drift with temperature than a conventional magnetron. However they have a hump about 100 MHz from the centre frequency and are not suitable for generating very short pulses; see Section 3.2.4 for a description of magnetrons. Due to the energy storage requirements of the coaxial cavity their use in very short pulse systems is limited. The up-front cost of a coaxial magnetron is higher than a conventional design however over the life of the radar the cost can be much lower due to the extended life of the tube[29]. In summary coaxial magnetrons give a cleaner spectrum close-in and last longer than conventional magnetrons.

From measurements and manufacturers information it is not clear if the coaxial magnetron gives better SE performance over conventional magnetron designs. However the Spurious Emissions of a magnetron can be significantly reduced by fitting a filter between the transmitter and the antenna, see Section 3.2.11 for a description of the filter options.

3.2.18.2 Driven Tube Transmitters

These can produce the same energy pulses as a magnetron, but using longer pulses at a lower power level, and recovering the range resolution by using frequency coding and pulse compression. Their risetime lies in the range 20 to 80ns and this, coupled with the longer pulse, gives a better spectrum than an equivalent magnetron. The Spurious Emissions are also lower.

However driven systems, due to their long pulses, need to use short fill-in pulses to overcome the minimum range dictated by the long pulse. These pulses are at a much lower duty cycle and result in spectra with much lower peak transmitter power values.

In some applications, driven tubes may be superseded by active arrays (see 3.2.18.4). However there will be some applications where wide bandwidths and high powers are needed, such as ECM for example, where driven tube systems will remain for the foreseeable future.

3.2.18.3 Solid State Transmitters

These operate at a lower peak power than tube transmitters and use long frequency coded pulses to achieve the required pulse energy. The risetime is typically 150 to 250ns giving the best spectrum efficiency.

Until recently, for medium to high-power applications where wide bandwidths were required, driven tubes were the only solution. However, recent advances in high power silicon transistors technology have increased their power and bandwidth capabilities making Solid State transmitters a practical option. There are still some issues associated with prime

[29] This is more significant in professional systems where tubes are changed when the system performance falls below a pre-set limit. It may not be as significant in other systems where tube replacement may only take place after catastrophic failure of the tube takes place.

power conditioning and environmental conditions that need to be fully addressed before solid state systems can be said to be a complete replacement for these systems.

Like the driven tube transmitters, solid-state systems due to their long pulses need to use short fill-in pulses to overcome the minimum range dictated by the long pulse. These pulses are at a much lower duty cycle and result in spectra with much lower peak transmitter power values.

Radars using solid state transmitters are more expensive and more complex than radars with magnetron transmitters having an equivalent mean power and resolution requirement. Other factors however need to be considered, an important factor in professional systems is the cost of ownership. For example, in an ATC application where the requirement is for a high continuity of service, it is generally considered that a solid state system with its "soft fail" characteristics can in many cases provide a more cost effective solution than the magnetron. This is particularly true if dual magnetron transmitters are required to maintain the continuity of service.

Solid-state transmitters have the problem of the short range pulses to consider, these pulse have the same necessary bandwidth as the long pulses (because the range resolution is the same), however, their short time makes them suitable for short range applications. Their spectrum however is not as well controlled as the chirped pulses with their large time bandwidth products, and spreads out further in the frequency domain. The energy in a transmitted short pulse is however lower than that for the long pulses as their duty cycle is lower; see section 3.2.6. It may be possible, subject to detection range requirements, to further reduce the effects of interference to other systems by reducing the peak power of the pulse. This could be achieved in a solid state system by turning off selected transistors or modules in the power amplifiers.

3.2.18.4 Active Arrays

For many higher power applications the active array radar is likely to provide the replacement for driven tube systems.

Active arrays have all the benefits of solid state and give the same opportunity for spectrum control by use of long time bandwidth product pulses. The ability to filter the active array for SE is more limited than for the lumped transmitters. Active arrays can also use a technique of transmit null steering to reduce the level of RF signal transmitted in a given direction. Unlike sector blanking, this method removes both main-beam and sidelobe radiation. The technique however is based on open loop control and is not as robust as receive beam nulling, the method is limited by the errors in the element control electronics and this limits the depth of the null that can be produced to the "average" level of the side-lobes.

3.2.18.5 Antenna Options

The use of good antenna design coupled with modern manufacturing techniques has led to the ability to control the unwanted emission in terms of sidelobes to a much higher level than in the past. However generally this leads to larger antennas and this has a knock-on effect in terms of larger tower and turning gear size and the possible requirements to use a radome - all this adds further to the cost.

3.2.18.6 Design Rules to Mitigate Spectrum Usage

- Choose a driven system
- Use the longest integration time possible (i.e. longest dwell, subject to the update rate)
- Select a transmitter with the highest duty cycle subject to the peak/ mean power considerations
- Determine the pulse energy for the required detection range
- Select the power level and pulse length

- Use the longest uncompressed pulse
- Select the longest range resolution acceptable
- Determine the compressed pulse length
- Use a pulse compression waveform
- Design a Pulse Compression law to meet the resolution and time sidelobes requirements that has a minimum sweep width
- Use the slowest risetime acceptable
- Minimise the use of fill-in short pulses
- Design the up-converter chain to generate the minimum amount of transmitter spurii and noise
- Add filters, subject to the insertion loss and distortion, to further reduce unwanted emissions in both OOB and SE regions
- Use the lowest sidelobe (co- & cross-polar) antenna possible

3.2.18.7 Application of Mitigation Options with Respect to UK applications

3.2.18.7.1 L-Band ATC

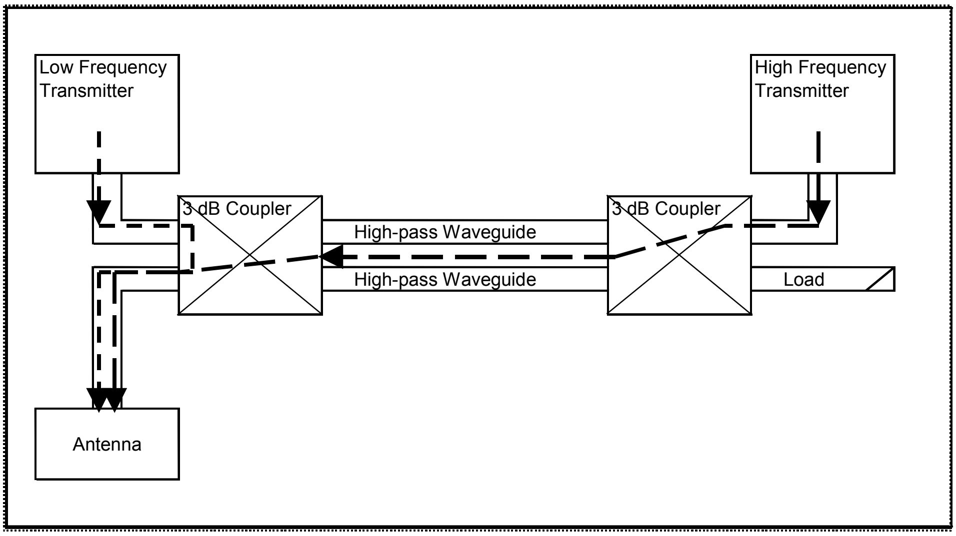
3.2.18.7.1.1 Current Systems

All UK's L-Band systems operate with tubes, the majority with driven TWTs. These systems are generally optimised in terms of pulse length and PRR to the duty cycle supported by the tubes hence there is generally little scope for increasing the time bandwidth product of the tube. Such a modification, if possible, would require the replacement of the sweep generator and the pulse compression system and re-timing of the radar. The only option to improve these systems is to add filters to clean up the spectrum further.

For the remaining magnetron systems, the unwanted emissions are likely to be very similar in nature to the S-Band magnetrons. If the output is unacceptable, then the only option is to add extra filters and accept the loss in system performance consequent on adding the extra loss into the feed chain.

This L-Band system uses two transmitters combined with a version of the constant impedance filter known as a Low-Pass/High-Pass Diplexer as shown in Figure 3.2.18-1. The energy from the Low Frequency Transmitter is rejected by the High Pass waveguide and is reflected back through the coupler to the Antenna. The energy from the High Frequency Transmitter passes along the High Pass waveguide to the Antenna. Similarly, the received signals are directed into the appropriate channel.

Figure 3.2.18-1 Low-Pass /High-Pass Diplexer



This is a low Q system and whilst it provides some attenuation in the OOB region to the high side of the low frequency transmitter and to the low side of the high frequency transmitter, it provides little rejection in the SE region.

3.2.18.7.1.2 Future Systems

The majority of new L-Band ATC systems likely to be installed in the UK will operate with solid-state transmitters so their performance in terms of unwanted emissions and spectrum occupancy is likely to be good, further mitigation may be possible on these systems by optimising the waveform and adding filters.

3.2.18.7.2 S-Band ATC

3.2.18.7.2.1 Current Systems

Of the three types of systems in use, the solid state system has the best SE performance and also has the narrowest OOB region. The TWT systems have a wider OOB region but meet the requirements of their appropriate mask. The system measurements had a minor non-compliance at the second harmonic. This could be rectified by the inclusion of a low-pass filter in the antenna feed line.

None of the magnetron systems in use were measured, however they are likely to have a very similar response to the results presented for the naval magnetron see Figure 3.1.2-5. The only option available for magnetron transmitters is to add filters.

3.2.18.7.2.2 Future Systems

Future systems used for ATC applications are likely to be solid state so should have good SE performance and minimise the required OOB region.

If single frequency magnetron systems are still used they will have to meet the requirements laid down for Cat B[30] SE limits and will have to be provided with appropriate filters.

3.2.18.7.3 SSR (L-Band)

SSR systems are very regulated and have their emissions well defined. The Standard NATO Agreement (STANAG) requirements are tighter than the ICAO and meet the requirements of the Cat A ITU regulations.

[30] ITU Radio Regulations, Appendix 3

Any further improvement could only be achieved by adding filters. The signals in space are defined by international agreement and could not be changed in the short term due to the massive installed base of interrogators and transponders.

3.2.18.7.4 PAR (X-Band)

The existing PAR Systems in the UK are currently being replaced with active array based systems. They should be capable of improved SE performance over the previous magnetron based systems. Little is known of the technical performance of the new military systems in terms of SE by the authors of this report. The PARs will be going into service over the next few years so will have to meet the requirements of Cat A emissions.

They are likely to be in service for greater than 20 years and it is unlikely that any further mitigation options are appropriate to consider at this time.

3.2.18.7.5 Airborne Weather (X-Band)

These systems are moving from magnetron to solid-state and little is known of the detailed waveforms being used and hence the OOB emissions. However they use longer waveforms which will give an improvement over magnetron systems. The radar pulse energy is the product of the pulse power level and the pulse length. A solid state transmitter can match a magnetron transmitter by using a longer pulse at a lower power level, which will reduce the interference with other radars. Extra filtering is also a possibility in these systems as generally the slight reduction in the EIRP that results is not a problem. Due to the nature of weather radar there is generally a large margin on the detection performance, thus the system can tolerate the reduction in EIRP.

3.2.18.7.6 Ground Weather (C-Band)

3.2.18.7.6.1 Current Systems

These are all magnetron single frequency systems using coaxial magnetrons. The system measured has a minor non-compliance at the OOB/SE boundary but a much larger non-compliance due to the high frequency "hump". They also do not meet the class B SE limit 0f -100 dB. The only option available is to add a filter.

3.2.18.7.6.2 Future Systems

In the short term future systems will need to include more output filters to improve the SE response. In the longer term much lower power systems could be developed to take advantage of the longer integration time possible on weather radars[31]. These could use long pulses with slow risetimes to improve the OOB response.

3.2.18.7.7 Marine VTS /ASDE Airfield Radars (X-Band)

3.2.18.7.7.1 Current Systems

Many of these systems do not meet the class A limits. All these systems currently use magnetrons, so the only options are possibly an improved magnetron which is socket compatible for existing systems and the use of filters. Given the number of magnetrons sold for these types of radars it may be possible to develop some improvements in the magnetrons to improve the OOB performance particularly the Π-1[32] resonance. Filters are also an option for the larger systems. Systems that have the transmitter/rotating joint directly coupled to the antenna may have more of a problem.

3.2.18.7.7.2 Future Systems

The use of solid state and active arrays could be advantageous for Airfield Radar and ASDE systems. There is already a solid state GCA radar available in the US along with the ASDE X and X-Band solid state systems. All these operate with long pulses on much lower

[31] See Section 3.1.2

[32] The Π-1 mode has a mode number one less than the number of resonant cavities. This mode cannot be sustained in a symetrical cavity so it precesses round the cavity. See also Section 3.4

power than their magnetron forbears. However they all use 9 to 9.2 GHz unlike the UK systems that operate in the band 9.3 to 9.5 GHz.

Marine and VTS systems have the further requirement to trigger Radar Beacons, Search and Rescue Radar Transponders, and Radar Target Enhancers which puts an extra burden on the design.

3.2.18.7.7.2.1 Radar Beacons (RACONs)

A typical modern RACON operates in both S-Band and X-Band, sending a response on the same frequency (± 2 MHz) as the interrogating radar. It will respond to radar pulses from 50 to 2000 ns in length. The RACON sensitivity is programmable from 0 to –50 dBm. Table 3.2.17-1 below shows the signal strength that the RACON would receive from 2 kW and 100 W radars at various ranges. The RACON can respond to the 100 W radar out to 40 km. The output of a typical RACON is 1W (30dBm) into an antenna with a gain of 6dBi giving an EIRP of 4W.

Table 3.2.17-1 RACON Sensitivity

Range (km)	RACON Rx Power (dBm)	
	100 W Tx Radar	2 kW Tx Radar
1	-18.0	-5.0
2	-24.0	-11.0
5	-32.0	-19.0
10	-38.0	-25.0
20	-44.0	-31.0
30	-47.5	-34.5
40	-50.0	-37.0
50	-52.0	-39.0

3.2.18.7.7.2.2 Search and Rescue Radar Transponders (SARTs)

SARTs are electronic units which react to the emissions of X-Band radars. When switched on, each time a SART detects a pulse from an X-Band radar, it transmits a signal which is displayed on the screen of the radar which activated it as a train of 12 dots. All compulsory Global Maritime Distress and Safety System (GMDSS) vessels up to 500 tons must carry at least one SART. Above 500 tons they must carry two.

When triggered, a SART sweeps the band 9.2 – 9.5 GHz in 7.5µs forward and 0.4µs back, 12 times and this will produce an echo on the interrogating radar's screen each time the sweep passes through the radar receiver pass band.

In general a SART receiver has a sensitivity of –50 dBm and a radiated power of 400 – 500 mW.

3.2.18.7.7.2.3 Radar Target Enhancers (RTEs)

RTEs are also sometimes referred to as Active Radar Reflectors. They are usually mounted on yachts, small vessels and rigid inflatable boats to provide a larger radar echo than that generated by the vessel itself. They amplify and retransmit any X-Band radar pulse that they receive. Their sensitivity is generally –50 dBm with an output level of 500 – 600 mW EIRP.

The range at which a RACON, SART or RTE is triggered depends on the power and antenna gain and height of the radar, and the position and height of the transponder. An airborne search and rescue aircraft or helicopter will be able to detect a transponder from a greater range than a surface vessel which will suffer multipath lobing and the horizon limit.

3.2.18.7.8 Ku-Band ASDE

3.2.18.7.8.1 Current Systems

The existing systems in the UK are magnetron based and they have problems meeting the Cat A limits in the OOB region; it appears to be due to a spurious magnetron mode, filtering may be possible.

3.2.18.7.8.2 Future Systems

For future systems, the use of solid state systems is more problematical at Ku-Band. X-Band systems have benefited considerably from the development of solid state power components carried out to meet military requirements, where there are many X-Band programmes.

The requirement for Ku-Band components is much lower and more expensive and would have to be funded from the ASDE market place. At a recent seminar[33], the following views were expressed.

"The largest growth however has been at X-Band (around 9 GHz). Here the development of lower cost, high performance components, the inherent lower sensitivity to rain clutter coupled with recent developments in both transceiver and antenna technology have yielded high performance lower cost systems. Recently many authorities has adopted X-Band radars including, the USA, Canada , and many European countries. Arguably, X-Band is now the frequency of choice for most new systems.

The growth of interest in the airport surface movement application is considerable. Radar remains the primary non co-operative sensor, but systems will increasingly use this in conjunction with other types of sensor to provide an integrated data fused solution to the surveillance problem.

Of existing technologies, X-Band (9 GHz) radar is currently being widely adopted due to advances in technology at this frequency band and lower inherent clutter difficulties than at least some of its competitors.

New technologies are being researched and considered for this application. What remains clear, however, is that radar will be used as a primary sensor in A-SMGCS for many years to come."

It may be that future developments of ASDE at Ku-Band are limited.

It is in the area of ground movement control that the use of passive tracking systems is being proposed with several trial systems under way.

[33] Dr A K Brown "A Review of Radar as a sensor for Advanced Surface Movement Guidance and Control Systems (A-SMGCS)" IEE Aviation Surveillance Systems Wed 23rd Jan 2002.

3.2.19 Summary

Primary radar detects targets by looking for the reflections from the surface(s) of the targets, i.e. its receiver is optimised for the detection of the transmitted pulses. The prime outputs are the range and bearing of the target; and height in the case of 3-D radars. The degree of resolution of these parameters is defined by the pulse length and the antenna beamwidth. The target size and velocity can also be determined by the amplitude of the echo and the doppler frequency shift. A succession of echoes from the target can then be used to determine the target's track.

When considering the spectral efficiency of a radar in terms of the information content/unit bandwidth used, the output data rate of the radar cannot be used as a measure of the efficiency, as it does not wholly depend on the bandwidth being occupied but is also a function of the amount of signal processing being carried out to extract information.

Given that the receiver is well-matched in bandwidth and there is a need to achieve an adequate signal to noise ratio then the spectral efficiency is wholly related to the total[34] bandwidth used to achieve the required range resolution or range cell size.

For a well-matched system the spectral efficiency depends wholly on the transmitted spectrum which in turn is a function of the transmitter. This determines how close the radar approaches the theoretical limit of N bits/sec/Hz where N is the number of data bits used to describe the contents of each range cell. That is how well the transmitter constrains the transmitted signal to the bandwidth associated with the specified range resolution.

Thus the spectral efficiency is related to how much bandwidth is used to achieve the required range cell size, as in radar range cell size is traded directly for bandwidth. When considering the bandwidth used, due account needs to be taken not only of the necessary bandwidth of the spectrum that is produced but the unused energy spread into the OOB and SE domains.

As described previously in this chapter the spectrum of the radar transmission is determined by the pulse length and the shape of the rise and fall-times. In the case of tube transmitters (i.e. magnetrons, klystrons, TWTs, etc.) the transmitter designer is limited in the range of options for extending the rise and fall-times because of the likely generation of unwanted modes and instability during these transitions from OFF to ON and back to OFF; these instabilities would reduce the ability of the radar to improve the target to clutter and noise ratio.

Although a near rectangular pulse is generated on transmit, the out of band emissions are not processed on reception and therefore could be removed on transmit.

Frequency Selective Surfaces are discussed in Section 3.2.8 but they are narrow band, expensive and have a greater loss than a pure reflective surface.

LPI waveforms have low peak energies but are limited to relatively short ranges by close-in clutter eclipsing distant targets.

Radars with a waveguide run between the transmitter and the antenna will suppress any unwanted signals below the cut-off frequency of the waveguide. A low-pass or band-pass filter after the transmitter offers the most cost-effective method of removing the harmonic and spurii from the transmitted signals. The cut-off frequency must be set to ensure that only the wanted frequency components are radiated.

Work has shown that filters with pass bands equal to the -40dB spectral bandwidth can be used to reduce the OOB emissions. These filters could be used to improve the roll-off in the specified -20dB/dec region. The use of such filters on legacy systems may go someway in helping them to meet the latest requirements for OOB and SE emissions.

[34] The word total refers to all the signal transmitted by the radar in both the necessary bandwidth, OOB and SE domains.

Further rejection can be achieved by setting the filter bandwidth equal to the necessary bandwidth. These bandwidths however can result in a distortion of the pulse shape and their use depends on the application. Filters with bandwidths less than the necessary bandwidth generally result in unacceptable levels of distortion. The distortion of chirped signals is generally less than for unchirped pulses given the same filter bandwidth at equivalent resolution requirements.

ATC radars use two or more frequencies to improve the target detection and decorrelation.

In the limit, bandwidth occupied depends to a first order on the resolution required and the technology used to implement the transmitter. Improvements in the design of transmitters can achieve output spectra close to the theoretical NB. However the achievement of this goal may be at the expense of much higher cost or loss of other features such as frequency agility. The spectrum used is only one of the trade-offs that has to be considered by the designer. However in the current climate of scarce spectrum resource and changes to international regulations, coupled with band sharing etc, much greater account needs to be taken of minimising spectrum occupancy of radars.

Each of the mitigation methods proposed has a cost involved and this will vary significantly with the radar system. Also, modifying an existing system is more expensive than incorporating the design change prior to the build of a new system. In many cases, changes would be made when a system is replaced.

If a low priced, simple radar were to have a complex mitigation method applied to it, the cost per system would be significantly increased and it would be priced out of its market. Conversely if a similar change was made to a high priced, complex radar, the percentage cost increase could be minimal. Table 3.2.19-1 below shows the complexity and cost implications of the proposed mitigation methods.

To reduce the Necessary Bandwidth of a radar would compromise the performance of the radar particularly in its range resolution. However the Out of Band and Spurious Emissions from the transmitter are filtered out in the receiver and could be removed from the transmitter signals with little affect on the radar performance. The limits on what could be achieved are determined by the cost and size of the filtering, which are determined by economic and physical constraints. The ITU are currently considering the levels of permissible unwanted emissions.

Table 3.2.19-1 Mitigation Methods - Complexity and Cost

Mitigation Method	Complexity	Cost	Comment
Magnetron Transmitters			
Fit coax magnetrons	Medium	Low	This will produce a cleaner spectrum; but is dependent on an equivalent coax magnetron being available.
Fit filter between Transmitter & Antenna	Medium	Medium	A filter could be fitted easily into the waveguide run of some radars, but would be more difficult in compact radar systems.

Mitigation Method	Complexity	Cost	Comment
Tube Transmitters			
Fit filters to oscillators & mixers	Medium	Medium	Relatively easy to fit if there is space but signal levels may need adjusting to compensate for the losses in the filters.
Minimise swept frequency and maximise rise and fall-times	Medium	Medium	The frequency sweep and pulse length determine the compressed pulse length, while the tube stability constrains the rise and fall-times.
Use longer pulse length, modify swept frequency and pulse compression	High	Medium	Using a longer pulse length may require that a longer short pulse is required to cover the eclipsed region.
Change to Solid State transmitter	High	High	This would involve major changes to a radar system involving virtually a complete replacement of the transmitter and receiver and significant changes to the signal processing.
Solid State Transmitters			
Minimise swept frequency and maximise rise and fall-times	Medium	Medium	The frequency sweep and pulse length determine the compressed pulse length, and therefore the range resolution.
Use longest possible pulse length	Medium	Medium	Using a longer pulse length may require that a longer short pulse is required to cover the eclipsed region.
Antennae			
Use solid reflector in place of mesh	Low	Medium	This would require the replacement of the antenna and possible upgrading of the motor and bearings due to the increased wind load.
Use latest design and manufacturing methods for low side & back lobes	Medium	Medium	This would require the replacement of the antenna with a new design.
Use single curve reflectors in place of double curved	High	High	This would require the replacement of the antenna with a new design.
Radomes			
Use dielectric space frame in place of metal space frame	Low	Medium	This is a relatively simple replacement task.
Frequency Selective Surfaces			
Frequency selective surfaces (not a cost effective solution)	High	High	A complex design and manufacturing task and only applicable to a few radars.

Mitigation Method	Complexity	Cost	Comment
Harmonic Suppression			
Fit Harmonic Filters	Low	Medium	A filter could be fitted easily into the waveguide run of some radars, but would be more difficult in compact radar systems.

The spectral performance, as has been demonstrated, is a function of both the role of the radar and the technology used to implement the role. It is not possible to calculate for any general class of radar a quantitative figure for the spectral performance. These types of calculations can only be made by modelling specific instantiations of the hardware.

It is however possible to make a qualitative comparison between different radar classes and the technology used.

Table 3.2.19-2 shows a comparison between the classes of radar used in the UK. This is based on an engineering judgement based on knowledge of the transmitter types and the possible application of mitigation options and/or filtering.

In the table the following definitions are used:

- **Bandwidth Control**: The ability to control the necessary bandwidth and match it to the role of the radar.
- **OOB Emission Control**: The ability of the radar to achieve an OOB performance approaching the theoretical shape derived from the necessary bandwidth.
- **Spurious Emission Control**: The ability to control other spurious emissions including harmonics.

Table 3.2.19-2 Table of Spectrum Management Performance

Radar Band	L-Band		S-Band			S-Band Marine		C-Band	X-Band		X-Band ATC			X-Band Marine				Ku-Band
Role →	ATC		ATC			VTS	SOLAS	Weather	Weather		ACR	PAR	ASDE	SOLAS	VTS	Pleasure	Fishing	ASDE
TX Technology →	TWT	Mag	Solid State	TWT	Mag	Mag	Mag	Coaxial Magnetron	Solid State	Mag	Mag	Solid State	Mag	Mag	Mag	Mag	Mag	Mag
Bandwidth Control																		
Excellent			*															
Good	*			*					*			*						
Medium								*										
Poor		*			*	*	*			*	*		*	*	*			*
Very poor																*	*	
OOB Emission Control																		
Excellent			*															
Good												*						
Medium	*			*					*									
Poor		*			*	*	*	*		*	*		*	*	*			*
Very Poor																*	*	
Spurious Emission Control																		
Excellent			*															
Good	*			*				*				*						
Medium		*			*	*	*		*									
Poor										*	*		*	*	*			*
Very Poor																*	*	

Section 3.3

An Investigation into the Radar Receiver Characteristics and Protection Criteria Required for the Protection of Radar Services.

Contents:

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3.3 An Investigation into the Radar Receiver Characteristics and Protection Criteria Required for the Protection of Radar Services

3.3.1 Introduction

This section of the report covers the issues surrounding the technological and operational practices employed by radar systems designers to protect the radar system performance in the presence of an interference source. It also covers the challenges imposed on a radar system in the current environment and also in the projected future environment.

Several interference environments will be discussed, including their impact on the ability of a radar system to maintain its required level of performance.

This section concludes with an overview of the possible technologies that could be implemented to improve the radar systems ability to operate and maintain the required level of service, in an increasingly harsh interference / sharing environment.

The depth of this particular subject depends greatly on the role and type of radar system under consideration, the nature of the interference signal in question and its impact on the performance of the system that the user will accept.

For any interference that passes through the antenna and feed, an attempt to reject the interference should be made as early in the system as possible, in the receiver chain of the radar system. The theoretical interference rejection scenario allows complete in-band rejection at this point. However this is impossible without an accompanying degradation in the genuine signal return as it moves throughout the system, towards the processing device.

A realistic rejection scenario would provide the system with a level of protection against certain types of interference and partial protection against other types, whilst maintaining a significant level of service. This does mean that some types of interference may be present at the front end of the processing device.

The only remedy currently available is to have a suitably sophisticated signal processor that recognises the interference and rejects it.

By performing any kind of interference rejection, the user runs the risk of:

- Allowing certain forms, types or portions of interference to pass through the system unmodified;
- Aggressively degrading genuine target returns;
- Inadvertently rejecting genuine target returns.

In all cases, the system performance can and will be significantly degraded. How devastating this degradation effect may be depends upon:

- The role of the radar system. (e.g. ATC, VTS etc.);
- The service requirements imposed on the system. (e.g. SOL);
- The minimum acceptable performance of the system. (User defined).

The end user must decide how much degradation to accept before performance is deemed below that required.

3.3.2 Current technology used to aid in the protection of radar services

3.3.2.1 Operational Practices and Technology

Several key operational practices are implemented to improve and protect the radar's ability to detect signals returned from maximum range, as discussed below.

3.3.2.1.1 Frequency Selective Down-Conversion

Adopting particular methods of frequency selection through down-conversion can provide the radar system with adequate protection from certain interference signals. Two common methods of frequency selective down-conversion are frequently adopted, they are:

- Direct Down-Conversion;
- Double Down-Conversion.

3.3.2.1.1.1 Direct Down-Conversion

A direct down-conversion method is shown in Figure 3.3.2-1. It shows a single mixer stage protected by front and back end Bandpass filtering, mixing down to an IF of 60MHz. It is clear to see that any interfering frequency components situated at the image distance are directly down converted to IF, as

$$IF = |RF - LO| \text{ Hz}$$ Equation 3.3.2-1

In the IF Case,

$$IF = |1.3 \cdot 10^9 - 1.24 \cdot 10^9|$$
$$\therefore IF = 60MHz$$

For the Image Frequency Case,

$$IF_{image} = |1.18 \cdot 10^9 - 1.24 \cdot 10^9|$$
$$\therefore IF_{image} = 60MHz$$

Figure 3.3.2-1 Direct Down Conversion Process

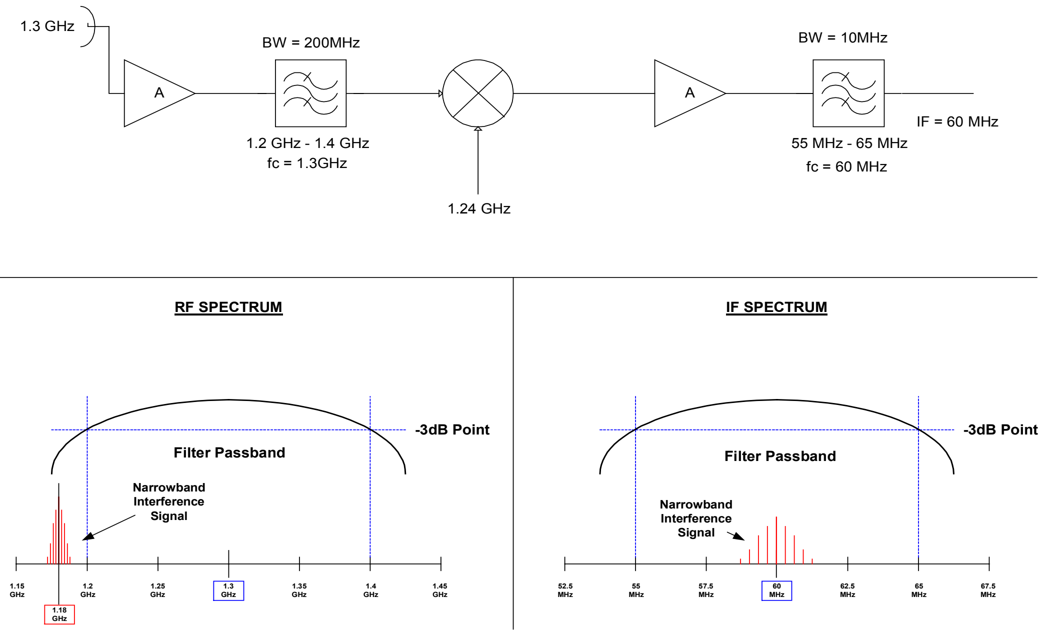


Figure 3.3.2-1 also shows that Narrow-band interference situated at Image Band frequencies can be easily down-converted to the IF of the receiver. The Local Oscillator in this application is 1.24 GHz, this leads to an Image frequency at 1.18 GHz. Although interference situated at this frequency is outside the 3 dB bandwidth of the front-end filter, the interference source could contain enough energy to have an effect at the receiver IF.

3.3.2.1.1.2 Double Down-Conversion

A multi-stage down-conversion method is shown in Figure 3.3.2-2. In this configuration, the RF signal is down converted via two separate stages that produce the 1st IF at around 500 MHz and then produce the 2nd IF at 60 MHz.

$$IF = |RF - LO| \; Hz \qquad \text{Equation 3.3.2-2}$$

In the 1st IF Case,

$$1^{st}\, IF = |1.3 \cdot 10^9 - 0.8 \cdot 10^9|$$

$$\therefore 1^{st}\, IF = 500MHz$$

In the 2nd IF Case,

$$2^{nd}\, IF = |0.5 \cdot 10^9 - 0.44 \cdot 10^9|$$

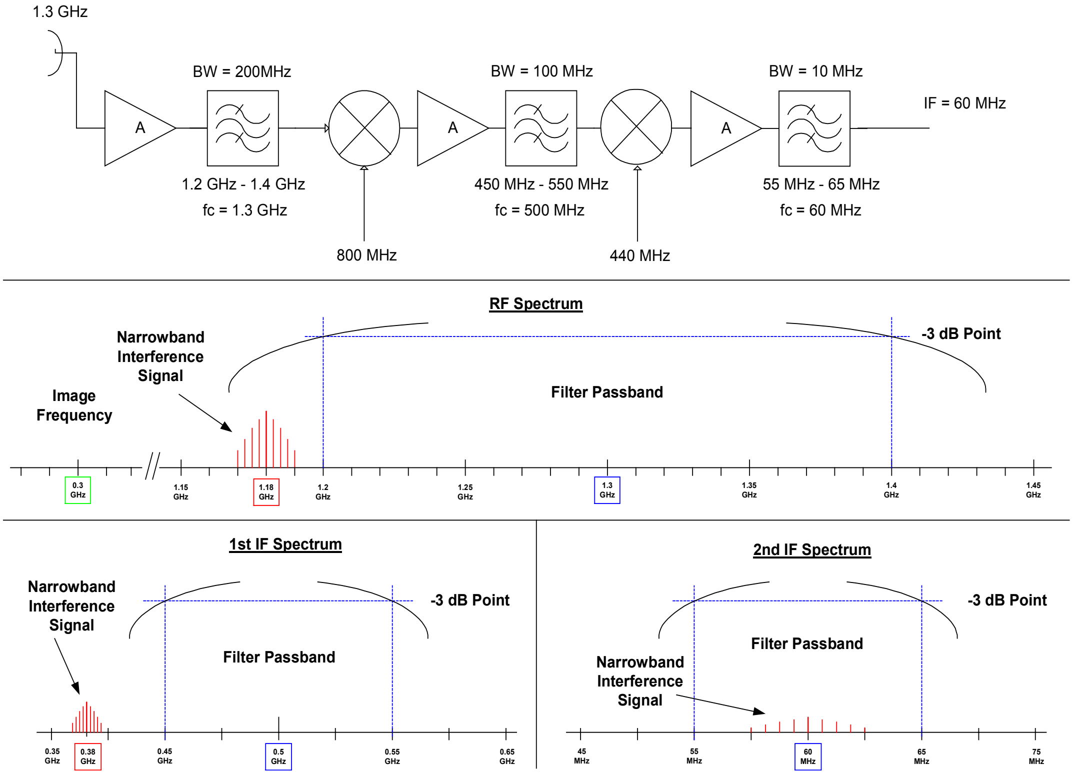
$$\therefore 2^{nd}\, IF = 60MHz$$

The Image Frequency in this Case,

$$IF_{image} = |0.8 \cdot 10^9 - 0.5 \cdot 10^9|$$

$$\therefore IF_{image} = 300MHz$$

Figure 3.3.2-2 Double Down Conversion Process



This process places any image component at a frequency well outside of the front-end Bandpass filter passband and in this case, the image frequency is situated at 300 MHz.

Now consider an interference source placed at 1.18 GHz, as in the Direct Down-Conversion example, as also shown in Figure 3.2.2-1. The interference source is down-converted to a 1st IF of 380 MHz, which is outside of the 1st IF Bandpass filter passband.

If the interference source contains enough spectral energy, it will be down-converted to a 2nd IF of 60 MHz, but will be heavily attenuated at the 1st IF Bandpass filter stage.

$$IF = |RF - LO| \text{ Hz} \qquad \text{Equation 3.3.2-3}$$

In the 1st IF interference Case,

$$1^{st}\, IF = \left|1.18 \cdot 10^9 - 0.8 \cdot 10^9\right|$$

$$\therefore 1^{st}\, IF = 380 MHz$$

In the 2nd IF interference Case,

$$2^{nd}\, IF = \left|0.38 \cdot 10^9 - 0.44 \cdot 10^9\right|$$

$$\therefore 2^{nd}\, IF = 60 MHz$$

In both cases, if any interference sources are situated within ± half the IF bandwidth from the incoming RF signal, they will be down-converted and situated within the IF filter passband. This makes interference rejection at prescribed frequencies particularly difficult at this stage in the receiver process.

The double down-converter has an added advantage over its direct counter-part, in that it has extra stages of filtering in which to attenuate overall interference. It also prevents interference located at image frequencies from entering the system.

However, the direct down-converter does save on component count and complexity, requiring only one LO stage and two filtering stages, whereas its counter-part requires two LO's to be generated and an extra stage of filtering.

The double down-converter is a more expensive option and gives improved image performance and more interference attenuation.

In civil radar systems the use of single down-conversion is the most common approach, this however is mainly driven by the large number of commercial Marine Navigational Radars in service. In the more sophisticated type of radars, the double down conversion is the most common, although triple down-conversion is used in a limited number of systems.

3.3.2.1.2 Main Beam Sector Blanking

This technique allows co-located radar systems to operate in close proximity to one another without causing damage to each other's receiver system. It achieves this in two ways:

- Prohibiting the transmission of pulses in a particular direction.
- Prohibiting the reception of pulses coming from a particular direction.

Consider the scenario as that shown in Figure 3.3.2-3.

Here, several radar installations are co-located with radar system 'A'. It is highly probable that at some point during its rotation, the beam of radar 'A' will illuminate one of the other radar installations. When this occurs, the transmitted pulse will be reflected back almost immediately. This high power reflection will cause receiver desensitisation.

The alternative situation occurs when radar 'A' is illuminated by the radar beam of one of the other radar installations. This illumination will take the form of pulsed interference aimed directly at radar 'A', again causing receiver desensitisation.

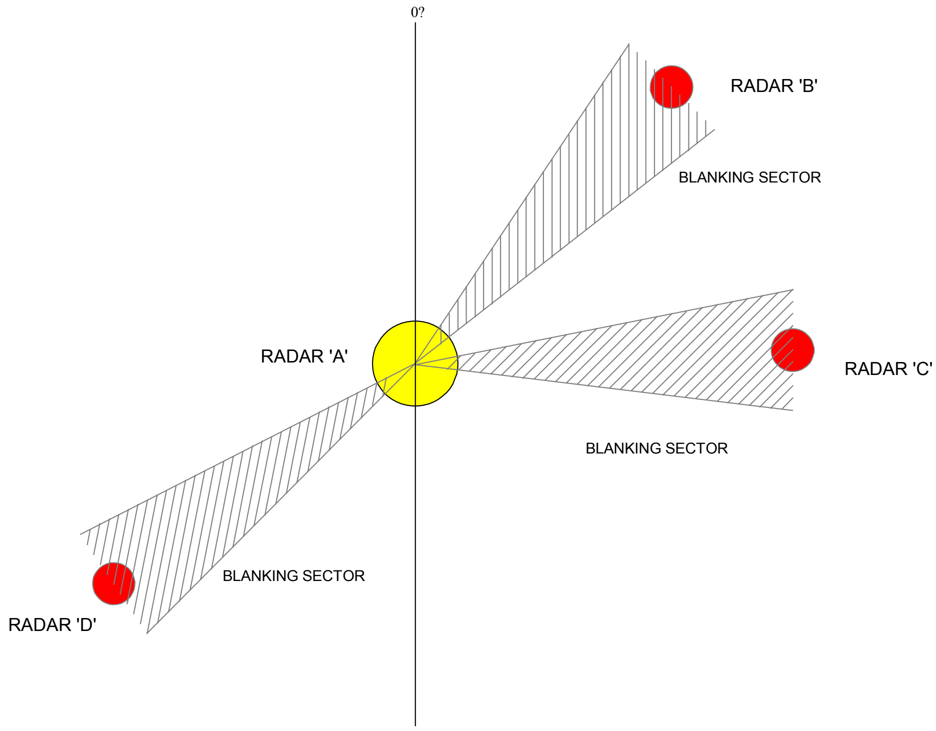
For close proximity co-location scenarios this presents a problem, as the sensitivity range of the receiving radars receiver could be drastically exceeded resulting in massive desensitisation or even, receiver damage.

Also, if the receiver of radar 'A' is desensitised for any amount of time, some valid target returns could be ignored.

Main Beam Sector Blanking allows problem areas to be purposefully 'blanked out' by inhibiting transmission during part or parts of its azimuth coverage.

The obvious drawback of this type of protection is that areas of coverage will be lost.

Figure 3.3.2-3 Main Beam Sector Blanking



As can be seen in Figure 3.3.2-3, to preserve the sensitivity of radar 'A', each possible illumination point has been blanked.

It is hoped that the other radar installations observe the same blanking procedure in return.

Sector blanking is used a lot in military systems and has been known to have been used by Air Traffic Control (ATC) service providers abroad. It is not believed to be used in Aeronautical Radio Navigation Service (ARNS) applications in the UK due to the density of civil air traffic. Vessel Traffic Services (VTS) sites use sector blanking particularly in areas where there are known to be no ships, such as over the land. The use of sector blanking is a balance of risks between interference and missing a wanted target. This risk can be mitigated in systems that have networked radars with overlapping coverage.

3.3.2.1.3 Sensitivity Time Control (STC)

The STC system provides protection against clutter echoes at close proximity to the radar being returned and saturating the receiver. It is essentially a 'swept gain' characteristic that varies the gain in the receiver with the timing of the transmitter pulse, as seen in Figure 3.3.2-4. It is also used to maintain a constant detection threshold for small targets that does not vary with range.

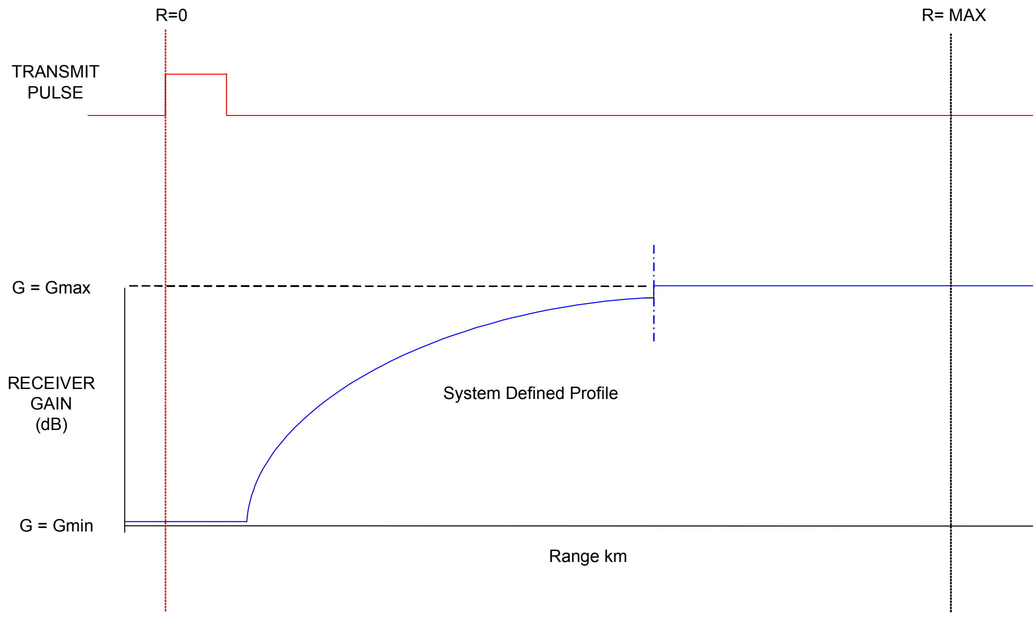
At 'R=0' the transmitter pulse is released, the gain of the receiver at this time is zero.

As the transmitted pulse travels further and further away from the transmitter the gain of the receiver is gradually increased, until at some value of range, the receiver is operating at its maximum performance level.

If high levels of STC are used to reduce large clutter echoes a drawback of STC is that close-in targets will not be detected due to the poor signal return strength transferring through the receiver.

The STC characteristics vary from terrain to terrain and can be matched to suit particular system positions.

Figure 3.3.2-4 Sensitivity Time Control



3.3.2.1.4 Out of Band Interference Traps

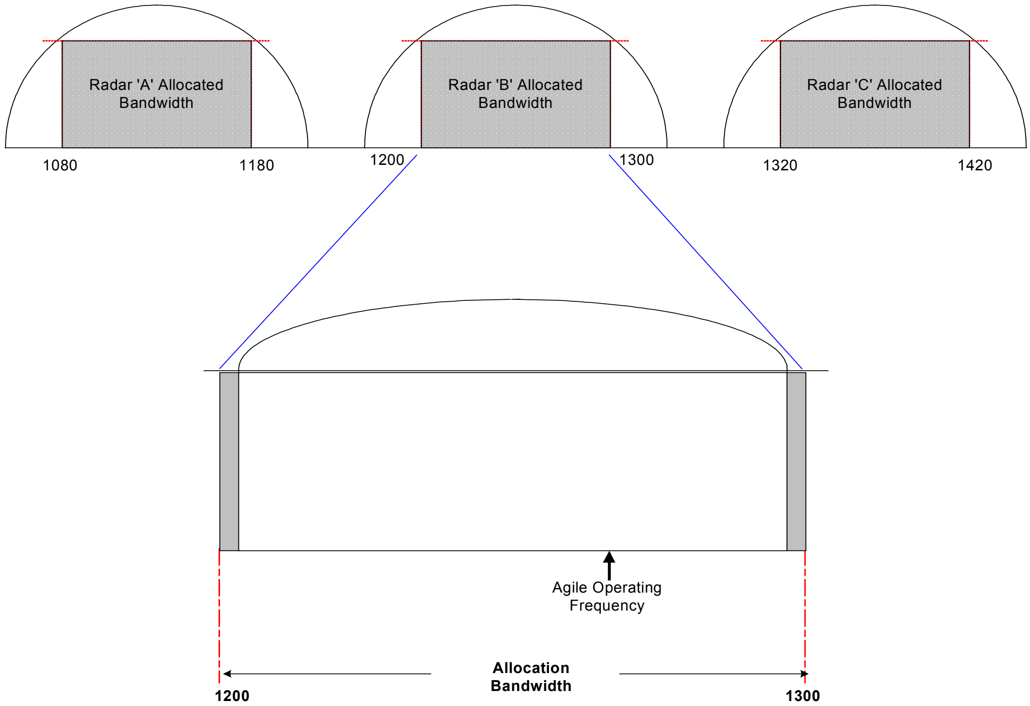
At times, and in particular areas, known out-of-band interference signals appear at significant levels of strength so as to disturb the reception of legitimate returns. If these interference signals are of a known power, frequency and duration they can be removed by placing Interference (notch) filters at suitable positions within the frequency band.

It must be made clear that, although the first stage of the down conversion process acts as a band-pass filter it may not have suitable frequency rejection at out-of-band frequencies. The interference traps provide 'additional' filtering to the down conversion process.

3.3.2.1.5 Multi–Frequency Selection (Frequency Agility)

Figure 3.3.2-5 refers. One key method of radar system protection through interference rejection is to implement frequency agility. A frequency agile system is capable of transmitting and receiving on any frequency within its allocation band.

Figure 3.3.2-5 Multi- Frequency Selection - Frequency Agility



When the performance of the radar on a given frequency is degraded by an increase in false alarm rate or the unacceptable raising of the noise floor in the receiver system the radar can change frequency. The radar control software and/or the operator can chose when and by how much to change operating frequency based on a number of criteria. In air defence radar these are usually concerned with avoiding hostile interference with the selection of a least jammed frequency.

Although in the civil arena the interferers are not necessarily ‘Hostile’ they are not under the control of the radar and are thus ‘non-cooperative’ and pose a similar problem to the radar. However, since these interferers will also provide a service (other than jamming the radar) this will lead to significant difficulties regarding the dynamic allocation of frequencies.

The frequency agility of the radar is achieved through the use of a frequency agile local oscillator (LO) operating in the up/down conversion stage. Although this LO is capable of choosing any frequency continuously across the allocation band (with the exception of sufficiently wide guard regions at the band edges), in practice the operating frequency is chosen from a finite selection of frequencies within the band.

Although frequency agility can be effective against interference it does require the allocation of a broad band to choose the operating frequencies from. While frequency agile LOs can be complex to engineer and will inevitably increase the cost of the overall system, a significant factor in expense is likely to arise specifically from the requirement to re-certify agile ATC radars at each of their agile frequencies.

Any radar used for civil ATC applications has to be certified by the relevant government authority. In the UK, this is undertaken by the CAA Safety and Regulatory Group.

The certification process involves the building of a case of evidence that the radar is fit for purpose. This case requires measurements being made on specified targets in order to demonstrate that the radar's performance meets the requirements defined by the user. These measurements are made using the specific frequency assignments for the radar. Changing the radar's frequency would currently require re-certification. It is thus not possible to automatically reconfigure the frequencies used by a network of radars in order to optimise dynamically frequency assignments.

3.3.2.1.6 Multiple Pulse Repitition Rates (PRR)

Multiple or Staggered PRR's are commonly used in Pulse Doppler Radars. The requirement to resolve target velocity drives the pulse repetition rate requirement upwards, towards twice the maximum likely target Doppler shift. However, if too high a PRR regime were adopted this would lead to target range ambiguities as returning echoes from distant targets would not return before the transmission of the next pulse. These competing requirements mean that compromise, medium PRR's are typically used. The problem with these medium PRR's is that they lead to ambiguities in both range and Doppler shift.

As a means of resolving these range/Doppler ambiguities, pulse Doppler radars use a number of medium PRRs selected such that the blind speeds from each PRR do not overlap. An Air Surveillance system might use 8 different pulse repetition rates, which may change on a pulse-to-pulse or burst-to-burst basis. As a result of this, if a real target falls into a blind speed region for one PRR, it is unlikely to fall into a blind speed region for another PRR and is hence detected. The detection rules for systems such as these usually require that a target be detected in 'N' out of the 'M' PRR's before it is further processed.

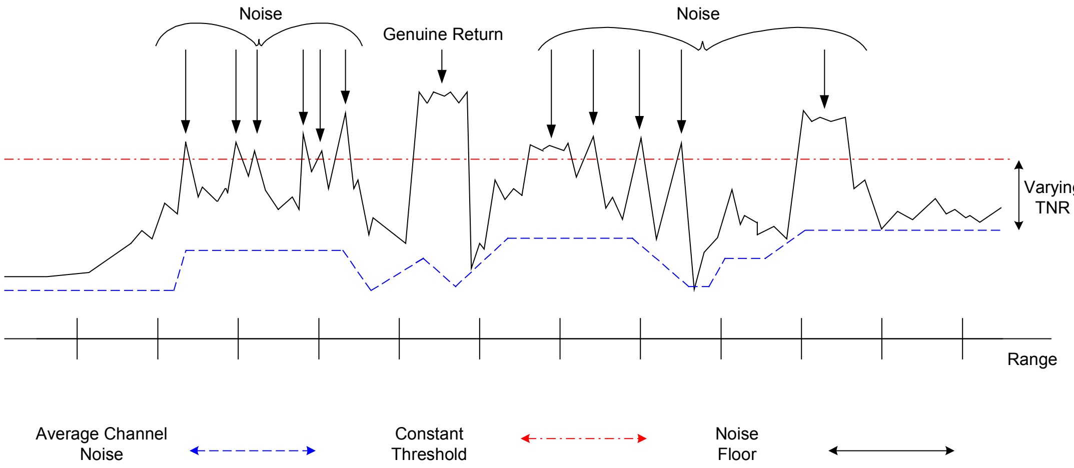
A useful side effect of this staggering is that an interferer with a PRR close to one of the radar systems PRRs will not be synchronous with the other PRRs and should not appear as a false target.

3.3.2.1.7 Constant False Alarm Rate (CFAR)

Radar systems are often required to maintain a constant false alarm rate under the influence of externally generated noise. If the signal detection threshold is set to a fixed, absolute value and the noise level fluctuates, it is reasonable to expect the probability of false alarm to vary accordingly. As the noise level present in a system with a constant threshold rises, the probability of false alarm increases as the threshold to noise ratio (TNR) changes. This is shown in Figure 3.3.2-6.

In the extreme, too many false alarms will swamp the detection system.

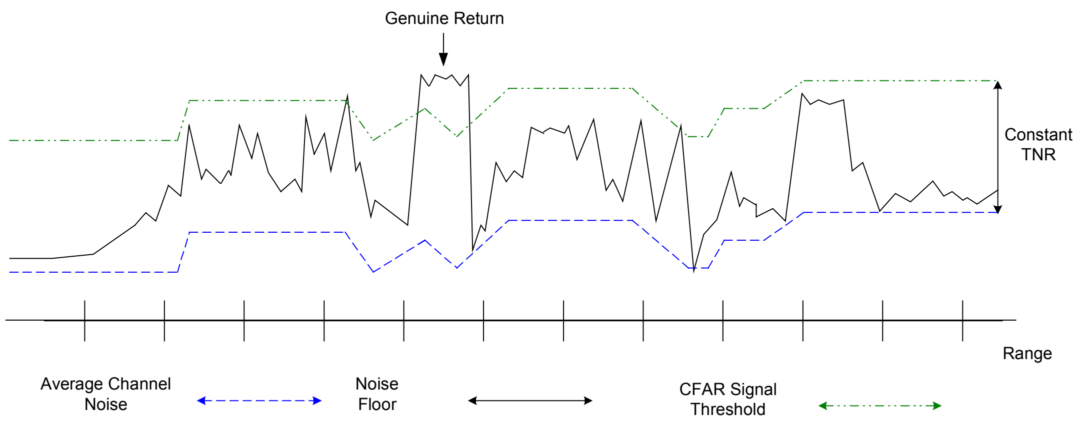
Figure 3.3.2-6 Average Channel Noise Increase



The CFAR principle relies on the fact that the noise level over a selection of range cells will approximate to the Rayleigh Distribution. This enables a good approximation of the overall noise level to be calculated for a given Target Cell (T). If the noise level over the same selection of range cells does not approximate to the Rayleigh Distribution, then the approximate noise level within the Target Cell (T) will not be a good approximation of the surrounding cell noise. This would severely degrade the performance of the CFAR system.

CFAR provides a method of keeping the noise floor a predefined level below the detectable return threshold. Incorporating CFAR ensures that the radar system can keep a constant Threshold-to-Noise Ratio (TNR) in the presence of a noise disturbance, as shown in Figure 3.3.2-7.

Figure 3.3.2-7 Channel with CFAR Applied



CFAR is an essential protection system. It provides an adaptive threshold, which reacts to the changes in the noise power entering the system and allows the probability of false alarm to remain at a sufficiently low level.

However, CFAR does inherently slightly reduce the ability of the radar system to detect weaker signals, which in turn leads to degradation in the maximum effective range.

Three Simple Methods of CFAR are:

- Automatic Gain Control (AGC)
- Range Cell Averaging (RCA)
- Double Thresholding

These are discussed below:

3.3.2.1.7.1 Automatic Gain Control (AGC)

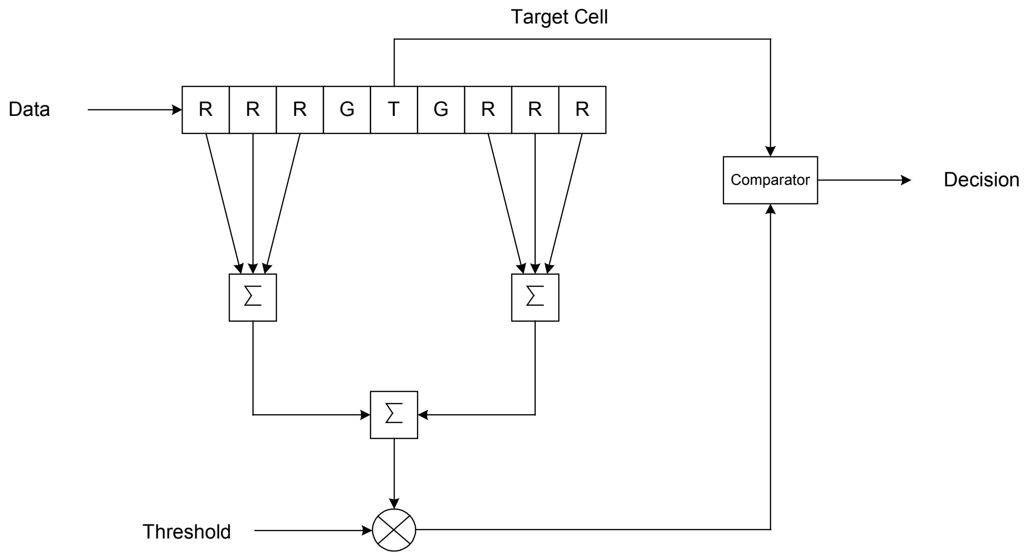
This is by far the simplest method of CFAR. An amplifier in the main processing chain is controlled via a feedback loop. The signal for this loop is derived from the noise power average of many range gates. A nominal level of background noise will produce average gain in the amplifier. If the noise level increases, the average noise power increases and causes the amplifier to reduce its gain accordingly. The reduction in gain forces the noise floor level to its original value. If the noise level decreases, the amplifier increases its gain value accordingly.

The gain of the amplifier is used to control the absolute value of noise in the system.

3.3.2.1.7.2 Range Cell Averaging (RCA)

This is a more complicated, yet common arrangement that takes the average value of range cells either side of the cell under scrutiny, (T). These cells are selected so that they are close enough to maintain the average noise power but not be contaminated by a genuine target return; these are designated as Reference Cells (R) in Figures 3.3.2-8 to 3.3.2.-10. Guard cells (G) are often employed to ensure this, as shown in Figure 3.3.2-8.

Figure 3.3.2-8 Range Cell Averaging



The signal produced is an estimation of average noise power in the cells either side of the cell in question, and is used to provide a means of threshold manipulation. As average noise power increases, the threshold increases to maintain the same probability of false alarm.

There are several alternative methods of implementing CFAR. Obviously, the more reference cells used, the more accurate an estimation of average cell power but the greater the risk of contamination by signals from other aircraft, clutter or interference. The method employed in Figure 3.3.2-9 uses azimuth and range cells to obtain an accurate estimation of target cell noise power, whereas Figure 3.3.2-10 demonstrates the standard range cell only method.

Figure 3.3.2-9 Range Azimuth Target Cell

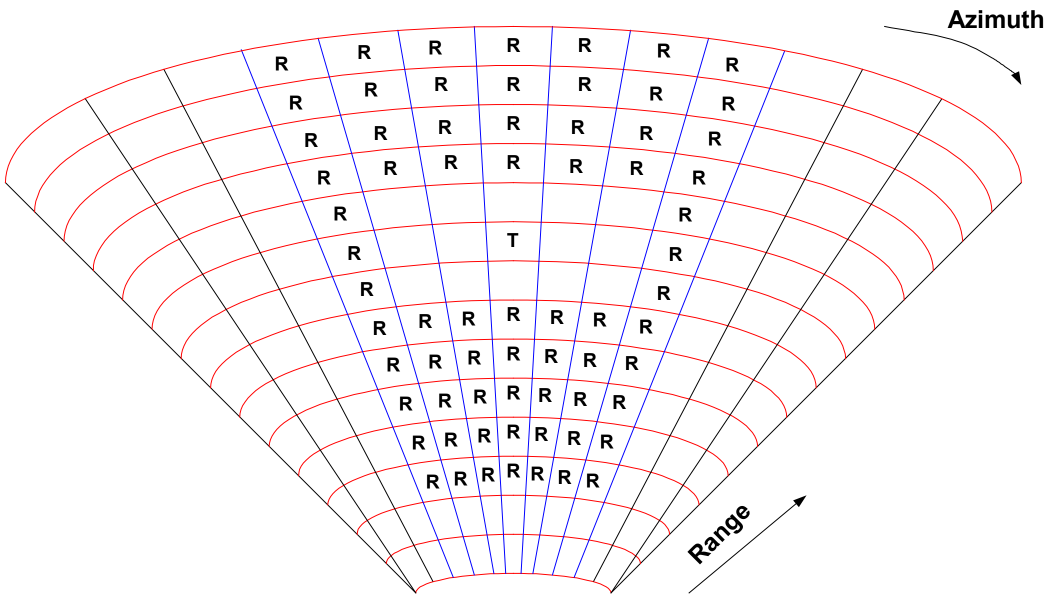
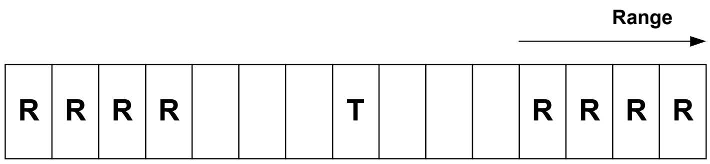


Figure 3.3.2-10 Range Target Cell



3.3.2.1.7.3 Double Thresholding

In some applications, such as with heavily contaminated reference cells, it is considered good practice to make a second pass over the data in question (if time allows).

This method allows the first pass to determine the largest signal powers and remove them, and the second pass is used to refine the process, increasing the sensitivity of the system and providing a more accurate representation of the average noise power.

3.3.2.1.8 Matched Filter Receiver

One of the many goals of a radar receiver is to maximise the output Signal-to-Noise Ratio (S/N) at the IF frequency. If this is achieved, the target detectability of the radar system will be maximised in a background of thermal noise.

The most common method used to achieve this goal is the use of a matched filter receiver, whose frequency response is matched to that of the returning signal.

The matched filter receiver employs an IF filter whose spectral characteristic is a close approximation to that of the returned signal.

For non pulse compression systems, the filter itself optimises the available bandwidth by closely conforming to the relationship:

$$BW = \frac{1}{\tau} Hz$$ Equation 3.3.2-4

where:

τ = Transmitted Pulse Width

The approximate loss in S/N for this configuration is 0.5 dB.

Employing strict limitations on the available passband frequency will result in pulse shape distortion, but pulse shape does not provide signal detection information and can be traded for maximum S/N.

The matched filter receiver performs a trade-off between pulse shape distortion, passband bandwidth, frequency response and output S/N. It is possible that some radar systems may find the pulse shape distortion wholly undesirable. Under these circumstances the trade-off remains in favour of the shape of the return.

In practice, because the ideal matched filter cannot be implemented, a percentage of loss in S/N will always occur.

Table 3.3.2-1 below (given for illustration only) lists a selection of filters against two of the more common pulse shapes. It illustrates the relationship between optimum bandwidth selection and the loss in S/N.

Table 3.3.2-1[1] Relationship between optimum bandwidth selection and the loss in S/N

Input Signal	Filter Type	Optimum B τ	Loss in S/N (dB)
Rectangular Pulse	Single Tuned	0.4	0.88
Rectangular Pulse	Rectangular	1.37	0.85
Rectangular Pulse	Gaussian Bandpass	0.74	0.51
Gaussian Pulse	Rectangular	0.74	0.51
Gaussian Pulse	Gaussian Bandpass	0.44	0 (Exact Match)

It should be noted however that current design implementations allow a much better match than those given in the above table to be achieved and consequently a lower loss to be achieved.

3.3.2.1.9 Pulse Compression

In order to achieve good range resolution (the smallest measurable range increment) the transmitted pulse width must be narrow.

This paragraph explains how a long transmitter pulse can be coded so that the receiver can process the target return to produce a narrow pulse and achive the required range resolution.

[1] Extract from Skolnik, Merrill I., Introduction to Radar Systems - 3rd Ed 2001

Figure 3.3.2-11 Pulse width and Pulse Repetition Interval

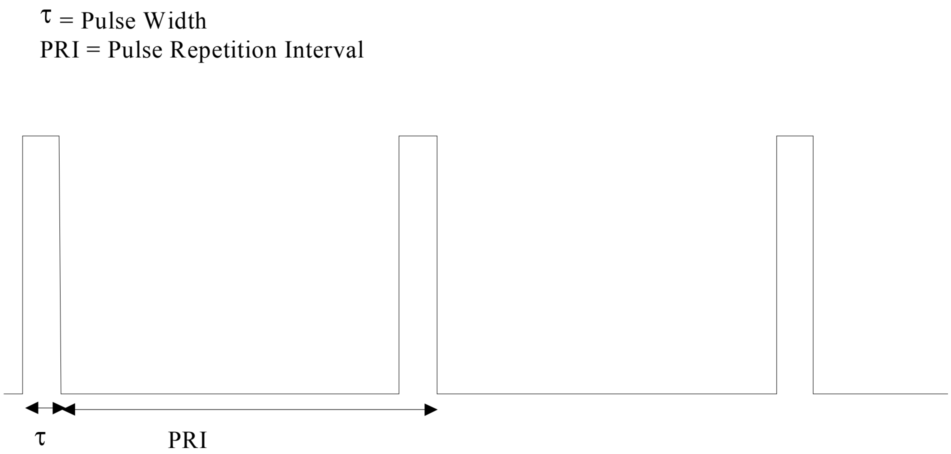


Figure 3.3.2-11 implies a wide transmitted spectral bandwidth, $1/\tau$.

Narrow pulses do give good range resolution, however, this, coupled with long pulse repetition intervals, means that not much energy will be incident on targets and detection performance may be compromised, particularly at long ranges, unless the transmitter power is significantly increased. The design of a pulsed radar waveform is therefore a compromise between range resolution and detection performance.

One means of improving detection performance is to increase the transmitter power. This is a costly option and for modern solid state transmitter devices, the maximum power is limited. A more practical solution is to use pulse compression.

A pulse compression system generates a wide transmitted pulse, thus maintaining detection performance, however, this pulse is also frequency or phase modulated in order to achieve the bandwidth for the required range resolution. On reception these wide pulses are processed to effectively trade the bandwidth of the incoming pulse for time/range resolution.

There are a variety of modulation schemes available to the radar designer that will impose the required bandwidth. These include bi-phase coded pseudo-random noise sequences such as Barker codes and maximal length sequences or, more commonly, frequency modulation such as linear and non-linear chirps. For a number of reasons the most popular schemes for use in radars are linear and non linear FM chirps.

Figure 3.3.2-12 though to Figure 3.3.2-14 illustrate the expanded transmitted waveform for an S-Band pulsed radar system with a range resolution requirement of 150m, the frequency spectrum of this waveform, and the resulting compressed pulse after processing through the receive chain. Note that the frequency is swept from negative to positive values, indicating that the chirp is symmetrical about the radar centre frequency. The Real and Imaginary parts of the signal are illustrated along with the amplitude envelope in black.

The uncompressed pulse width in this example is 35μs and the compressed pulse width is 1μs (giving a range resolution of 150m). The compression ratio is therefore 35. These figures also illustrate that the compressed pulse does have time sidelobes, the worst appearing around –20dB.

Figure 3.3.2-12 Expanded Pulse

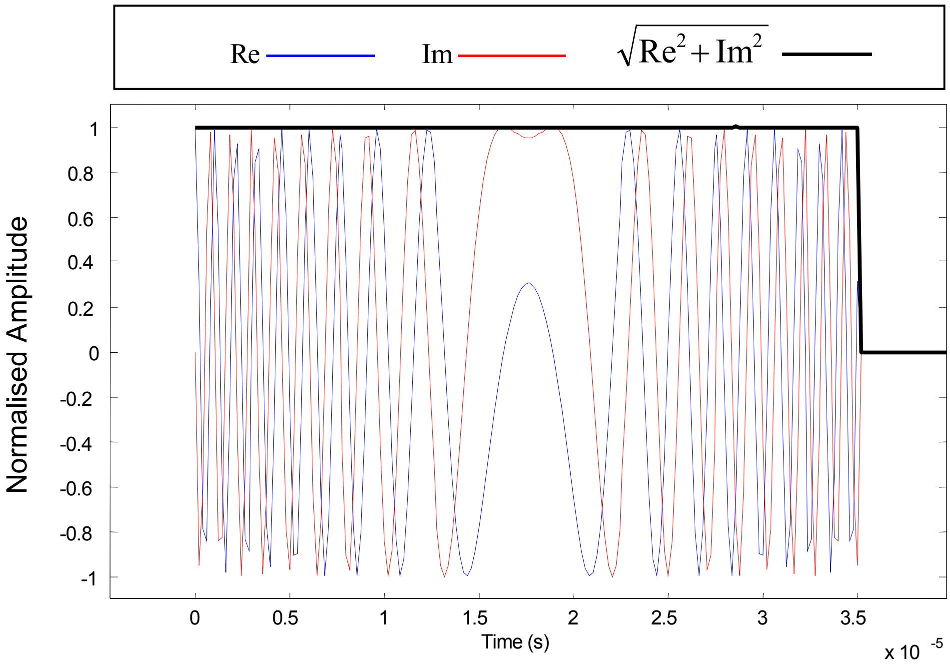


Figure 3.3.2-13 Spectrum of Pulse

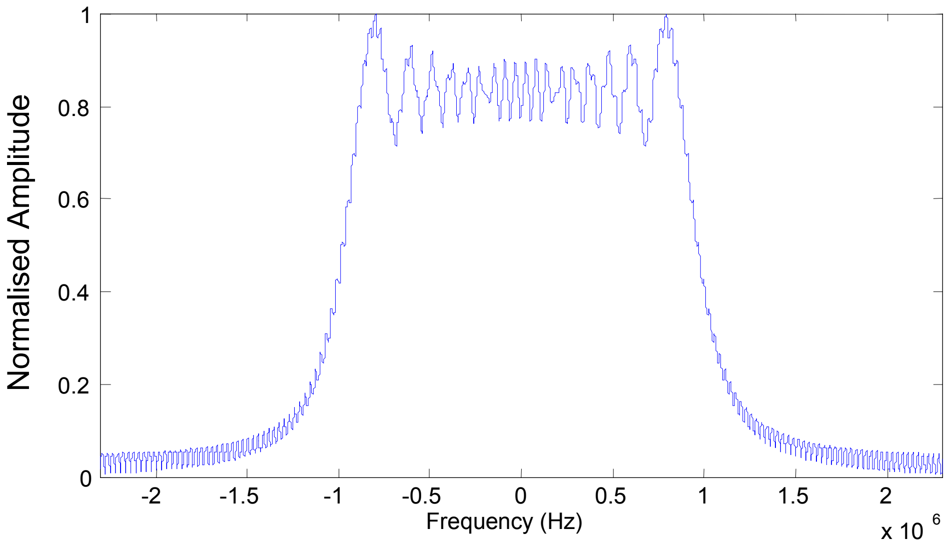
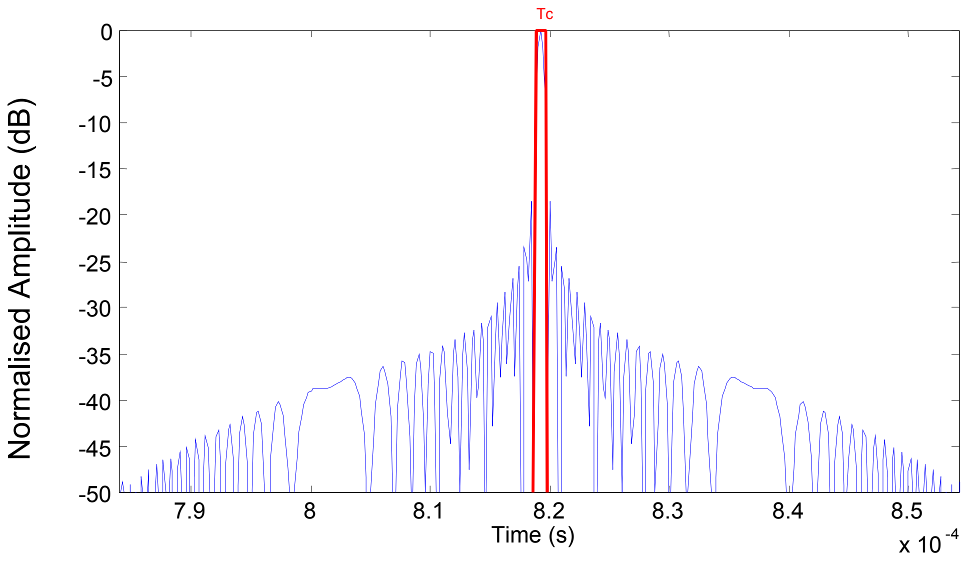


Figure 3.3.2-14 Compressed pulse, width 1μs, corresponding to a range resolution of 150m



Radar designs vary in the implementation of their pulse compression systems on both the transmit and receive sides. The technology used can be classified as either active or passive. In passive systems, the generation of the wide, expanded, transmit pulse usually involves the excitation of a frequency dispersive device such as a Surface Acoustic Wave (SAW) device by a short pulse. This results in the time expanded waveform as the various frequency components in the exciter pulse propagate across the SAW at different rates. On reception a matching SAW is used to compress the expanded waveform back to the original short pulse having the required time/range resolution. Active systems generate the expanded waveform by modulating the carrier at the appropriate rate without the occurrence of a time expansion from a short pulse. On reception, active systems process the incoming uncompressed waveform by mixing with delayed replicas of the transmitted signal to produce the short, compressed pulse. Digital Pulse Compression (DPC) systems, are by definition active.

Although a combination of active and passive techniques may be used in the same system, traditionally most systems will employ the same type for both transmission and reception. In general, older systems tended to use SAW devices on both transmit and receive while advances in computational speed, size and memory capacity have made digital pulse compression systems more practical and affordable in modern systems. However due to the difficulty in the production of matched pairs of SAW devices, many older systems are being upgraded with digital expander and SAW compressor units. In these units, the SAW is first manufactured and measured and the appropriate coefficients are programmed into the digital expander to provide a matched waveform.

An important aspect of this process, as far as interference rejection is concerned, is that the pulse compressor at the receiver should only give a good response to signals with similar properties to the transmitted signal.

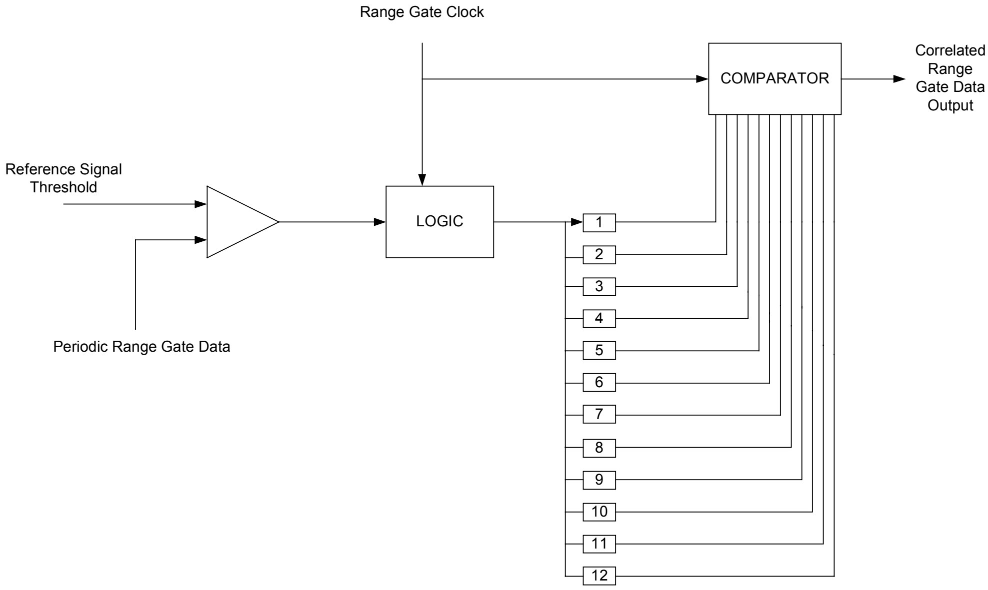
It should be remembered that Pulse Compression systems are by their nature matched filter systems. The performance requirements of such systems are such that bandwidth losses as described in Table 3.3.2-1 are no longer an issue.

3.3.2.1.10 Pulse-Pattern Correlation

The Pulse-Pattern Correlator allows the detection of returned signals that have a low S/N, even those signals that are below the noise level of the system.

The system uses a low front-end threshold level to detect very low strength pulsed returns. It employs pulse comparison over a specified number of received periods (Figure 3.3.2-15).

Figure 3.3.2-15 Pulse Pattern Correlator



Suppose that a system receives ‘x’ genuine target returns that are accompanied by ‘y’ noise spikes. The genuine target returns will occur in the same range gates consistently, whereas the noise spikes will occur randomly across many range gates. All returns and noise spikes cross the front-end threshold level.

A logic-based sub-system is now employed to produce a positive signal that is one range gate in width for each time the front-end threshold is crossed. This results in a signal that is processed on a single range gate basis over receiving period ‘z’.

If the same positive value is detected in the same range gate over several receiving periods, then a genuine target is declared.

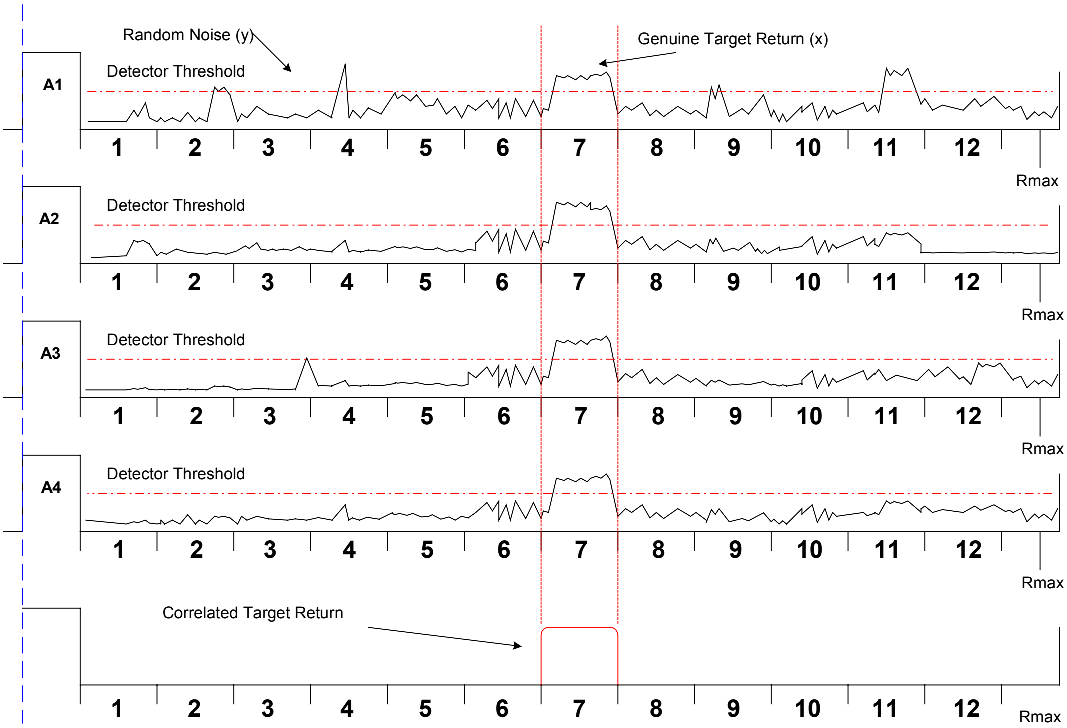
This system configuration rejects the random noise threshold crossings in favour of consistent threshold crossings. It would be most effectively utilised in situations where the returned pulse S/N would be particularly low, as the detection of this signal in normal circumstances would require an accordingly matched signal threshold, which would in turn increase the probability of false alarm.

Figure 3.3.2-16 shows the response from four receiving periods (A_1 – A_4). The genuine return is accompanied by various levels of noise, some of which cross the target detection threshold.

As the periods progress, the same target return appears in Range Gate 7, the noise level randomly varies.

When the four periods are applied to the Pulse-Pattern Correlator, Range Gate 7 produces a constant amplitude signal. This is detected by the comparator and acknowledged as a genuine target return. All other spikes are rejected.

Figure 3.3.2-16 Pulse-Pattern Correlation



3.3.2.1.11 Pulse Integration

A common way to improve the signal to noise ratio at the output of the receiver is to integrate many pulsed target returns. In reality, many pulses are directed to, and thus returned from, a target (Figure 3.3.2-17). In this case, the radar will receive more than one pulse back from the target. The receiver IF output S/N can be improved if all of the target returns are integrated to form one overall target return.

The process of Pulse Integration falls into two categories:

- Pre-detection or Coherent Integration
- Post detection or Non-coherent Integration

3.3.2.1.11.1 Pre-detection or Coherent Integration

This form of integration takes place in the radar receiver before the detection device, and in theory is a loss-less process. However, to maintain the loss-less (or near ideal) integration response, the transmitter must be pulse to pulse phase coherent, and the phase of each returning pulse must be preserved throughout the process. This process is used in ATC radars fitted with Moving Target Detector (MTD) processing.

3.3.2.1.11.2 Post detection or Non-coherent Integration

In this case, the integration takes place after the detection device; this produces a loss in any phase relationship between the returning pulses. This form of integration is somewhat easier to perform than the coherent type. This is due to the fact that only the pulse envelopes need be aligned. However, the integration improvement is not as large in post detection processing as in pre-detection processing for the same number of integrated pulses.

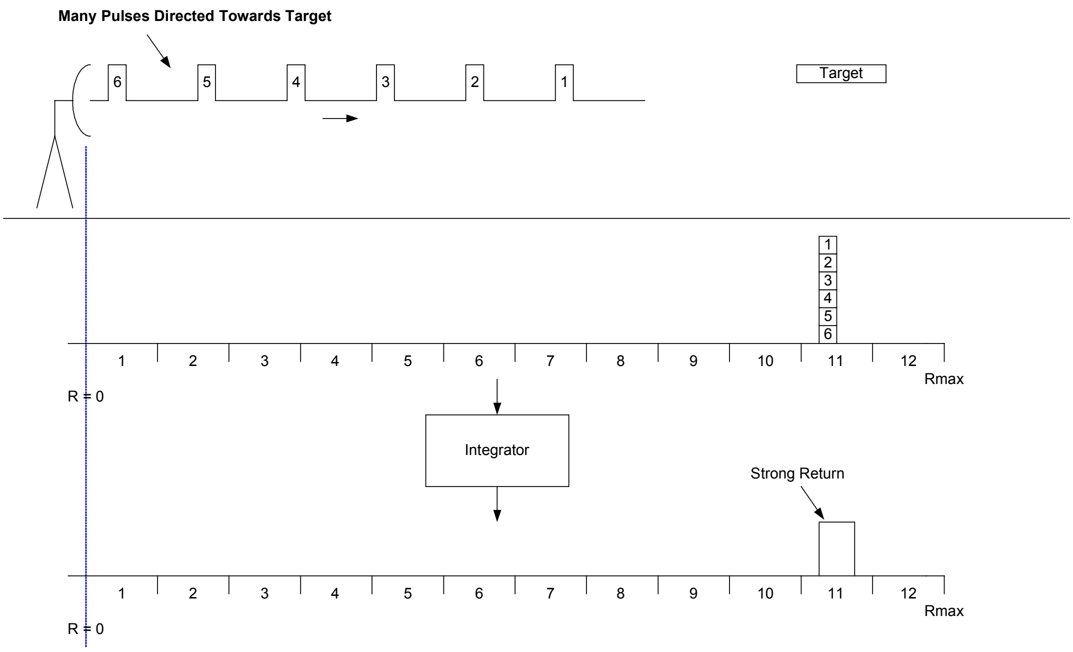
If a subject radar system integrates *n* pulses, each with identical S/N, using an ideal pre-detection process, the integrated S/N would be exactly *n* times the S/N of a single pulse.

If the same *n* pulses were now integrated using a post detection process, the integrated S/N would be less than *n*-times that of a single pulse. This loss is attributed to the non-linearity of the detection device.

Thus, if the two integration processes were to be compared, the post detection integration process would require more pulses to be integrated than the pre-detection integration process to achieve the same overall S/N improvement factor. This does assume that the single pulse S/N is identical for both cases.

It can be argued that the pre-detection process provides better results. However, as indicated above, the process requires a phase coherent transmitter in addition to increased technical complexity in the receiver. The post detection process does provide a (reduced) improvement factor but with the added benefit of reduced technical complexity.

Figure 3.3.2-17 Pulse Integration



The overall benefit of implementing a multiple pulse integration process is that the receiver can accept signal returns that are low in S/N. This is due to the S/N improvement factor generated. A single pulse system could not operate on such a low S/N.

The integrator also reduces the number of false alarms, as noise spikes have to occur in the same range cell over a number of scans before they can integrate up and cross the integrator threshold.

3.3.2.1.12 Pulse Blanking

Pulsed interference can cause several undesirable effects, the most serious being an increase in false detection. When the main beam illuminates a pulsed interference source, the received energy will pass through the receiver and may generate a false target.

The addition of a Side Lobe Blanking system (SLB) (see 3.3.6.2.3.2), will limit the interference to the narrow sector when the main lobe scans across the bearing of the interference source.

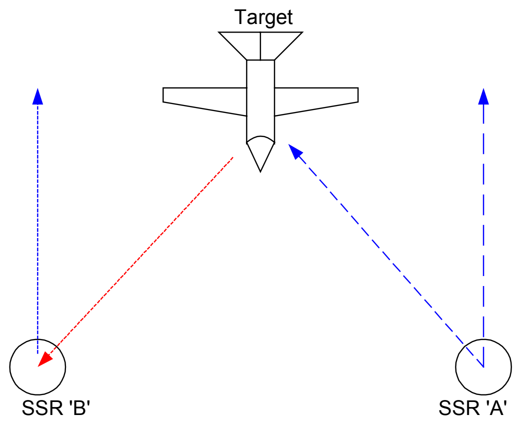
This approach does have the effect of reducing the coverage area of the radar in question, thus causing genuine targets to be missed.

3.3.2.1.13 De-Fruiting

One of the main problems encountered in Secondary Surveillance Radar (SSR) is 'False Replies Unsynchronised in Time' or FRUIT.

This occurs when the target aircraft transponder is interrogated by SSR 'A' and then returns its response signal to SSR 'B'. It is obvious that SSR 'B' receives a reply that it was not expecting (as shown in Figure 3.3.2-18).

Figure 3.3.2-18 SSR Fruiting



This type of interference is a problem due to the fact that the replies received are at the correct frequency (1090MHz). This allows unsynchronised replies to pass through any filtering that takes place before the processor.

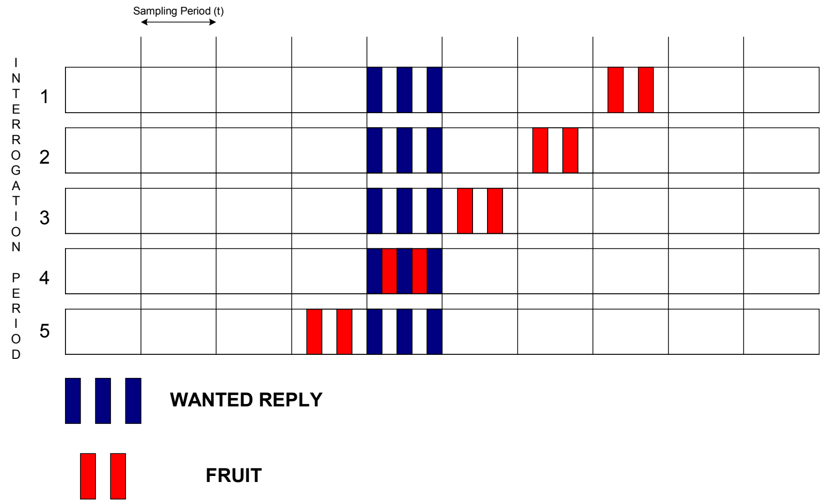
If many FRUIT occurrences take place, the operator's screen becomes crowded with unwanted replies, making it difficult to identify genuine interrogation responses.

One method of removing FRUIT is to use a DE-FRUITER. This system is essentially a 'synchronous detector unit' that detects 'time correlated' replies. If a received response does not correlate with the system timing then it is rejected as FRUIT. If it does correlate then it is allowed to pass to the processor.

The DE-FRUITER operates on the received 'history' principle, where several interrogation periods are analysed; this allows many sets of returns to be correlated. It can be seen that any returns that do not match the system sampling period will be asynchronous to the previous and following replies (as asynchronous replies tends to vary randomly in range), this process will enhance genuine returns and remove FRUIT. An example of this is shown in Figure 3.3.2-19.

SSR systems also suffer from garbling. This occurs when two aircraft at similar ranges and in the same antenna beamwidth, both reply to an interrogation. This produces overlapping replies. The de-garbling process identifies the leading edges of the component pulses of the replies and separates the two messages (see 3.1.1.20.3.9).

Figure 3.3.2-19 Time Correlation of FRUIT and Wanted Replies



3.3.2.1.14 Automatic Tracking

Due to the inherently large coverage areas scanned by a radar system, many targets will be present within the maximum detectable range in any one coverage scan. Excluding false plots, some plots will represent new targets, just entering cover, while others will have been in cover for a number of scans. It is convenient for an operator to be able to associate a plot with a particular target and to maintain a movement history, or track, for the target. For a surveillance radar this functionality is called 'Track-While-Scan' (TWS).

Such an automatic tracking system must perform a variety of functions:

- Track Initiation.
- Track Association.
- Track Smoothing.
- Track Termination.

3.3.2.1.14.1 Track Initiation

In principle, it is possible to initiate a target track from location data obtained during two successive scans. Practical systems, however, tend to require data for three or more scans before a valid target track is initiated. This will limit the probability of a false track being initiated. The number of scans used depends greatly on the target density of the coverage area.

3.3.2.1.14.2 Track Association

When a new target detection is made, it is the tracking system's function to attempt to associate it with an existing track. To achieve this a window of opportunity is situated around the existing track, within which the next target detection is predicted to be. If a plot appears in this association gate it is immediately associated with the existing track. If this window is too small, highly manoeuvring targets may be missed, and if the window is too large, there is an increase in the probability of a track merge occurring, where two or more target returns are associated to one existing track.

To overcome this sizing problem, modern radar tracking systems use a variable window. When the target is following a steady course, the window size is minimised. If the target is not found within the window on a scan, the window is enlarged and the presence of the target rechecked. If the target is found in this enlarged window, the target is flagged as manoeuvring, however if the target is again not found, the window is further enlarged (to a preset maximum size) and the presence of the target is again checked. When the target has been relocated and is again following a steady course, the window size is reduced.

Older systems use just two window sizes, the larger being used for tracking manoeuvring targets.

If the predicted detection is missing, the tracker does not immediately drop the track but can maintain it for several successive scans using predicted target positions.

3.3.2.1.14.3 Track Smoothing

The automatic tracking system also smoothes out current tracks based on previous and current data. This provides an estimate of the current target position and also provides an estimate of any future target position. Performing such an exercise does rely heavily on the use of computer processor power.

3.3.2.1.14.4 Track Termination

Once a track has been initiated, the tracking system uses probability analysis to predict the next position of the target. If the system does not receive any target data for a particular scan, the tracking system can estimate the target position. However, when the target data is missing for several consecutive scans the decision is made to terminate the track.

In general, the automatic tracking system is configured so that target data from three consecutive scans is adequate enough to initiate a track, and that five consecutive missed scans are adequate to terminate a track.

3.3.2.1.14.5 Interference considerations

Since a TWS system is able to ‘coast’ tracks using predicted positions in place of target detections, the problem of missing plots is somewhat alleviated. This may go someway to explaining the lack of interference reports on shared radar/RNSS frequencies. In addition, if a noise-like interferer causes an increase in false alarms, since the generation of false alarms is essentially a random process, they are much less likely to initiate or be associated with a track. However, these properties of TWS do not address the underlying problem of reduced Probability of Detection (P_d) of a target.

Due to the high processing load, the TWS functionality of a radar system is usually implemented in a dedicated data processor. It also requires a complex interface with the operator display and MMI. Typical systems employing TWS include VTS and importantly ATC radar. These systems provide ‘Safety Of Life’ services and are consequently very tightly specified in terms of performance requirements.

3.3.2.1.14.6 Tracker Development Issues

Development of ATC trackers is a time intensive and hence costly exercise. The algorithms used have to be rigorously tested in order to validate them and their instantiation in the software code has to be extensively reviewed. Any software code developed for any SOL related application is subject to rigorous development and testing processes to guarantee that the required level of integrity has been achieved.

3.3.2.2 Cost Considerations

Each of the protection criteria listed is invaluable in the on-going fight against external interference. However, with the added protection comes an added cost, and some of the implementations are more economically intensive than others.

This added cost results from the increased complexity and interfacing requirements placed on designers and systems engineers.

It must be understood at the outset that, the overall economic effect of each of the protection criteria specified will depend greatly on the type of radar system concerned.

For example, if a relatively low-priced, low complexity radar system were to have an intricate pulse compression system added to it, the per-system cost could increase dramatically, making the design uneconomical in its target market.

Alternatively, if a high-priced, highly complex radar system were to have an intricate pulse compression system added to it, the relative per-system cost change would be minimal.

The economic effects of each of the specified protection criteria are, in all cases, relative to the system to which they are being applied.

Table 3.3.2-2 below lists each of the protection methods together with their relative cost and complexity weightings.

Table 3.3.2-2 Protection methods - Cost / Complexity weightings

Implemented Technology	Cost	Complexity	Comments
Frequency Selective Down Converter	low	low	Easy to specify and implement at low cost.
Main Beam Sector Blanking	low	medium	Required when possible interference source is in a known location. Has a SOL implication when blanking arc blanks a major coverage area.
Sensitivity Time Control (STC)	low	medium	As above.
Out of Band Interference Traps	low	low	Relatively simple to design-in when interference source is in a known location.
Frequency Agility	medium	high	Can be extremely intensive to design and implement. Requires a more complex transmit - receive chain. Radar must be certified on all frequencies.
Multiple PRR	medium	high	Can be intensive to implement and integrate within overall system.

Implemented Technology	Cost	Complexity	Comments
Constant False Alarm Rate (CFAR)	medium	high	This method can become complex depending upon the level of statistical accuracy required. Much reliability now placed on signal processing to effect this function. Does rely on Rayleigh Statistical Distribution of noise signal to operate at optimum level.
Matched Filter Receiver	low	low	Relatively easy to design and implement.
Pulse Compression	high	high	Probably the most complex protection method due to waveform generation, transmission and reception requirements. Requires complex signal processing to effect target detection.
Pulse - Pattern Correlation	high	high	Complex to implement due to signal processing required.
Pulse Integration	high	high	As above.
Pulse Blanking	medium	medium	This method can be implemented efficiently, but may require complex processing strategies.
De-Fruiting	medium	medium	As above. SSR only - normally fitted as standard to modern systems.

Implemented Technology	Cost	Complexity	Comments
Automatic Tracking	high	high	Intensive to implement due to its SOL requirement. Requires complex signal processing routines.

3.3.3 Challenges imposed on Radar services

3.3.3.1 Current Environment

In the past, radar systems have been robustly designed to deal with low level interference from established transmission equipment and the spurious output from neighbouring radar systems. However, the increases in the implementation of communication links have introduced the possibility of degradation to radar system integrity and overall performance.

Currently, the spectral environment is populated by many and varied systems, including mobile/personal communications and GPS/GLONASS[2], which incorporate the use of satellite technology, and a multitude of military and civil radar systems. To this end, each system allocated to a particular frequency is required to adhere to specific rules of transmission to ensure that they do not interfere with a cohabiting system.

Current radar system installations are spectrally located so as not to cause service degradation to co-habitant radar systems via transmitted interference. However, a maturing personal communications industry has introduced possible interference sources that could, if not studied, monitored and analysed, cause harmful interference to a victim radar system and reduce its performance below that specified by the user.

The current radar communities have declared that such an interference signal should reside no less than -6dB from the victim radar receiver noise floor. At this level, the interfering signal is deemed a suitable distance from the victim receiver noise floor so as not to cause unacceptable degradation to the performance of the radar system. However, this subject matter is under much discussion.

One such paper discussing radar system performance degradation through cohabitation of GPS RNSS (RadioNavigation-Satellite Service) and radar systems in the 1215 – 1300 MHz Band is commented upon in Section .3.3.12.

Current technical challenges involve determining how transmitted interference affects individual radar systems, evaluating the effects such interference would have on the radar system's ability to maintain the required level of service and investigating the introduction of alternative methods of reducing the effect of current interference signals.

However, a significant obstruction in assessing the current spectral environment is quantifying the degrading effect of the interference on the victim radar system. Due to the very nature of radar (detecting weak signals in all conditions), it is difficult to gain hard evidence that any degradation witnessed is caused by interference from an out-of-band source.

This situation is exacerbated by the following facts:

- Each radar system has its own set of individual mission requirements.
- Each radar system is required to operate in a different environment (terrain, weather conditions etc.).
- Each radar system has its performance requirements specified by the end user, not the designer.

These factors indicate that each individual radar system may behave in a different manner when presented with the same interference signal. Thus, generating inconsistent and invalid evidence.

3.3.3.2 Future Environment

The future of the radio spectrum when considering radiolocation services is somewhat unclear. The assessment of this perceived situation is complicated, to say the least. For

[2] Global Positioning System/Global Navigation Satellite System (Russian equivalent to US GPS)

many years, radar has maintained its primary position within the radio spectrum, occupying significant areas of the available bands. However, this situation may have to be revised, as it is quite clear that radar frequencies are under threat from the many and varied communications systems making their way into the world.

This phenomenon should be assessed in the following ways:

- Technical Reasoning
- Economic Reasoning

3.3.3.2.1 Technical Reasoning

The communications sector is one of growth, and continues to grow at an undefined rate. The need for communications comes, potentially, at a high cost, especially to the radar user community. It is envisaged that the communications sector will continue to push for higher bandwidth to support future trends, higher data rates and, due to the target frequencies, this could impact and impinge on the bandwidth utilised by neighbouring radar systems.

In the future this impact may become evident to the radar community in a number of ways:

- Radar services currently enjoying primary status may be re-assigned to co-primary or secondary with communication services
- Bands currently allocated only to radar may be opened up to allow communications services to share as secondary or co-primary.
- Parts of the currently allocated radar bands may be re-allocated to communications systems.

In the first two cases, the radar systems will operate in an environment where interfering signals may be competing with the radar target returns. Depending on the nature and strength of these interference signals, the radar will be faced with a number of protection challenges. These cases will need to be the subject of future possible sharing studies.

In the third case the spectrum availability is reduced while the required number of operational radar systems is unlikely to be reduced. This could lead to more crowding and radar systems are then more likely to suffer interference from other radar systems than from communication systems.

3.3.3.2.2 Economic Reasoning

The future will bring many challenges for radar on an economic front. Services that utilise the future spectrum must consider the following four topics with care, as they will impact on the economic constraints of any service:

- The amount of required bandwidth for the system
- The efficiency of the system
- The amount of value gained per Hz of bandwidth within the system
- The amount of identifiable redundancy within the system

As has been discussed before, the required bandwidth is mostly dependent on the range resolution requirement of the radar and is thus central to the customer requirement definition process.

The second topic relates to the amount of bandwidth needed to maintain an efficient system. This topic will become extremely important as the price of spectrum increases through demand. It is envisaged that the price of spectrum and bandwidth will increase as the number and variety of communications systems continues to increase.

This will place extreme pressure on radar services to compete on a bandwidth and efficiency level with the communications sector, which it clearly cannot. The unfortunate truth is that the communications sector, being of a commercial nature, can provide a high revenue for a smaller spectral allocation as opposed to the commercial radar service that requires a larger bandwidth for less return. This is not favourable to the operation of a radar service.

The third topic places a value on the information content present per Hz of the leased bandwidth. Information (or lack of it) is of particular importance to the successful operation of a radar service. When a pulse is transmitted, the information value of that pulse is high, whether it detects a target or not.

This leads to the observation that all radar transmissions provide valuable information. The fact is that a transmission that detects no target is equally as informative as a transmission that detects a target.

This demonstrates that within a radar system, there is a large information value associated per Hz of bandwidth allocated.

The fourth topic encompasses the ability of the radar service to be streamlined through redundancy identification. For example, in communications system waveform design, redundancy is identified at an early stage. This enables bandwidth requirements to be reduced. In a radar system most information is required at all times, this does not leave much room for redundancy.

The analysis of these topics will provide great insight into the economic aspects of future systems. Bandwidth will be at a premium and the most efficient services will be viewed as the most favourable for allocation. Services that provide poor efficiency, cannot demonstrate good information value per Hz and cannot limit their required bandwidth could be put at a financial disadvantage.

This probable future scenario means that the radar community must move ahead with research into ways of improving systems spectral efficiency in order to remain in competition with the communications sector and to conduct sharing studies to evaluate the effect of possible sharing of frequency bands with communication systems.

3.3.4 Consideration of Interference to Noise ratio (I/N)

A radar receiver is designed to detect a specific minimum returned signal power at a specified maximum range; this value denotes the sensitivity of the radar over the bandwidth specified.

Radar receivers are designed to provide the maximum sensitivity whilst producing the minimum amount of internally generated noise. If an external noise source is injected into the receiver, then the receiver noise floor increases accordingly; this has the effect of reducing the sensitivity of the receiver as already described for the CFAR system (section 3.3.2.1.7).

However, the externally generated noise does not necessarily have to reside above the receiver noise floor to contribute to loss of sensitivity, it can cause a significant level of degradation even if it resides below the noise floor.

Current ITU recommendations specify that an I/N of –6dB is a safe margin so as not to degrade the sensitivity of radar services. However, it has been suggested that this value should be reduced further to –10 dB for SOL services. The example below demonstrates the effect on maximum range when I/N is increased.

3.3.4.1 L-Band Range Reduction caused by variation in I/N

The following example data shows the effect that varying I/N values have on an L-Band Radar. The example has been calculated using the basic Single Pulse Radar Range equation. Details of the parameters used, and the calculations are given in Section 3.3.13.1.

$$R\max^4 = \frac{Pt.Gt^2.\sigma.\lambda^2}{(4\pi)^3.N.(S/N).L_{tot}} \text{ m} \qquad \text{Equation 3.3.4-1}$$

where:

P_t	=	Peak Transmitted Power (W)
G_t	=	Total Antenna Gain
σ	=	Radar Cross-section (m^2)
L_{tot}	=	Total Overall Loss
S/N	=	Minimum Signal/Noise Ratio for detection
λ	=	Wavelength (m)
N	=	Receiver Noise Floor (W)

Table 3.3.4-1 shows the effect that increasing noise floor has on the maximum operating range of the radar.

Table 3.3.4-1 The effect of increasing noise floor on the maximum operating range

I/N (dB)	Range (km)	Loss (km)	% Rmax Reduction
IDEAL	161.016	N/A	N/A
-20	160.616	0.400	0.248
-10	157.225	3.791	2.355
-6	152.244	8.773	5.448
-3	145.466	15.550	9.658
0	135.398	25.618	15.910
3	122.394	38.622	23.986
10	88.414	72.602	45.090

The appropriate value of loss introduced by the I/N has been added to the system loss in this particular case, so that:

$$L_{tot} = L_{sys} + L_{inr} \qquad \text{Equation 3.3.4-2}$$

where:

L_{tot} = Total Overall Loss

L_{sys} = Total System Loss

L_{inr} = Loss due to Interference

It can be seen that at the ideal (no external interference) the maximum range is 161 km.

If the I/N value for this example is defined as -6 dB, a reduction in range of approximately 9 km is witnessed, leading to a maximum range of 152 km.

Compare this value of reduction to that of an I/N of –10dB, which leads to a range reduction of only 4 km from ideal.

3.3.4.2 Hostile Source Transmit Power Required To Cause Range Reduction

(Calculations shown in Section 3.3.13.2)

In practical situations, the interference present in the victim radar receiver is transmitted from an external source, and is treated as 'hostile' interference. The equation below can be used to calculate the minimum effective transmitter power required from a hostile interference source so as to inflict the I/N values already calculated in the example above.

$$Pt = \frac{\Pr(4\pi R)^2 L_{tot}}{GtGr\lambda^2} kW \qquad \text{Equation 3.3.4-3}$$

where:

P_t = Peak Transmitted Power (kW)

P_r = Power Received (kW)

G_t = Transmit Antenna Gain

G_r = Receive Antenna Gain

L_{tot} = Total Overall Loss

λ = Wavelength (m)

R = Range (m)

The first portion of this example assumes that the hostile interference source is located at the maximum range of the victim radar system, i.e. 161 km. and that the Victim radar system has the same parameters as the previous example.

Figure 3.3.4-1 Effective power at victim Radar Receiver when transmitted from a hostile interference source

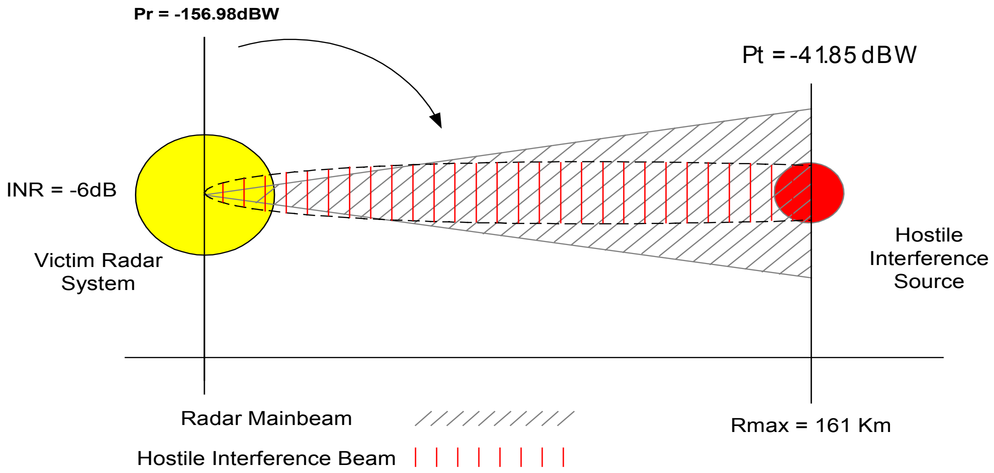


Figure 3.3.4-1 shows, that to maintain an I/N of –6 dB, at a range of 161 km, the hostile transmitter must produce –41.85 dBW. This will inflict an interference level of –156.98 dBW on the receiver within the victim radar system.

This analysis is expanded to include a selection of I/N (from –20 to +10) and the powers required to maintain them, as shown in Table 3.3.4-2.

Table 3.3.4-2 I/N and the powers required to maintain them with Interferer at 161km

Hostile Transmitter 161 km Distance From Victim		
Equivalent I/N (dB)	**Hostile Transmit Power (dBW)**	**Power Level at Victim Rx (dBW)**
-20	-61.85	-170.98
-10	-45.85	-160.98
-6	-41.85	-156.98
-3	-38.85	-153.98
0	-35.85	-150.98
3	-32.85	-147.98
10	-25.85	-140.98

In the second portion of this example (shown in Table 3.3.4-3), the hostile interference source is moved closer to the victim radar system – in this case 1 km.

Table 3.3.4-3 I/N and the powers required to maintain them with interferer at 1km

Hostile Transmitter 1 km Distance From Victim		
Equivalent	Hostile Transmit	Power Level at
I/N (dB)	Power (dBW)	Victim Rx (dBW)
-20	-105.98	-170.98
-10	-89.98	-160.98
-6	-85.98	-156.98
-3	-82.98	-153.98
0	-79.98	-150.98
3	-77.98	-148.98
10	-69.98	-140.98

As can be seen, the power transmitted need not be so great at the distance of 1 km to induce the same range degradation as before. In this case, to inflict an I/N of –6 dB, the transmitter power of the hostile interference source need only be –85.98 dBW.

3.3.4.3 Variation in Detection Probability (Pd) Due to Variation in I/N

(Calculations shown in Section 3.3.13.3)

The previous treatment of the I/N problem has taken into account that the S/N must remain at the required system level, and is held constant throughout the analysis. One alternative method of treatment would be to introduce the varying I/N value and monitor the decrease in detection probability, whilst attempting to maintain a given false alarm probability (P_{fa}).

To perform this analysis, the same L-Band radar parameters will be used, assuming a fixed detection range at Rmax of 161.016 km and a fixed P_{fa} of 10^{-6}. The equation for this analysis is a transposed version of the radar range equation used in section 3.3.4.1, as shown below:

$$S/N_{dB} = 10 \times \log\left(\frac{Pt.Gt^2.\sigma.\lambda^2}{(4\pi)^3.N.R_{\max}{}^2.L_{tot}}\right)$$

Equation 3.3.4-4

(All parameters are as in 3.3.4.1, but for validation the transposed calculation is included in Section 3.3.13.3)

In this case, the I/N value is once again added to the system loss to produce a total loss (L_{tot}).

The table of results for this equation is shown below in Table 3.3.4-4.

Table 3.3.4-4 I/N Vs S/N

I/N	S/N(dB)	I/N	S/N(dB)	I/N	S/N(dB)
Ideal	12.983	1	9.444	-10	12.569
		0	9.973	-11	12.651
10	2.569	-1	10.444	-12	12.717
9	3.468	-2	10.859	-13	12.771
8	4.344	-3	11.219	-14	12.814
7	5.193	-4	11.528	-15	12.848
6	6.001	-5	11.790	-16	12.876
5	6.790	-6	12.010	-17	12.897
4	7.528	-7	12.193	-18	12.915
3	8.219	-8	12.344	-19	12.929
2	8.859	-9	12.468	-20	12.940

These results show that the S/N is drastically reduced as the I/N value increases.

The variation in S/N can now be used to predict the effect on P_d whilst attempting to maintain a defined P_{fa}. This is achieved through the use of a standard probability graph as shown in Section 3.3.10, Figure 3.3.10-1. This graph demonstrates the relationship between S/N, P_{fa} and P_d.

A selection of approximate P_d`s have been taken from the graph using the S/N values shown in Table 3.3.4-4, these are shown in Table 3.3.4-5.

Table 3.3.4-5 I/N, S/N, P_d and P_{fa} (constant P_{fa})

I/N	S/N	P_{fa}	P_d
Ideal	12.983	10^{-6}	0.85
-10	12.569	10^{-6}	0.75
-6	12.010	10^{-6}	0.60
0	9.973	10^{-6}	0.24
6	6.010	10^{-6}	0.01

Table 3.3.4-5 shows that for an I/N of –6 dB the resultant S/N is 12.010 dB. When the P_{fa} is held to a constant, the detection probability is affected. In this case, the noise-like interference signal has caused the S/N to reduce by 1 dB, which in turn has reduced the probability of detection from 0.85 to 0.6.

3.3.4.4 Variation in False Alarm Probability (P_{fa}) due to variation in I/N

Another alternative method of demonstrating the effect of I/N is again to analyse how I/N affects S/N, but in this instance hold P_d constant and monitor the variation on P_{fa}, for a given fixed Rmax.

This example assumes that the value of Rmax is fixed at 161.01 km and that the P_d to be maintained is 0.85. Any variation in I/N will cause a proportional variation in the P_{fa}.

As the effect of I/N has already been calculated in Table 3.3.4-4, there is no need to repeat the calculation. Using the probability graph provided in Section 3.3.10, Figure 3.3.10-1 the variation in P_{fa} can be seen for a constant P_d.

Selected approximate values of P_{fa} have been provided in Table 3.3.4-6.

Table 3.3.4-6 I/N, S/N, P_d and P_{fa} (constant P_d)

I/N	S/N(dB)	P_d	P_{fa}
Ideal	12.983	0.85	10^{-6}
-10	12.569	0.85	10^{-5}
-6	12.010	0.85	10^{-4}
0	9.973	0.85	10^{-3}
6	6.010	0.85	10^{-1}

Table 3.3.4-6 shows that an I/N value of –6 dB results in an S/N of 12.010 dB. This causes the P_{fa} value to increase from 10^{-6} to 10^{-4}. The result of this is to decrease the amount of time between each detected false alarm.

An additional interpretation of the effect of a noise-like interference signal is discussed in Section 3.3.8.2. This material encompasses the direct relationship between I/N and degradation in service and coverage. It also provides a derivation of the loss incurred on the radar system per dB of noise-like interference.

3.3.4.5 Treatment of Minimum Detectable Radar Cross Section (RCS) Vs Varying I/N

This is another method of addressing the degrading effect of I/N, and involves the increase of the minimum detectable RCS, at a given range, experienced by a victim radar system when the system noise is increased by an external interference source.

Assuming ideal conditions, if the victim radar receiver has no external interference applied to it, then the radar will detect, at maximum range, a target with the minimum specified value of RCS.

However, now assume that an external noise source has been introduced to the victim radar receiver, thus causing I/N to increase. In order to maintain the maximum detection range, the minimum value of RCS must increase. The result of this action is that smaller targets fail to be detected in favour of maintaining maximum detectable range.

3.3.5 Interference scenarios

Interference can manifest itself in several ways, and once it has entered the radar system it is particularly difficult to eradicate completely, some residue will always be present.

The following section analyses several interference scenarios, where each scenario includes a discussion as to the overall effect of the interference on the radar system's ability to continue satisfactory operation.

Scenario 3.3.5.1.1 and 3.3.5.1.2 illustrate interference effects in the Frequency domain, whereas the rest concentrate on illustrating the effects in the Time domain.

3.3.5.1 Interference Signals in the Frequency Domain

3.3.5.1.1 Broad-band Interference Signal Scenario

Broad-band interference can be thought of as interference that has a significant level of constant energy over a wide range of frequencies. From the point of view of the radar receiver, broad-band interference covers the entire frequency range of the passband. In most cases, the interference signal actually covers a wider band than that specified by the passband of the receiver. Hence, the term 'Broad-band'.

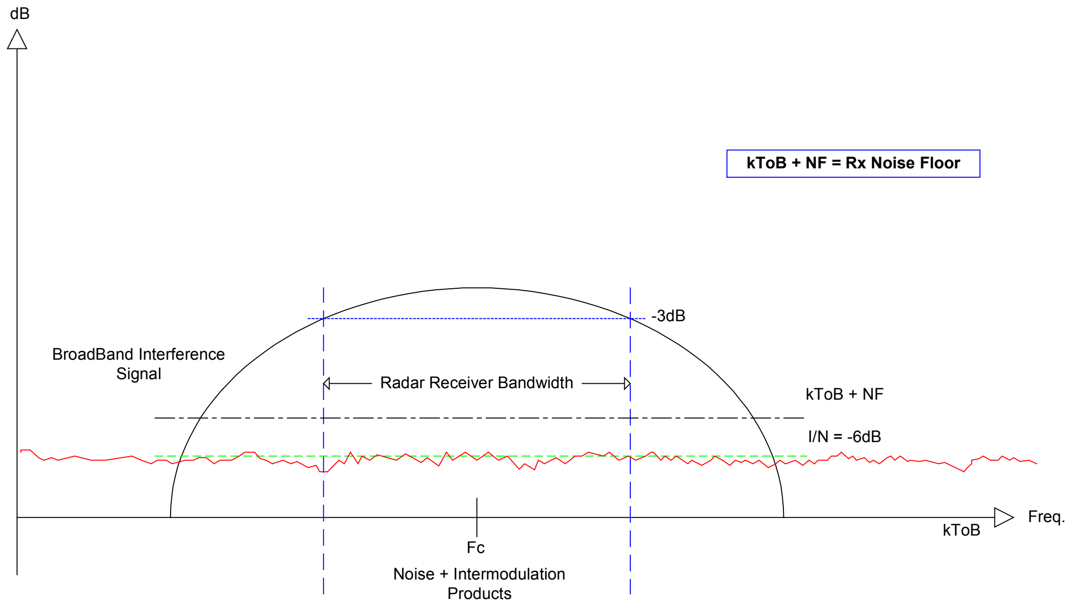
This particular scenario presents two cases of broad-band interference generation:

- Broad-band Noise-Like Interference
- Broad-band Non Noise-like Interference

3.3.5.1.1.1 Broad-band Noise-Like Interference

Figure 3.3.5-1 shows a broad-band interference signal present in the passband of a radar receiver. Purely through its nature it has the effect of increasing the radar receiver noise floor by the appropriate amount. If the radar system operates a CFAR system, the increase in noise floor will be matched by an increase in the minimum detectable signal threshold, effectively reducing the maximum detectable range.

Figure 3.3.5-1 Broad-Band noise-like interference signal present in Receiver Bandwidth.

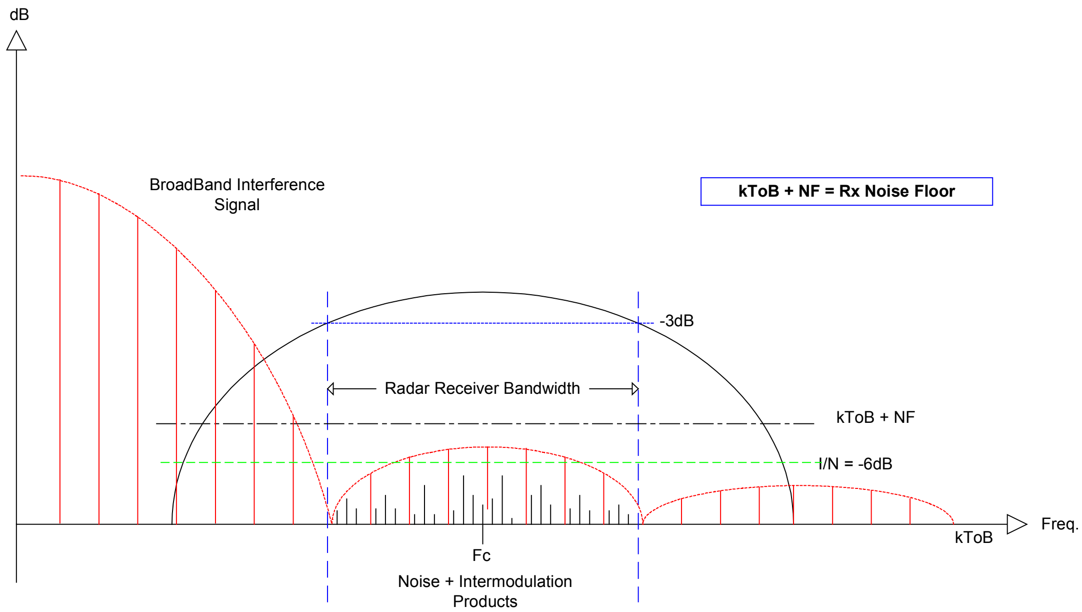


The view of broad-band interference shown in Figure 3.3.5-1 is the traditional representation.

3.3.5.1.1.2 Broad-band Non Noise-like Interference

Figure 3.3.5-2 shows a large pulsed interference spectrum present within the vicinity of the radar system receiver. The interference has several spurious harmonic lines that enter the receiver bandwidth and mix with other harmonics to form inter-modulation products that fall directly into the radar band of interest. These products and associated harmonics form a constant amplitude interference signal just below the noise floor of the radar receiver.

Figure 3.3.5-2 Broad-Band non-noise-like interference signal present in Receiver Bandwidth.



Even though the receiver bandwidth is clearly defined, it fails to remove the interference from the band of interest.

These interference signals have been included to demonstrate the fact that the interference can be constructed from many harmonics mixing together within the band of interest (as opposed to a continuous rolling floor that is constructed from an infinite number of harmonics). Its effect is identical to the broad-band noise-like interference signal.

In both Figures 3.3.5-1 and 3.3.5-2, the interference is shown situated well below the noise floor of the receiver, but it is within the –6dB specified value of I/N. As mentioned earlier, the effect of this is to cause the noise floor of the radar receiver to rise accordingly. For a radar system operating a CFAR regime the effect can be minimised at the expense of maximum detectable range, but if a radar system is operating a non-CFAR regime, the effect is to increase the false alarm rate to an unacceptable level as the probability of false alarm increases.

Broad-band interference causes a gradual degradation of the receiver, as it becomes marginally desensitised to targets at certain ranges and ultimately degrades the performance of the radar, until its performance is below that which is required.

This scenario has represented interference in two of its most common forms, that of constant spectral power with infinite harmonics, and with several harmonics that produce inter-modulation products when mixed with other signals present. Both methods produce a constant floor that is particularly difficult to remove and can cause significant degradation to the radar system performance, even when situated below the radar receiver noise floor.

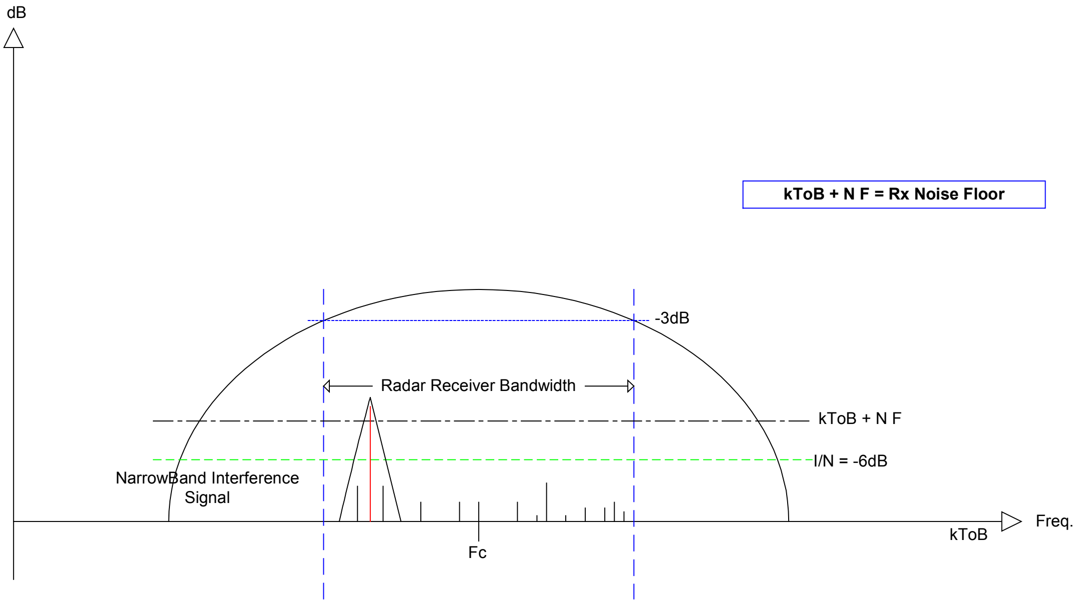
3.3.5.1.2 Narrow-band Interference Signal Scenario

Narrow-band noise is a more selective form of interference. The term ‘narrow-band’ comes from the fact the interference signal is much less than the bandwidth of the victim receiver. In practical terms this is not much of a problem if the signal is situated below the noise floor.

However, it becomes more problematic when its energy level takes it above the noise threshold of the victim receiver.

In this scenario, several small amplitude harmonics are generated by an interference source situated in close proximity to the radar receiver bandwidth. (Alternatively, the narrow-band signal could have been generated by a large signal quite some distance away, that has high energy harmonic orders). In this case, a small group of harmonics is placed directly in the passband of the radar receiver. This is shown in Figure 3.3.5-3. The power integral of the spikes over the passband determines the level of interference.

Figure 3.3.5-3 Narrow-Band interference signal present in Receiver Bandwidth.



Although off-tune, the collection of harmonics produce a narrow-band interference signal.

Assuming that the double down-conversion process does not remove the narrow-band interference signal and that the power contained within the interference signal is large, it is possible that a very small increase in noise floor could be noticed. However, the effect of this increase will not be as severe as the effect delivered by its broad-band counterpart. (See Section 3.3.11)

Now assume that the narrow-band interference source is situated within the receiver bandwidth. If its spectral response were that partially resembling a pulsed return, if it is synchronous with the radar Pulse Repetition Interval (PRI) and pulse duration and has sufficient energy, the possibility of false target generation is increased.

It must also be considered that narrow-band noise can have long time duration, to the extent that if it tended towards Continuous Wave (CW), it would then infect the receiver on a continuous basis.

3.3.5.2 Interference Signals in the Time Domain

The following set of scenarios assume that the interference signal has adopted the approximate spectral form of a pulsed target return, has adequate spectral energy and is situated in the receiver bandwidth.

3.3.5.2.1 Aperiodic, Pulsed Interference Signal Applied to a Non-Compressed Radar System

Assume that the victim radar system utilises a non-compressed, pulsed CW waveform. Figure 3.3.5-4 illustrates a pulsed interference signal that occurs within the system PRI, but is aperiodic on a pulse-to-pulse basis.

Figure 3.3.5-4 Aperiodic, Pulsed Interference Signal Applied to a Non-Compressed Radar System

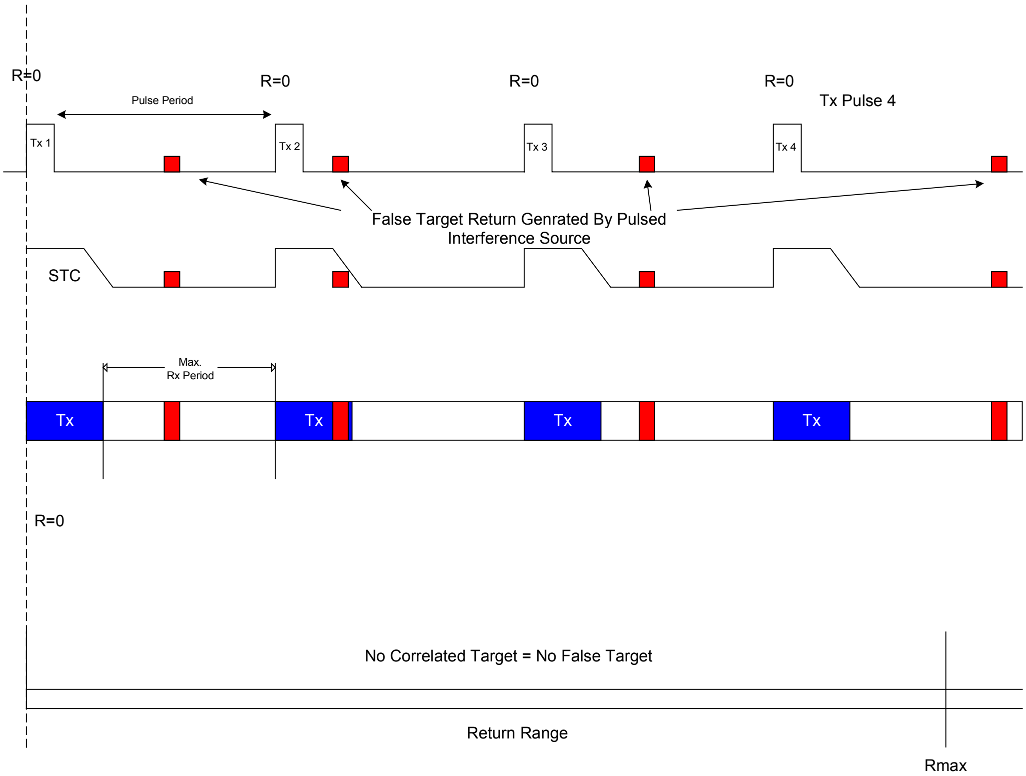


Figure 3.3.5-4 illustrates a possible interference scenario where a false target return could be generated by a pulsed interference signal. It shows four transmit periods for one particular sector in azimuth, in each period the interference occurs at a different range – appearing random in nature.

For a victim radar system that employs pulse correlation, the randomness of the interference will result in rejection as it does not correlate on a periodic basis. Genuine target returns correlate.

Also in this scenario, pulsed interference signal 2 appears in the STC region, so this signal will be ignored.

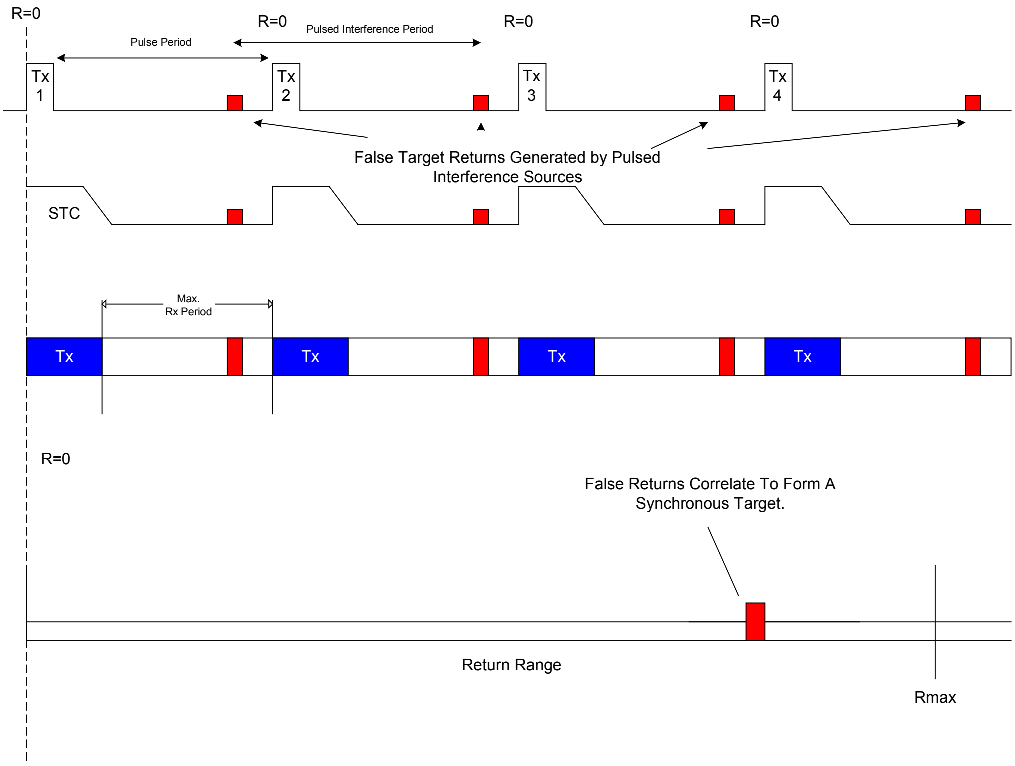
If the victim radar system were basic enough not to employ some form of pulse correlation, then for each transmitted pulse, a corresponding target return would be detected. This could lead to many false targets being generated.

The victim radar system illustrated in this scenario relies on the principle that the pulsed interference is asynchronous with the radar's pulse pattern. This allows the use of a pulse correlation system to make a decision on signal acceptance or rejection. The success of a pulse correlation system, when supplied with data from an interference source, does hinge on the periodicity of the pulsed interference signal.

3.3.5.2.2 Periodic, Pulsed Interference Signal Applied to a Non-Compressed Radar System

This scenario now assumes that the pulsed interference signal is periodic in its nature and is synchronous with the victim radar system PRI. This scenario shows that a false target will be generated and is shown in Figure 3.3.5-5.

Figure 3.3.5-5 Periodic, Pulsed Interference Signal Applied to a Non-Compressed Radar System



The simplistic Figure 3.3.5-5 shows a false target return generated by a pulsed interference signal at the same point for all four receive periods. These are passed to the detection / correlation system and deemed to correlate. The returns are coherent to the PRI of the system.

In this particular scenario the probability of false target detection is drastically increased due to being synchronous with the radar PRI. These returns will correlate, as they occur within the same range for each successive PRI.

3.3.5.2.3 Periodic, Multiple Pulsed Interference Signals Applied to a Non-Compressed Radar System

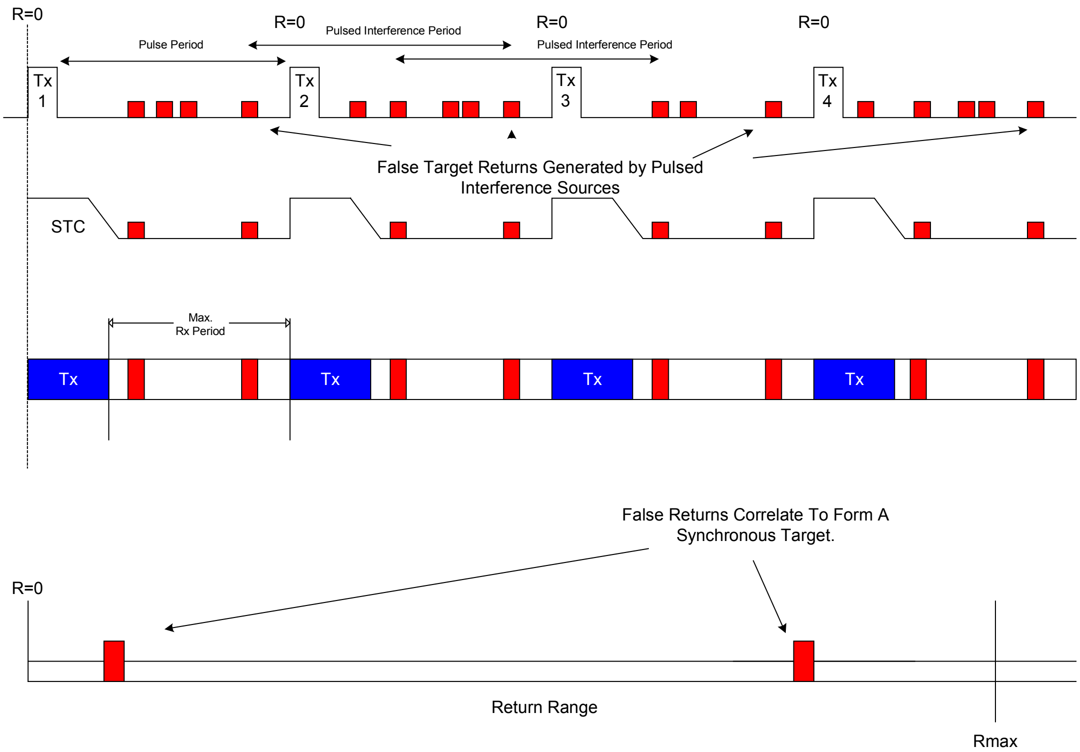
This scenario now assumes that many false target returns are generated by many pulsed interference signals. This leads to a varying set of situations.

In the frequency domain, if enough pulsed returns are present over a span of time, then the interference would act as near broad-band noise. This would result in the scenario as per broad-band noise and would cause false alarms, as the characteristic noise would not follow the Rayleigh distribution and prevent the correct operation of CFAR systems.

If the returns were randomly distributed in time, with no discernible periodic component, a pulse correlation system could remove the unwanted returns, as they would not correlate on a pulse-to-pulse basis.

However, the situation shown in Figure 3.3.5-6 is the most likely occurrence.

Figure 3.3.5-6 Periodic, Multiple Pulsed Interference Signals Applied to a Non-Compressed Radar System



This shows multiple pulsed interference signals, many are aperiodic in nature but when passed through a correlator that operates on a periodic principle, it is clear to see that many aperiodic returns have the potential to become 'periodic' to the radar system. This is purely on the basis that they occur at the same range for many pulse periods. The figure shows that two periodic components have been identified, and when passed through the pulse correlator, will be correlated to show two false target returns. Both are at a different range, but are on the same azimuth.

In practice it is possible for many more false targets to be generated, and once again it all depends on the correlation of returns between pulse periods. This phenomenon will cause the radar display to become heavily cluttered with false returns.

3.3.5.2.4 Periodic, Pulsed Interference Signal Applied to a Compressed Radar System

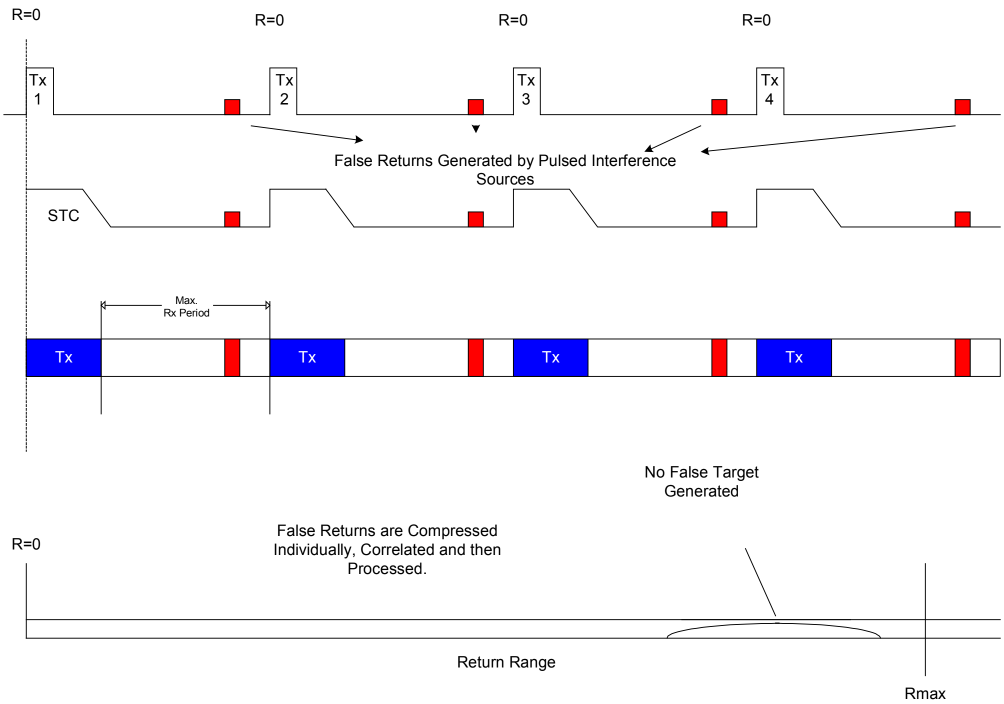
This scenario assumes that the radar system uses pulse compression. As has already been discussed, false returns that are aperiodic in time are effectively rejected through correlation, but if the false returns are periodic, there is a possibility that a false target will be generated.

However, now the attention is directed to the reception of interference signals into pulse compression systems.

Figure 3.3.5-7 illustrates a periodic pulsed interference signal that is coherent to the radar system PRI.

The false returns are passed through a pulse compressor system, correlated and processed. However, since the pulsed interference is not matched to the compression of the radar system, the application of the compression system causes the returns to flatten out, as none of the available processing gain is being applied.

Figure 3.3.5-7 Periodic, Pulsed Interference Signal Applied to a Compressed Radar System



Ideally, the compression system should attenuate and reject any signal that is not within its specified parameters. In practice, however, it is quite possible for the radar compression system to allow a pulsed interference signal to pass through, whilst only applying a certain amount of processing gain, (see Section 3.3.13.3). Even if a pulsed CW signal is applied to a compression system, some of the processing gain is applied. If the pulsed interference signal is periodic in nature, then it is entirely possible for a false target to be generated, but generally the CFAR circuit will reduce this interference.

In addition, because the interferer is not matched to the pulse compressor, then it is not compressed in time as much as the radar signal. This means that the time sidelobes of such an interferer would be large and span many range gates in the signal processor.

3.3.5.2.5 Periodic, Multiple Pulsed Interference Signals Applied to a Compressed Radar System

The Periodic, Multiple Pulsed Interference scenario discussed above applies equally to this scenario.

3.3.5.2.6 Periodic, Compressed Pulsed Interference Signal Applied to a Compressed Radar System

This scenario is possibly the most problematic of all pulsed scenarios discussed.

Suppose that a pulsed interference signal is frequency swept, or digitally encoded to match its own compression system. It is possible that the compression encoding used in the radar system could be close to the interference signal compression encoding, This would result in the false returns passing through the radar system compressor, being partially compressed, and generating a false target return. This scenario would occur between two radars of the same model.

In this scenario only a portion of the processing gain need be applied, since pulse compressors are rarely perfect. This would result in partial gain being applied to a false return. Once the periodic correlation has been processed, a false target return could be generated.

In the commentary on receiver protection requirements in Section 3.3.8.2, it is illustrated that a pulsed CW waveform can have processing gain applied.

3.3.6 Future Possibilities and Considerations for the Protection of Radar Services

Interference signals are detrimental to the overall operation of the victim radar system. They can induce false plots and/or a reduction in the probably of detection.

In some cases, where the end user has specified so, particular types or levels of interference may be tolerable; however, in general, any type or level of interference will result in some kind of reduction in radar system performance.

Several possibilities exist for the future of radar services within an interference rich environment, including:

- Persuading future sharers to lower the out of band and spurious emissions produced, whilst also persuading future sharers to minimise transmission in portions of the spectrum that are ‘radar rich’.
- Introducing Military style, Electronic Anti-Jamming measures to reduce effects of interference.
- Improve the overall adaptability of the Signal Processing System to implement noise reduction.
- Move away from the traditional antenna array in favour of the more progressive ‘Phased Array’ technology.
- Employ data fusion techniques to eliminate interference in favour of genuine returns.

Each of these will be discussed in turn.

3.3.6.1 Responsibilities of the sharing partners within the frequency spectrum

It is fair to say that not all interference signals are ‘intentional’, especially when related to civil applications. However, the first and foremost consideration for service protection would be to impose stricter out of band emissions controls on possible interference sources. The current recommendation is that an out of band emission resulting in an I/N of –6 dB should, in fact, be extended to –10 dB. This recommendation is particularly applicable to SOL services (See Section 3.3.8).

Potential sharers should also be made aware of the implications of spurious emissions and their effect on the operating performance of the radars with which they interfere.

Potential sharers should avoid transmission within certain bands that are heavily populated by radar transmissions. This is particularly applicable when considering the SSR arrangement that operates on a set of well-defined frequencies (1030 MHz and 1090MHz).

3.3.6.2 Adopting the Military Attitude to Interference

For many years, military radars have had to deal with extremely hostile environments, where the interference is definitely ‘intentional’. These hostile interference sources intentionally generate interference to perform two functions:

- Noise Jamming
- Confusion / Deception Jamming

3.3.6.2.1 Noise Jamming

This is a blatant attempt to swamp the victim radar receiver with enough energy to render any genuine target return ‘undetectable’. This is exactly the same as using a broad-band interference signal to increase the victim radar receiver noise floor, thus rendering the radar blind at all ranges in the direction of the noise.

This was demonstrated in Section 3.3.4 using a jammer to generate the appropriate signal.

3.3.6.2.2 Confusion / Deception Jamming

A more efficient way of reducing radar system performance is to radiate signals that mimic genuine radar returns. These enter the system and generate a multitude of false targets and false plots. The generation of false targets can cause the receiving system to become crowded with returns, creating much confusion. This allows the genuine target to pass undetected.

Alternatively, the false plots generated cause multiple tracking errors, forcing the system to waste precious processing resources.

This type of jamming has a nature that is similar to the pulsed interference scenarios discussed in Section 3.3.5.

The similarities in the nature of unintentional and intentional interference are prominent. In the military environment, these interference signals are expected, whereas in the civilian environment they are not. It is clear to see that it may be possible to implement certain Anti-Jamming techniques to minimise the effect of interference, especially where the civilian radar is involved in a safety of life application. However, Anti-Jamming techniques are expensive to implement as they can rely on complex algorithmic structures, bordering on adaptive signal processing and more complexity in the hardware.

3.3.6.2.3 Viable Anti-Jamming techniques for civil applications

Some Anti-Jamming techniques do present an opportunity for implementation, these are:

- Generating Ultra-low Sidelobes;
- Sidelobe Blanking;
- Sidelobe Cancellation;
- Frequency Hopping.

The initial set of techniques involves the rejection of any interference received via the antenna sidelobes.

3.3.6.2.3.1 Generate Ultra-low Sidelobe Levels

An obvious decision is to design the radar system so that the antenna has extremely low sidelobe levels, whilst maintaining the adequate value of mainbeam gain.

3.3.6.2.3.2 Sidelobe Blanking System

When an antenna arrangement has particularly poor sidelobe performance it allows interference signals to enter the receiver system. A Sidelobe Blanking system can be employed to prevent unwanted signals entering the system via the antenna sidelobes.

This particular arrangement uses an auxiliary antenna with an omnidirectional pattern to monitor signal strengths entering via the main antenna sidelobes. The gain of the omnidirectional antenna is greater than the sidelobe gain of the main antenna. Signals from the mainbeam of the main antenna and the auxiliary antenna are compared, and if the signals are stronger in the mainbeam then they are accepted. If the signal is stronger in the auxiliary beam they are rejected based on the assumption that they are being received in the main antenna sidelobes.

This technique causes the system to blank out areas of coverage whenever the auxiliary antenna receives signals that are stronger in strength than those received by the main antenna sidelobes.

3.3.6.2.3.3 Sidelobe Cancellation System

This technique is primarily used in the application of Phased-Array Antennas, although it is also applicable to other antenna types. It involves adapting the weights applied to multiple receiving channels so that nulls are steered in the direction of a known interference source. The number of interferers nulled in this way, is equal to the number of extra channels used.

3.3.6.2.3.4 Frequency Hopping

This technique allows the frequency agility principle described in Section 3.3.2.1.5 to be used to full effect.

In this case, instead of waiting for an interference source to be detected (through channel degradation and detection), the system operates a pseudo-random transmit / receive cycle. The radar system now hops from channel to channel, spending a prescribed amount of time at each frequency. This minimises the effect of an interference signal.

3.3.6.3 Improvements in Signal Processing

3.3.6.3.1 Signal Processing

Signal processing routines employed within civilian radar systems are quite complex. However, a popular area of research involves pushing the limits of the signal processor with a view to improving the detectability of signals against all types of clutter and interference.

In modern radar systems, many of the duties previously carried out in hardware are now accomplished in an integrated software / hardware environment. This allows techniques such as Pulse Correlation and Pulse Integration to be achieved through the application of the correct software algorithm and also enables systems such as CFAR to be completely adaptive and particularly flexible. Added to this, pattern recognition could be used to ‘recognise’ particular common parameters associated with certain interference types.

It is a common opinion amongst radar system designers, that the digital portion of a radar system is gradually moving further towards the antenna. With this movement comes the possibility of being able to detect heavily contaminated channels and apply the appropriate algorithm before the signal has moved too far into the system. Thus enabling the detection and rejection of interference at an increasingly early stage in reception. Ultimately, the ideal is to produce a radar system that has a library of interference detection and rejection algorithms, each of which can be applied to reduce the effect of an interference signal.

However, the downside to any witnessed improvement is accompanied by an increase in system complexity and thus system cost.

3.3.6.3.2 Adaptive Filtering

A technique is available that allows interference to be removed from a genuine signal, namely adaptive filtering. This process involves the use of a digital filter that alters its characteristics on a time-related basis. This allows the filter to adopt the necessary characteristic at the appropriate time. A signal passed at one instant in time will not necessarily have the same filtering process applied at another instant in time.

This is the strength of the adaptive process, it provides the signal processing system with the ability to alter its channel characteristics at the appropriate time.

Adaptive filtering systems utilise many sensors which monitor the interference characteristic of a channel at many points. The data from these points are then combined to form an overall response which is used to set the characteristics for the filtering process. In some respects it is very similar to the CFAR process but it is used to cancel the interference component.

3.3.6.3.3 COTS Signal Processing

The advent of Commercial off the Shelf (COTS) processors and field programmable gate arrays have simplified the task of updating the processing algorithms. They only require reprogramming rather than replacement by newly developed processors.

3.3.6.4 Alternative Antenna Approach

Traditional antennas have limited elevation and significantly large beamwidths, providing an interference source with ample illumination time with which to interfere with the victim radar reception system. A new breed of antenna design involves the Active Phased Array, which has many advantages over its traditional counterpart.

Passive phased array antennas have lower sidelobe levels than reflector antennas. An antenna with a lower sidelobe level will be less sensitive to interference being received via the sidelobes.

Interference through the sidelobes can also be reduced by fitting a sidelobe canceller (with its associated receiver channel) to the antenna.

3.3.6.4.1 The Active Phased Array Antenna Radar

This modern approach to radar design incorporates the use of many small transmit / receive modules that are arranged in an array. These modules are miniature transmitter and receivers that transmit the required signals at microwave frequencies, then receive the target return and downconvert to the required IF. In effect they are many miniature radar systems acting as one.

This advance in systems thinking allows the phased array radar to produce fine pencil beams that can scan in azimuth and elevation for fractions of time, beamwidths and profiles can be altered to suit the environment. The advantage of this being that pencil beams illuminate small areas for only a small duration in time, thus minimising the illumination placed on a potential interference source in both illumination time duration and in total illumination power. With both of these parameters reduced, the effectiveness of an interference source is greatly diminished.

The arrangement can implement a stacked beam antenna, thus avoiding short-range interference and allowing full system resources to be placed on the long-range scanning. It also provides the ability to produce complex scanning patterns, enabling problem coverage areas enveloped in interference to be avoided – but not to the same level of degradation as found in the traditional antenna radar.

The greatest asset in the Phased Array repertoire is the ability to eliminate constant interference sources through the use of null steering. This is explained in Section 3.3.6.2.3. The nulls are arranged so that they fall in the direction of the interference sources.

The null steering however only works if the system is not saturated. If the level of interference is high then other considerations need to be addressed. Considering the case of on-boresight interference, the power seen by the first stage of the receiver is, in the case of a conventional system related to the incident power density multiplied by the effective aperture of the receiving antenna (this is proportional to the physical area multiplied by an efficiency factor related to the aperture distribution used in the antenna design). In the active array antenna, the power seen at the front end of the receiver (now distributed over the number of elements) is the incident power times the effective aperture (now equal to the physical area of the aperture) divided by the number of elements. Thus assuming similar saturation levels and neglecting antenna and feeder ohmic losses, the first stage of the conventional system will see more power than the active array. However once the signals have been combined in the later stages of the receiver chain the difference is less. Remember however that adaptive active array systems have multiple receivers. Off axis however, the power received in the first stage in the active modules is reduced proportionally to the change in the projected area. In the conventional system the reduction is related to the fall off of gain with angle. Thus in a conventional antenna, rejection of the off-axis signals at the first LNA stage will follow the far-field antenna gain pattern. In an active array, the off-axis rejection of signals at the first LNA stage will fall off as the individual element pattern, that falls off at a much lower rate of approximately $\sin\theta$.

The situation is further complicated if the interference source is very close and does not illuminate the antenna with a plane wave. The conventional antenna will provide rejection (mismatch) to the spherical wave front over and above the array factor. In the case of an active array, each of the modules will act as an individual low gain receiver and provide a higher level of coupling to the near-field source.

In the case of out of band interference the situation is slightly different. Because the design of the active array requires very close physical coupling between the radiator and the receiver front end, there is very little room to add any frequency selective components to suppress out of band interference. In the conventional system there is generally room if needed to add such components and to make use of the natural frequency selectivity of the feed system i.e. the high pass nature of waveguide for example. In conventional systems it is also possible to fit more robust active limiting components to provide protection to the low noise front end of the receiver.

However, the Phased Array radar is an expensive item. Each array can use in excess of 10,000 individual array elements, making the array an expensive piece of equipment. It also requires an enormous amount of processing power as opposed to its traditional counterpart. This is largely due to the adaptive beam forming capability.

3.3.6.5 The Employment of Data Fusion and Sensor Networks

Data fusion techniques are based on the principle of bringing together data from a variety of sensors at different locations, possibly having different performance characteristics. This has an advantage in that the detection probability for the network will be greater than for a single sensor. While target locations from each sensor should agree, false alarms probably will not. Data from the various sensors is processed by an overall decision making system to provide the final fused output. This data fusion, however, is a computationally intensive process.

There are a number of advantages to using data fusion techniques, over a network of sensors, for the protection of radar services. The sensors in the network may operate on different frequencies and thus will not all be affected by the same interferer at a given frequency. In addition, being at geographically different locations means that an interferer in a given direction for one sensor will be in a different direction for another and will not obscure the same targets.

Data fusion networks could involve multiple radar installations providing each other with genuine target, false target and interference data. This approach could also provide installations with a certain level of adaptability, in that, one radar installation could provide long-range data, whilst others connected to the network could provide short-range data. This effectively creates an overall radar system that would possess the characteristics of many radar systems combined.

An example of a simple data fusion system is the combination of primary radar plots and secondary SSR replies onto a single operator display such as used in air traffic control centres.

3.3.7 Comments on Radar Receiver Protection Criteria

3.3.7.1 Introduction

The previous sections have addressed the issues of how interference affect a radar receiver and what options can be used to mitigate any effects. This section addresses the issue of what level of interference is acceptable and how this can be turned into a meaningful protection requirement. This section reviews the current available information on this topic as regards radar and makes suggestions as to an appropriate level.

There have been discussions as to the appropriate protection level for radiodetermination systems. The current protection requirements are defined as levels of interference, below which the interfering signals have no, or a maximum acceptable, effect on the operation of a radio service.

Within the ITU the protection requirements for radar are given in the following documents:

M.1460 Technical and operational characteristics and protection criteria of radiodetermination and meteorological radars in the 2 900-3 100 MHz band.

M.1461 Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services.

M.1462 Characteristics of and protection criteria for radars operating in the radiolocation service in the frequency range 420-450 MHz

M.1463 Characteristics of and protection criteria for radars operating in the radiodetermination service in the frequency band 1215-1400 MHz

M.1464 Characteristics of and protection criteria for radionavigation and meteorological radars operating in the frequency band 2 700-2900 MHz

M.1465 Characteristics of and protection criteria for radars operating in the radiodetermination service in the frequency band 3100-3700 MHz

M.1466 Characteristics of, and protection criteria for radars operating in the radionavigation service in the frequency band 31.8-33.4 GHz

M.1313 Technical characteristics of maritime radionavigation radars

This list is not exhaustive and further documents exist for other radar bands.

Protection requirements are used to assess the possibility of sharing between systems. Virtually all these papers define the protection requirements in terms of an I/N ratio, which has traditionally been set to -6 dB. There is no evidence as to where historically the I/N - 6 dB level was derived from.

where:

I/N : interference-to-noise ratio at the detector input (IF output) necessary to maintain acceptable performance criteria (dB)

N : receiver inherent noise level (dBm)

$N = -144 \text{ dBm} + 10 \log B_{IF} + NF$ Equation 3.3.7-1

Or

$N = -168.6 \text{ dBm} + 10 \log B_{IF} + 10 \log T$ Equation 3.3.7-2 where:

B_{IF} : receiver IF bandwidth (kHz)

NF : receiver noise figure (dB)

T : system noise temperature (K).

Generally within the ITU[3] a I/N protection level of - 6 dB is assumed acceptable if no other level is specifically given. There have been proposals by the US and the UK to reduce this level for Safety Of Life services (SOL) to -10 dB.

This section addresses two issues:

What is an "acceptable" level of Interference?

Where and how, in the system should this "acceptable" level be defined?

3.3.7.2 What is an "acceptable" level of Interference?

To answer the question what is an acceptable level of interference it is necessary to address two issues.

What is the effect of interference on a radar system?

At what level does the effect of interference become unacceptable to the user[4]?

The effect interference has on the operation of a radar system depends on:

The level of the interference (power level);

The type of interference (signal type, pulsed or CW);

The type and role of the radar.

3.3.7.2.1 What is the effect of interference on a radar system?

Interference can come in several types however it can generally be classified as pulsed or continuous. The pulsed interference can be further divided into synchronous or asynchronous.

Pulsed interference tends to appear in one, or a group of contiguous range cells, depending on the pulse length. Continuous interference appears in all range cells. The effect of interference is two fold, it can produce false targets or groups of false targets on a display or target data output (i.e. it increases the false alarms). It can also desensitise the radar such that targets are lost. In practice both effects can occur at the same time. Initially it affects the small targets in difficult detection conditions. In the limit however, it can totally desensitise the radar, leading ultimately to physical damage to the radar receiver.

False alarms can appear as individual speckles on the screen up to the complete filling of one or more sectors of the screen with a "white out". In this case all targets on one or more bearings are lost.

The suppression of targets is much more difficult to identify. Generally it manifests itself as missed plots or broken tracks. It is more apparent on small targets in difficult detection conditions (i.e. rain or ground clutter). This effect is particularly difficult to spot by an operator due to its insidious nature, it not being immediately obvious.

The effect of continuous interference occurs at all ranges and again depending on the spectral properties of the interference, it can either, be seen as false alarms, or it desensitises the radar. In this case however the desensitisation may cover a greater area than for pulsed, as it will occur in many range cells.

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[3] ITU-R Recommendation M.1461 "Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services."

[4] The acceptability must be defined in terms of the user, not some arbitrary level.

When the interference is "noise" like it can be thought of as effectively raising the system noise level in the radar. This reduces the radar's Signal to Noise ratio (S/N) and causes the CFAR (Constant False Alarm Rate) circuits in the radar to increase the detection thresholds thus reducing the radar sensitivity to keep the false alarms at a constant rate.

As the interference increases in power, the radar becomes progressively less and less sensitive. The result of this on the display is a steady reduction in the number of targets being displayed. This can be very insidious, particularly if the noise is very uniform as it may go unnoticed. (The increase in interferfence can be viewed if the radar is fitted with a display showing raw, unprocessed video.)

3.3.7.2.1.1 Reduction of Pulsed Interference

Where interference on the display is seen as a problem there are techniques[5] for removing pulsed interference[6]. These however cannot be implemented without some penalty in processing loss. This loss however may not be a problem if the system is designed to take this into account from day one.

3.3.7.2.1.2 Reduction in CW interference

One way to mitigate a CW or noise-like modulation is to use higher transmitter power and higher antenna gain[7]. This results in the signal being returned from the target increasing compared to the interference. Alternatively the radar can be tuned to a frequency far enough away to make use of the spectral roll-off of the interference and the selectivity of the radar. Military radars use frequency agility to defeat jamming which is an extreme form of interference. They look for the least jammed frequency and choose their operating frequency appropriately. Unfortunately civil radars generally do not have this luxury. Either of the two methods however, cannot be said to be very friendly to other users of the spectrum.

3.3.7.2.2 At what level does the effect of interference become unacceptable to the user

In simple terms the level of interference is only acceptable when it does not reduce the operational integrity of the radar to an unacceptable level. In the end only the user of the system, and those who have to demonstrate that the system is of suitable integrity, can decide this. Generally systems are specified to have a safety margin, for example the radar may be designed with an instrumented range of say 70 nm but only used out to say 50 nm.

In terms of loss of detection this can manifest itself as a reduction in PD below the specified level. Typically ATC radars are specified for an 80% PD. Generally a reduction of 3 or 5 % would be considered unacceptable. This loss of detection manifests itself as loss of targets or track dropouts. As for false plots and false tracks, air traffic service providers and safety regulatory authorities generally have a requirement to not exceed a maximum number of false tracks. To some extent this can be traded against the track initiation rules, however delaying the track formation results in late declaration of targets. At some point however the display will be considered unusable.

The detection of targets in noise by a radar system is a statistical process and is a balance between the probability of a correct detection, P_d, and the probability of a false alarm, P_{fa}. The probability that a valid target report will be output by the radar for a given false alarm rate depends on the S/N and the number of hits on the target per scan. The S/N is a function of the target size and range and radar parameters such as noise figure and EIRP. Thus for a given target and a given scan, the probability that a valid target report will be

[5] ITU-R Recommendation M.1372 "Efficient use of the radio spectrum by radar stations in the radiodetermination service."

[6] PRR Stagger and defruiting.

[7] In some cases it is possible to achieve more detection by increasing the number of target hits by upping the PRR or widening the radar beamwidth.

produced varies due to the natural fluctuation of the target (due to propagation loss and target aspect changes within the radar beam) and the statistical nature of the process.

For a single target within the coverage, the P_d is defined as the number of valid target reports (target detections) divided by the number of times that the antenna scans past the target, or transmits a complete set of pulses in the direction of the target. For a mix of target sizes and aspects (i.e. opportunity traffic), the P_d is defined as the number of valid target reports output from the detection process expressed as a percentage of the expected possible number of valid target reports. A large number of detection decisions are required for this number to be statistically significant.

The radar detection requirement is specified by air traffic service providers to be greater than 80% P_d on a single target with a 1 to 2 m^2 radar cross section at a false alarm rate of 10^{-6} in free space conditions at the specified maximum range, i.e. with no clutter anywhere in the coverage region. In practice this means at the edge of the coverage region, as the P_d increases as the target closes on the radar. Experience has shown that for a mixed target scenario (aircraft of differing sizes at all ranges) the detection criteria of 80% on 1 to 2 m^2 targets specified translates into an average P_d (overall) of greater than 90%. This means that on every scan of the radar antenna, more than 90% of the targets inside the coverage will produce valid target reports. The specific targets producing valid reports will differ between each scan depending on the range, size and orientation of the target from the radar.

In order to prove the single target detection criteria a flight trial is required. This is carried out by having an aircraft of known target size fly a predetermined course, generally radials, whilst the number of detections is recorded. The height and position of the aircraft are known and recorded and the trials manager is in radio contact with the pilot hence the "ground truth" is known. This process is both time consuming and invasive as it generally requires the radar to be taken out of service during the trial.

Eurocontrol have determined the fact that the detection performance of a system can be quantified from the average P_d by developing a tool that can be used by making measurements on targets of opportunity. The SASS-C[8] tool can be used to record targets of opportunity and to analyses the results to provide the average P_d. The SASS-C tool calculates the average P_d.

The formula which is used by SASS-C to calculate the probability of detection of the primary radar is given by the following equation:

$$P_{d\ prim} = \frac{number\ of\ \mathbf{acknowledged}\ primary\ plots}{number\ of\ \mathbf{expected}\ primary\ plots} \qquad \text{Equation 3.3.7-3}$$

where a primary plot maybe primary only or a combined plot (primary and secondary).

The number of expected primary plots in the flight trial comes from absolute knowledge of the aircraft's position. In the SASS-C tool the expected position is obtained from secondary radar returns. Aircraft without secondary transponders are not used in the calculation. The secondary return is thus assumed to provide the ground truth and to have a P_d of approximately 100%. This assumption is generally true and if some secondary tracks are poor they can be excluded from the analysis or repaired by the tool. SASS-C also has the ability to form tracks on primary targets only from which expected plots may be derived.

At least 50000 plots inside the primary coverage volume (less than 60 nm range) are recorded for each measurement. Depending on the amount of traffic this corresponds to a duration between 1 hour 20 minutes and 2 hours.

Thus the measurement of average P_d on opportunity traffic provides a quantitative measure by which changes in detection performance can be measured.

[8] Eurocontrol's 'Surveillance Analysis Support System for ATC Centre' Software Tool.

Studies are currently underway using the SASS-C tool to relate the levels of interference to the effects observed on the radar and hence to assess a level of acceptability in terms of the variability of system performance. It must be realised that the results for these studies will be specific to the physical implementation of the radar, receiver, signal processor etc. and that the level of acceptability will depend on the user's assessment of the effect in the specific radar environments tested. These studies are specific sharing studies, they are not designed to provide a global protection level. However they will provide an indication of the practical effects of interference and can be used to support any general level proposed.

It is possible with the work carried out to date, to gain an accurate assessment of the protection level that should be adopted.

Considering the following issues:

3.3.7.2.2.1 Specification Limits

The user specifies the performance required from the radar to meet the operational requirements. In general the user has a design margin to allow for high integrity operation. Experience suggests that users are very reluctant to accept systems that fall outside these specification limits.

3.3.7.2.2.2 Reduction in radar coverage due to noise-like interference

Section 3.3.8.2 shows that if the interference was continuous and noise-like the radar coverage is reduced. It concludes:

> The effect of 1 dB loss equivalent to interference 6 dB below system noise can start to produce degradation to the radar detection. The radar still achieves detection out to the full-instrumented range but both low-level cover and high level cover become eroded. Civil aircraft usually have relatively large radar cross-sections and many will have areas much larger than the $1m^2$ assumed in the analysis. The problem comes in detecting small uncontrolled targets such as some military or general aviation aircraft (which may not have or do not choose to use SSR).

As well as a reduction in cover it would be expected that the interfering signals would be highly non-homogeneous in time. It would therefore be expected that the radar's CFAR circuits would perform badly when subjected to this form of interference and would produce large numbers of false alarms. This can produce high levels of operator nuisance and if large enough can lead to an overload of the radar plot extraction and filtering functions possibly resulting in target loss.

At the required levels of P_d a 1 dB reduction due to interference would result in a reduction of azimuth accuracy. Weak targets at lower P_d and under conditions of interference at the minimum protection level, (6 dB below the System Noise Level (SNL)), could considerably exceed the limits. Selective interference on one frequency of a two-frequency diversity radar can have more drastic effects.

3.3.7.2.2.3 Simple analysis of the statistical nature of radar targets

In a radar system there is natural variability in the S/N achieved, mainly caused by the variation in target echoing area.

If the interference were also variable, the increase in the overall RMS S/N would be from 2.3 to 3.2 dB (i.e. 0.9 dB) for a 1 dB increase in noise.

If the interference were not variable then this would result in a constant 1 dB offset.

3.3.7.2.2.4 Flight Trials evidence

Flight trials are used in many cases to demonstrate the performance of radar systems. There is an uncertainty related to these trials due to variations in target size[9] and

[9] This uncertainty can be reduced by flying a calibrated target. Most authorities however prefer to use a well characterised aircraft preferring to rely on comparative rather than absolute results.

environmental aspects. Thus design proving is generally based on a combination of trials, modelling and sub-system tests. The uncertainty in trials has led to a belief in some areas, that because of the difficulty in making accurate measurements, small variations in system performance are not important. This belief is fallacious. The fact that a reduction in performance cannot be accurately measured does not mean it is not present or is not significant.

However extensive flight trials on approximately 100 ground ATC radars at fixed sites have shown that variations in system performance of the order of 1 dB can be detected if a well-characterised and repeatable target aircraft is used. This has been demonstrated at both the same geographical site and between sites fitted with similar equipments. Variations of the order of 0.5 dB are generally not capable of being detected using this method.

3.3.7.2.2.5 Measurements on a Radar Receiver

Paper SE 34(01)15[10] reports work carried out on how the Minimum Detectable Signal (MDS) of a radar receiver is affected by both noise and CW interference. It concludes:

"The MDS of an ARNS radar system was measured and found to be within 3 dB of the system noise power. Signals between 6 and 10 dB below the MDS were found to give an observable effect. The relation between the MDS and the system noise depends on the match between the signal and interference waveforms. This work indicates that the proposed ITU protection level of greater than 6 dB below the system noise may not be adequate for a SOL service.

Received signals at around the MDS level were found to be seriously corrupted by interfering signals of a similar level. Interfering signals approximately 16 dB above the system noise power were assessed to seriously overload the receiver. Interference sources, co-frequency, anywhere in the line of sight of the radar, were unacceptable. Off-frequency sources would need to be separated by a significant portion of the band if they were not to affect the MDS level. Off-tune signals at a still higher level would result in receiver blocking as well as MDS corruption."

3.3.7.2.2.6 Measurements on Live Traffic

Three sets of measurements have been made by simulating the effect of interference on radars measuring live traffic. In these measurements signals representing various interfering sources were injected into the front end of a radar system and the effect on the overall P_d was measured using the SASS-C tool described above.

Work has been carried out under the sponsorship of Eurocontrol on three radars in Europe; a Magnetron based system TA 10 M, a Kylstron based system SRE-M5 and a Solid State system Star 2000.

The test set up used in each case is similar to that given in Figure 3.3.7-1 for the Star 2000.

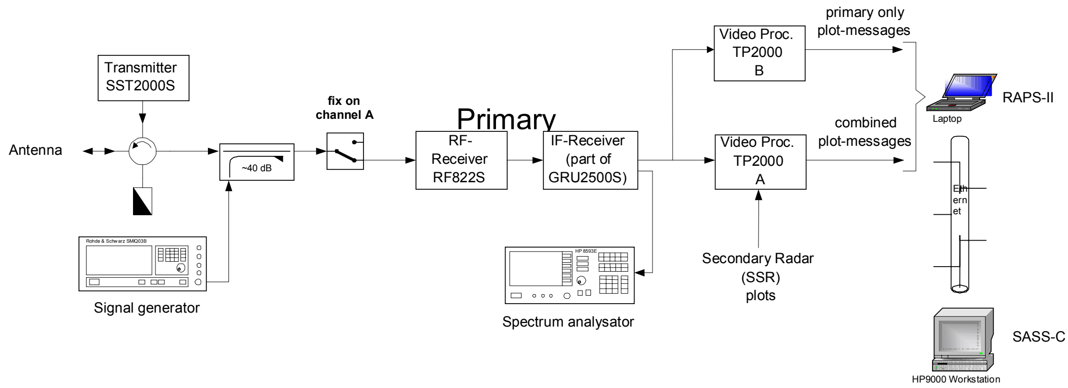
---

[10] Paper SE34 (01) 15, London, 23 January 2001

Subject: Study into the Effects of Interference on an ATC Radar system.

Origin: Eurocontrol, BAE Systems, Airsys ATM.

Figure 3.3.7-1 Test Set-up



The work carried out on the Magnetron and the Solid State have been reported in the following documents:

SE 34(01) 32 Study on 2700 MHz – 2900 MHz Frequency Band sharing between existing Aeronautical Radar Equipment and planned Digital ENG/OB[11] and Digital Aeronautical Telemetry Services.

SE 34(01) 54 Study on 2700 MHz – 2900 MHz Frequency Band sharing between existing Aeronautical Radar Equipment and planned Digital ENG/OB and Digital Aeronautical Telemetry Services. Part 2 - Description and Evaluation of Interference Simulation on Thales STAR 2000 ASR Salzburg

Both these experiments used digital communications signals and noise as the source of interference. SE 34(01) 32 concludes that:

"Considering that relevant EuroControl standards request at least 90 % probability of detection P_d, at less than 20 false alarms per antenna round scan to be provided by an operationally used ASR, and that for the S/N associated with such probability 1 dB change in S/N can produce, depending on signal type and detection/processing scheme, between 3 and 30 percentiles change in P_d, then it is evident that the maximum allowed interference level I_{max} = N – 6 (dB) stated in ITU-R recommendation M.1464 (this is just the level reducing S/N by 1 dB) cannot longer be hold for this category of radars, and for interference of type OFDM (Orthogonal Frequency Division Multiplex).

This restrictive statement is underlined by measurement results obtained with the Graz ASR, where injection of OFDM interference signals caused considerably higher P_d degradation than such caused by interference of type white noise. For I/N = - 10 dB (i.e. interference power is 10 dB below noise), detection probability P_d changed against the undisturbed probability

by -2.15 percentage points for white noise,

by -10.3 percentage points for 8 MHz ENG/OB, and

by -8.3 percentage points for 5 MHz Aeronautical Telemetry interference.

These results tell us that interference signals of type OFDM can have much higher impact on P_d than such of type white noise. While for noise the sensitivity is 5.2 percentage points per dB change in S/N, for OFDM signals this can go up to 25 percentage points per dB."

SE 34 (01) 54 concludes that:

[11] Electronic News Gathering/Outside Broadcast

"Altogether the measurements on the Salzburg ASR, a modern and advanced pulse-compression system, have again shown that a protection ratio I/N = - 6 dB is not sufficient for maintaining an air surveillance/control radar's necessary quality and safety standard. An I/N ratio of –12 dB is to be recommended. This result receives particular support from actual events which have shown that secondary radar (SSR) alone cannot guarantee continuous availability of air traffic constellation status. This applies also to planned position determination by means of satellite navigation services."

These conclusions are used in the Draft ECC Report 6:

"Technical Impact on Existing Primary Services In the Band 2.7 - 2.9 GHz Due to the Proposed Introduction of New Systems".

In this report reference is made to protection requirements in the range of -6 to -12 dB and that the current ITU requirement of -6 dB may not be adequate for any individual case.

Further work yet unpublished has been carried out using RNSS type signals in L-Band concludes that for the specific radar type under consideration in the I/N should be reduced to -11 dB.

3.3.7.2.2.7 Other Evidence

Several other papers have been placed into the ITU considering this topic. These provide further inputs for consideration.

US paper 8B/77-E references work carried out in the UK and the US. This paper concludes that the current - 6dB I/N may not be adequate.

US paper 8B/78-E studies the effects of interference from IMT-2000 stations and concludes that -6 dB I/N may not be adequate and studies to confirm - 10 dB I/N are required.

US paper 8B/31-E recommends a -10dB I/N for radionavigation and meteorological radars.

Document 8B/TEMP/63-E concludes that interference at the - 6dB level could cause unacceptable interference.

Current proposal for modifications to ITU-R Recommendation M.1313-1 ("Technical characteristics of maritime radionavigation radars."), contain proposals to adopt protection levels of -10 dB I/N

France paper 8B/63 concluded that there was an effect on the detection performance with a - 6 dB I/N as described in other papers but that it was not operationally significant.

UK Working Party document 8B/C WP(01) 032 addressed these issues and supported the change to -10 dB I/N.

3.3.7.2.2.8 Summary of evidence to date

When considering the level of protection requirements that should be recommended inevitably the role, the undisturbed performance and the detailed operation and implementation of the radar must be considered in the light of the form of the interfering signal. The use of a blanket protection level would thus seem a little too crude an approach. However its recognised that in order to study the feasibility of sharing that some guidance must be given.

The problem is defining the level of deterioration that can be accepted by a radar service given the unacceptable nature of an air traffic accident. Some would argue that no deterioration should be permitted, however this begs the question, "why not strive to achieve a P_d of 100%?". In which case no primary radar would be adequate. It must be remembered that primary radar is only part of an overall air traffic control service and that acceptable level of integrity of the complete service is what is required. Eurocontrol have adopted the 90% average P_d criterion though generally one would expect a higher level of this to be achieved in practice. Care must however be taken when looking at average figures as these can distort the view. The acceptability of the radar is not just measured as the average P_d. This figure is used only as a long term monitor to detect any changes. The "safety case" supporting the radars consists of evidence covering, design calculations, factory and installed measurements on the equipment hardware, evidence as to the integrity and fitness for purpose of the software, manufacturing quality records and dedicated flight trials.

The use of average P_d can mask problems associated with reduction due to bad weather and to the detection of small targets particularly at long range and it is specifically these types of targets in poor propagation conditions that are most likely to be lost first with the type of interference being considered. Taking a specific target type the reduction in P_d may be much greater than that indicated from the average.

The evidence to date presented in this and other papers is that signal levels of - 6dB below the system noise do have an effect on the performance of the radar. When considering that Safety Cases related to SOL services need to consider worst case, as even a very rare event with a high accident severity is unacceptable. It is thus required to adopt a safety net level based on ALARP[12] principle. This approach would result in the conclusion that - 6dB is unacceptable for SOL services. The current evidence suggests that this level needs to be reduced to a maximum of -10 dB I/N to -12 dB I/N. There is some evidence that for certain combinations of radar and interferer, higher levels of protection are required. Thus when recommending a protection requirement it must be recognised that the need for a new service not to interfere with an existing service must be maintained and that specific sharing studies must be carried out prior to the introduction of a new service.

SE 34 (01) 54 recommends that:

> *"It is strongly recommended to reduce permissible noise-like interference level further, at least down to -12 dB relative to system noise (causing 0.27 dB S/N reduction or up to 8 percentiles P_d reduction)."*
>
> *"Detection probability reductions of 10.3 percentiles (for 8 MHz ENG/OB signal) and 8.34 percentiles (for 5 MHz Aeronautical Telemetry signal), caused by an interference level –10 dB relative to system noise, unambiguously support the recommendation to reduce permissible interference level for this signal type even further to below –12 dB relative to system noise level."*

3.3.7.3 Where in the system should this "acceptable" level be defined ?

One issue that seems to be missed in many papers on this issue is the effect that the characteristics of the interfering signal has on the acceptable I/N level. There are two areas affected by the type of signal. The first is the effect that the spectral and temporal variations have on the signal that is being processed. This issue is addressed for a specific case in Section 3.3.12.3 but the result is very dependent on the radar type and to some extent how it has been set-up (optimised). Page 47, para 5.2 of ITU Working Party document 8B/100 "Characteristics of radiolocation radars and criteria for protection of their mission" touches on this topic.

As well as looking at the effect that the type of interfering waveform has on the signal processing it is also necessary to look at the effect it has in the receiver if a sensible I/N value is to be defined. ITU-R Recommendation M.1461 "Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services", specifies at what point the I/N is to be defined.

Page 5 of the ITU recommendation defines I/N as at the detector input (IF output). This stage is prior to any digitisation, prior to the Phase Sensitive Detector.[13] This is not necessarily the same value as at the input to the receiver.

[12] As Low As Reasonably Practical

[13] Direct Digital Receivers excepted.

To illustrate the point, consider the example given in Section 3.3.8.8. This gives an example of a pulse compression system. In such systems typically the minimum detectable signal[14] before compression (i.e. at the receiver input) is below the thermal noise calculated using KBT + NF.

The compression process enhances the return echo, in this case by 19 dB, to an acceptable S/N ratio, in the range cell of the target, see Figure 3.3.8-10.

Section 3.3.8.9 Figure 3.3.8-11 shows the effect of this process on another signal type, in this case a pulsed CW signal of equal pulse length to the wanted signal. In this case the signal is not enhanced by the 19 dB as the wanted signal, but it still experiences a gain of 6 dB.

If the level of this interfering signal had been defined as a I/N_r of -6dB at the receiver input, at the detector input it would be an I/N_d of 0 dB.

When making these considerations it is necessary to also include any loss due to the mismatch of the signal to the receiver bandwidth.

In this case the bandwidth of the pulsed CW is lower ($\approx$ 1/Pulse Length) than the compressed pulse ($\approx$1/Compressed Pulse Length) for which the receiver is matched, so very little bandwidth loss would be seen.

This level of signal would have a serious effect on the radar performance. The fact that the compression process was not complete has also resulted in an interference signal equal to the system noise N, existing over many range cells. This would seriously upset a background averager used in the CFAR process.

Thus it is necessary when considering the definition of I/N to specify that it is either prior to the detector, or if it is to be defined at the receiver input. If it is to be defined at the receiver input then a term in I/N allowing for any coding gain is required.

The current ITU recommendation for the calculation of interference to radars[15] defines the I/N at the detector input but confuses the issue by later defining "I" as "peak power of the undesired signal at the receiver input". This document is under review; document 8/67-E proposes changes, however it does not address changes in this area.

3.3.7.4 How should this "acceptable" level be defined ?

The definition of I/N needs some mention here. The definitions in ITU documents ITU-R Recommendation M.1464[16], ITU-R Recommendation M.1463[17] etc. define the noise in terms of spectral noise power density in units of dBm/MHz. This is confusing, as what is really required is the total noise power in the receiver. The I/N should then be expressed as:

$$\frac{I}{N} = \frac{\text{Total Interference Power}}{\text{Total Noise Power}}$$ Equation 3.3.7-4

integrated over the receiver bandwidth.

---

[14] The MDS is the lowest level of signal that can be detected in the noise. In non-compression or coded receivers it is typically N+3 dB.

[15] ITU-R Recommendation M.1461 "Procedures for determining the potential for interference between radars operating in the radiodetermination service and systems in other services."

[16] ITU-R Recommendation M.1464 "Characteristics of and protection criteria for radionavigation and meteorological radars operating in the frequency band 2 700-2900 MHz."

[17] ITU-R Recommendation M.1463 "Characteristics and protection criteria for radars operating in the radiodetermination service in the frequency band 1 215 to 1 400 MHz."

If the bandwidth of the interference is equal to, or wider than the radar bandwidth then the equation above can be expressed as a spectral noise power density. If the interference is narrower in bandwidth than the radar then spectral power densities cannot be used.

It should also be remembered that the bandwidth of the radar is defined as the narrowest bandwidth in the receiver, generally in a matched receiver the bandwidth that is associated with $1/\tau$. Where 'τ' is the pulse length of a non pulse compression radar, or the compressed pulse length if appropriate. This is not necessary the IF bandwidth.

3.3.8 Effect of Noise-like Interference on Radar Coverage[18]

3.3.8.1 Introduction

Many types of civil radars systems provide "safety of life" services. These include, but are not limited to, ATC and VTS systems. Since meteorological radars provide essential information to both ATC operators and aircraft pilots in particular, there is a strong case for including these radars in this category.

Also ground based weather radars are used in association with hydrological models to predict effects of rainfall on ground water. This is used to predict the possibility of flash flooding. Both these applications have a SOL element.

It is thus essential that these radars be protected from harmful interference. Other radars whilst not being strictly "safety of life" should not be subject to unacceptable levels of interference.

The effect of the interference however on the safety of life can only be analysed in "operational terms", depending as it does on the specific role being played by the radar sensor. It depends on how much reliance is placed on the data in strictly safety terms and what backup systems exist.

Work has been carried out that shows that signals greater than -10dB compared to the system noise can noticeably affect the received signal.

This section assesses how noise-like interference can affects the overall system performance of the radar sensor in terms of detection and coverage. The coverage used in this analysis is based on that specified in CAP 670 ATS Safety Requirements, Pt C, Section 3/RAD 02 paragraph 12 "Coverage".

A section is included on the effect of pulse compression on different signals. This indicates that pulse compression gain in signal to interference ratio can be claimed when the interference is noise-like. However, when the interference is pulsed CW, the pulse compressor also produces a gain on the pulsed CW signal. This means that the effect of interfering pulsed CW signals will be worse than noise signals. It should be remembered that this analysis is based on one type of radar and different radar designs may react differently to interference. This is especially true when considering false alarms.

3.3.8.2 Effect of increased Noise level on Target Detection

A radar is normally designed to produce a constant number of false alarms so that when the interference changes, the thresholds are automatically adjusted to maintain the false alarm rate. When the thresholds are raised, the ability to detect targets is reduced so that the effect on radar performance of an increase in noise level is to reduce the range at which a target can be detected.

For the special case of white noise, the effect of interference can readily be calculated. When the noise level is raised due to external noise-like interference, the loss of sensitivity can be calculated as:

$$Signal / noise = \frac{Signal\ \ power}{Noise\ \ power + Interference\ \ power} \qquad \text{Equation 3.3.8-1}$$

---

[18] This analysis is based on that originally presented in:

Paper SE34(01)15, London, 23 January 2001,

Subject: Study into the Effects of Interference on an ATC Radar System

Origin: Eurocontrol, BAE SYSTEMS (AMS), Airsys ATM

Using the more common log notation:-

$$S/N = 10 \times Log(Signal\ \ power) - 10 \times Log(Noise\ \ power + Interference\ \ power)$$

Equation 3.3.8-2

The loss of detectability in dB due to any interference then becomes: -

$$Loss = -10 \times Log(Noise\ \ power) + 10 \times Log(Noise\ \ power + Interference\ \ power)$$

Equation 3.3.8-3

Now, writing the noise as unity, the loss becomes: -

$$Loss = +10 \times Log(1 + \frac{Interference\ \ power}{Noise\ \ power})$$

Equation 3.3.8-4

Where any level of interference need now only be defined with respect to noise.

Hence, if interference is 1/10th of the noise power, the loss will be 0.4dB and if it is equal to noise power, the loss will be 3dB.

3.3.8.3 Basic Radar Performance

The coverage of a typical ATC radar in the clear and with no added interference is shown in Figure 3.3.8-1. Full coverage for both the high beam and the main beam coverage are plotted and the antenna has a nominal zero degree tilt. In normal operation, the antenna tilt and the high beam to main beam switchover range are optimised to the local site conditions. The radar is instrumented out to 60nm.

The coverage diagrams are produced for a 1m^2 target at 80% P_d in the clear with a false alarm rate of 10^{-6}.

Figure 3.3.8-1 Standard Radar Coverage

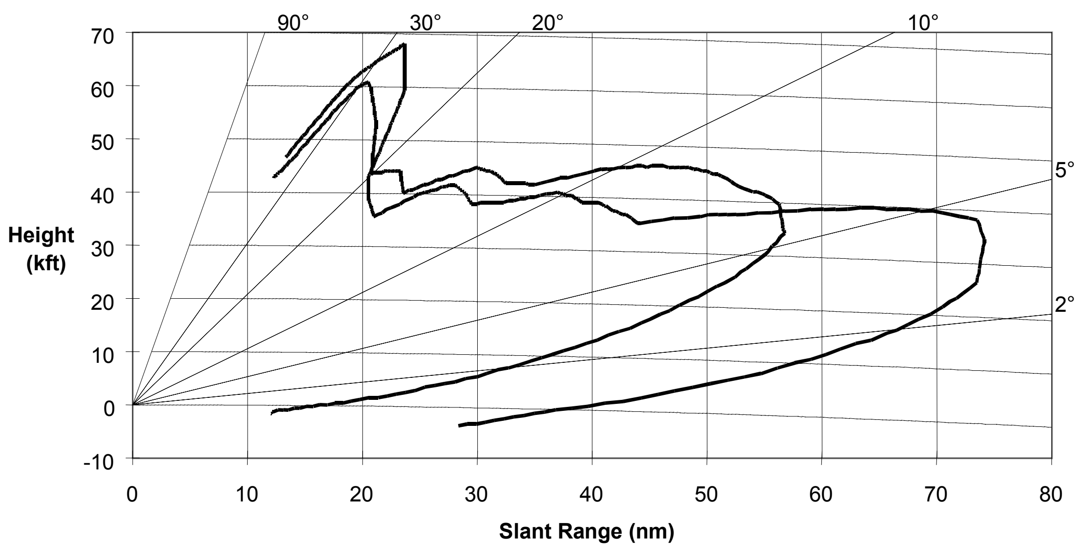
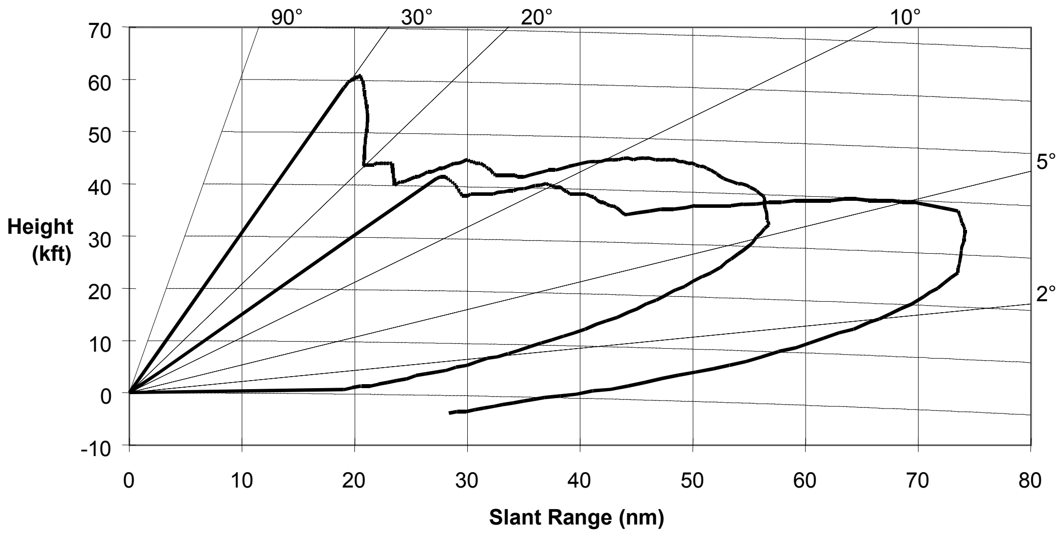


Figure 3.3.8-1 shows that the radar can detect a target out to the full instrumented range and up to 40kft.

The radar would rarely be operated without sensitivity time control (STC) so Figure 3.3.8-2 shows the coverage with an STC setting starting at 27nm in the main beam and 19nm in the high beam and in both cases increasing at the fourth power of the Range.

Figure 3.3.8-2 Standard Radar Coverage with Typical STC

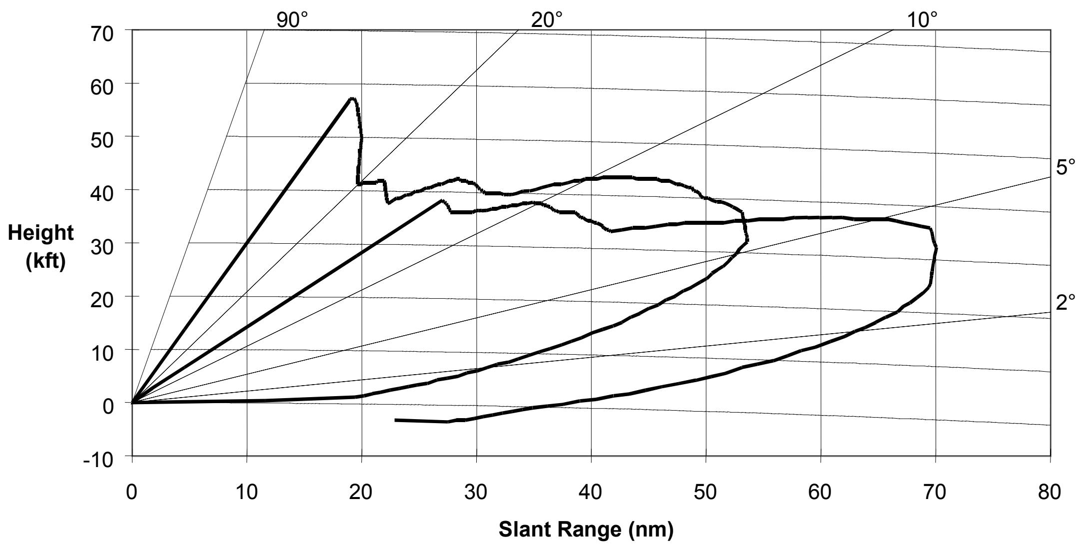


3.3.8.4 Effect of Loss

The effect on the coverage diagram of various degrees of loss due to broad-band noise interference can now be assessed.

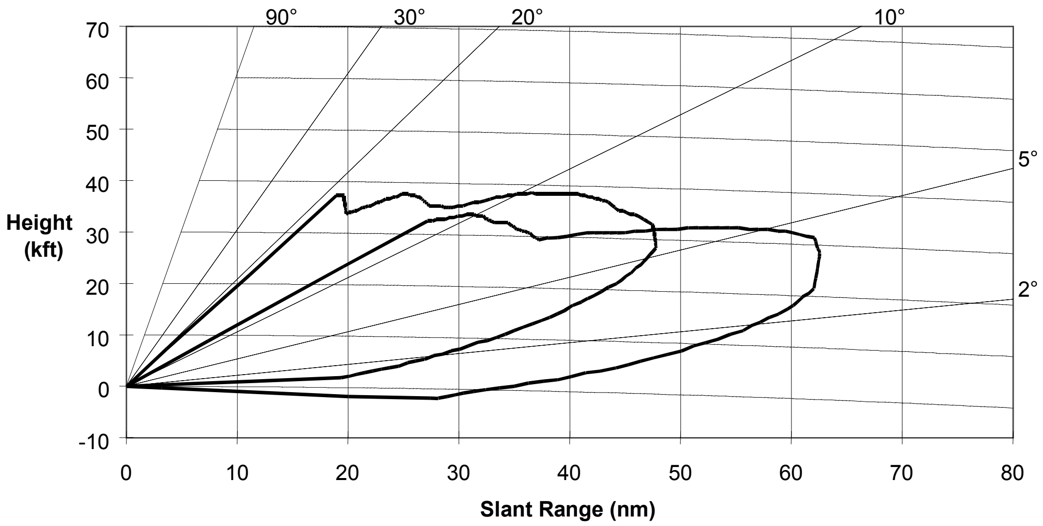
In Figure 3.3.8-3 the effect of 1dB of extra loss applied to Figure 3.3.8-2 is shown. 1dB of loss would result from noise interference that is almost 6dB below system noise, at a level consistent with the protection requirements defined by the ITU for this class of radar.

Figure 3.3.8-3 Standard Radar Coverage with Typical STC and 1dB Loss



When the interference increases to be equal to the noise level, the effective loss increases to 3dB, producing a cover diagram as shown in Figure 3.3.8-4.

Figure 3.3.8-4 Standard Radar Coverage with Typical STC and 3dB Loss



The effect of 3dB loss is seen to produce a significant reduction in the coverage. The radar still achieves detection out to the full instrumented range but both low-level cover and high level cover have been eroded.

3.3.8.5 Detection of Low RCS Aircraft

Civil aircraft usually have relatively large radar cross-sections and many will have echoing areas much larger than the $1m^2$ assumed above; large commercial airliners can have radar cross-sections greater than 50 m^2. The radar cross-section of military aircraft is reducing, and whilst the figures are classified, it is generally accepted that areas of $0.1m^2$ and possibly below are being achieved. The detection of stealthy military aircraft is not normally a requirement for civil air traffic control, however a recent near miss incident in the U.S.[19] highlights the risk of such aircraft straying into civil airspace. However small commercial business jets can have radar cross-sections as low as $1m^2$. The RCS of any aircraft is also highly variable with aspect angle.

[19] 'Invisible' Plane in Near Miss with American Airliner (By Ben Fenton in Washington, Daily Telegraph 9th Sept. 2000)

The pilot of an airliner carrying 173 people had to take evasive action to avoid a mid-air collision with an F-117 stealth jet after the fighter, which is supposed to be invisible to radar, showed up on his detector screens.

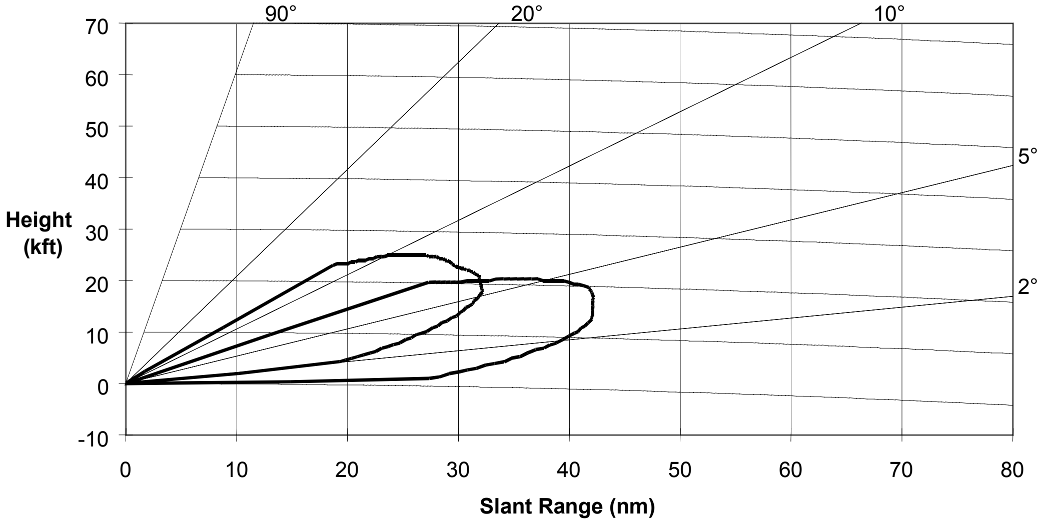
The stealth fighter was apparently flying into unauthorised airspace above Los Angeles international airport on Thursday morning as a United Airlines Boeing 757 took off bound for Boston. As the airliner climbed to 10,800ft anti-collision radar detected an aircraft approaching fast. The airline pilot stopped his climb and levelled off so that the other plane could pass safely overhead.

A spokesman for the Federal Aviation Administration said the pilot told officials that the stealth fighter had passed within 500ft above him and less than 1,000 yards to one side. That is classified as a "near miss"; aircraft are supposed to keep three miles apart near airports.

A spokesman for the US air force confirmed that one of its F-117s, part of the 410th Flight Test Squadron, had been involved in the incident, but said there would be no comment until an investigation was complete. The spokesman added that the fighter was "not in stealth configuration", meaning that it was using a transmitter to let other planes know where it was.

Figure 3.3.8-5 shows the cover, in the clear, of a 0.1m^2 aircraft. As would be expected from a reduction of 10dB in the aircraft cross-section, the coverage envelope has reduced substantially.

Figure 3.3.8-5 Detection of a Low RCS Aircraft

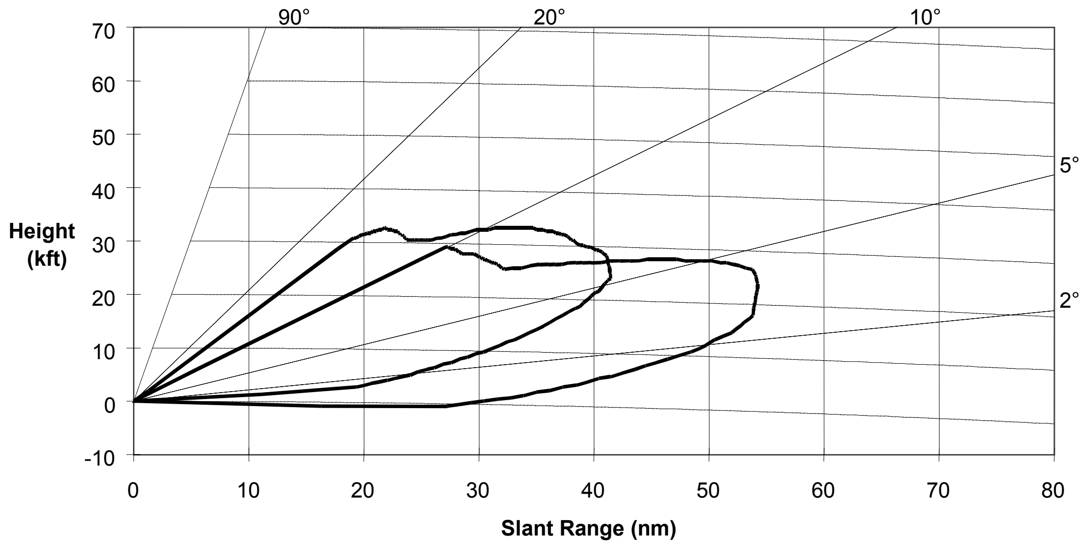


3.3.8.6 Performance in Heavy Clutter

The above analysis was devoted to the performance of the radar in benign conditions i.e. no ground clutter or rain clutter. It is important to remember that the radar must be able to detect aircraft flying over heavy ground clutter (hills, buildings etc.) even in the presence of heavy rain. The inclusion of processing to remove the effects of clutter does not come ‘for free’ so that the detection of targets will be reduced in the presence of clutter. Figure 3.3.8-6 shows the performance of the radar, without any added interference loss, in the presence of simultaneous heavy ground and rain clutter.

Note that the coverage envelope has reduced significantly, although there is still adequate cover out to 50nm and up to 30kft. It should also be noted that the assumed target size is 1m^2 and that larger targets will be detected at longer ranges.

Figure 3.3.8-6 Coverage in Simultaneous Heavy Ground and Rain Clutter



Assuming that the processing has reduced the clutter and only left a low level of clutter residue, the effect of 1dB and 3dB loss can now be added to Figure 3.3.8-6 and this is shown in Figure 3.3.8-7 and Figure 3.3.8-8 respectively. The effect of extra loss in a combination of heavy ground and rain clutter can now be seen in that the coverage is now seriously eroded with cover only useful for 40nm and 25kft. Figure 3.3.8-8 also shows a loss of low cover, although this could be recovered by reducing the STC.

Figure 3.3.8-7 Coverage in Simultaneous Heavy Ground and Rain Clutter with 1dB Loss

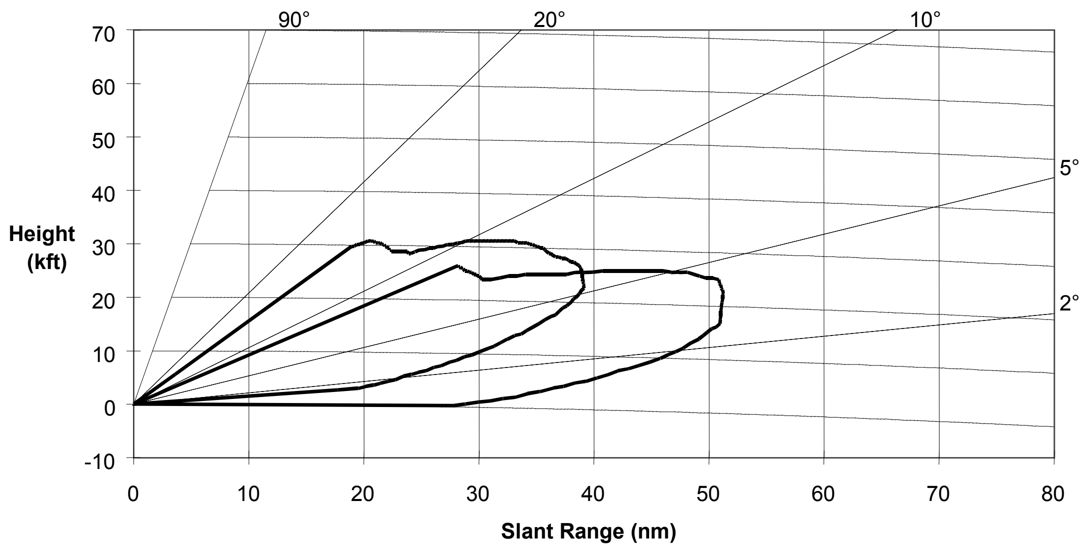
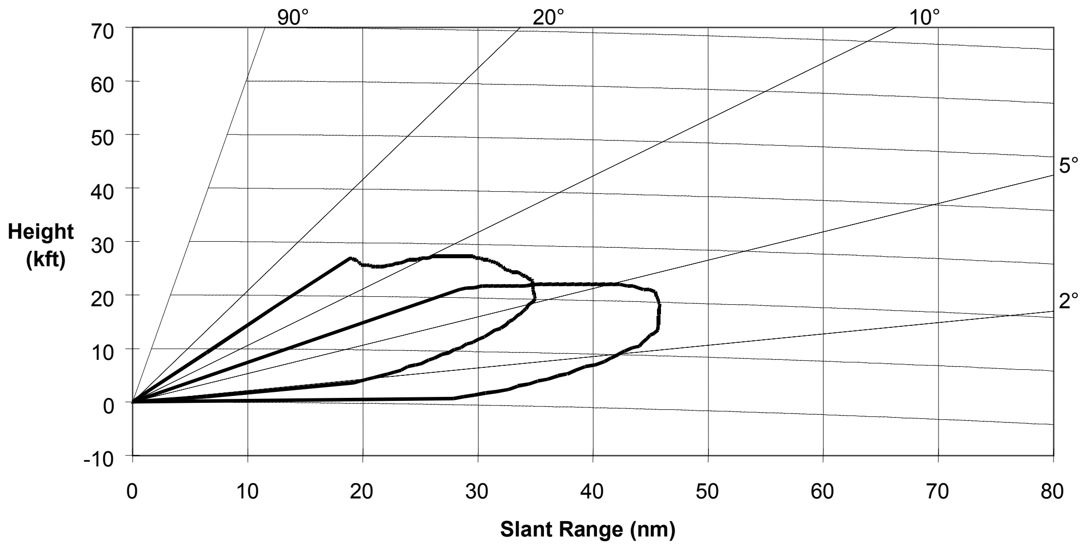


Figure 3.3.8-8 Coverage in Simultaneous Heavy Ground and Rain Clutter with 3dB Loss

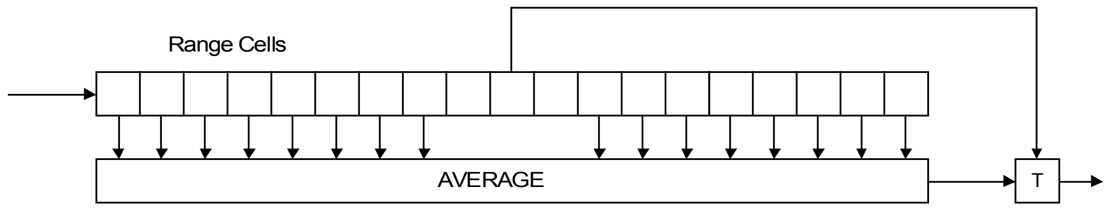


3.3.8.7 False Alarm control

There is a requirement in radar systems to minimise the number of false alarms shown to the operator. False alarms will contribute to the operator load and can present a safety risk e.g., an aircraft could be instructed to take evasive action.

In order to achieve this, radars contain false alarm control circuits, commonly referred to as CFAR circuits. Whilst there are a large number of types of CFAR circuit, they are usually based around the 'background averager' (sometimes referred to as cell averaging CFAR). A simplified block diagram is shown in Figure 3.3.8-9.

Figure 3.3.8-9 CFAR Circuit



This circuit estimates the level of noise or interference in radar range cells on either side of a range cell and uses this estimate to decide if there is a target in the centre cell. The process steps out one cell in range and is repeated until all range cells have been investigated. The basis of the circuit is that when noise is present, the cells around the cell of interest will contain a good estimate of the noise in the cell of interest, i.e. it assumes that the noise or interference is spatially or temporarily homogeneous. It can be shown theoretically that the circuit will produce a constant false alarm rate, which is independent of the noise level so long as the noise has a Rayleigh distribution in all range cells.

This CFAR circuit is widely used and its limitations well understood and it is known to give widely varying false alarm rates when the returns do not meet the criteria of homogeneous Rayleigh statistics. Such a situation can occur in the presence of ground clutter that is highly non-homogeneous, and without the addition of other techniques designed around the unique characteristics of ground clutter, it is known that many hundreds, sometimes thousands, of false alarms can occur.

It might be expected that the interfering signals from say mobile communications would be highly non-homogeneous in time as telephones and base stations transmit randomly. However the more modern forms of modulation, such as CDMA (Code Division Multiple Access), do strive to make their signals as 'noise-like' as possible.

Work is currently underway within Europe to model the effects of communications signals on radar CFAR circuits however, as yet, the results of this study have not been put into the public domain.

3.3.8.8 The effect of Pulse Compression on Noise

The effect of pulse compression on signals and noise is well known. When a matched pulse is passed through the compressor, the signal to noise ratio at the output is increased with respect to the signal to noise ratio at the input. The improvement in signal to noise ratio across the compressor is the compression ratio and so will vary with the detailed design of the radar. In order to circumvent this, in Section 3.3.2, the interfering noise was defined with respect to the radar system noise. By doing this, it is not necessary to take account of the pulse compression when assessing the effect of interfering noise so long as both are measured at the same point and in the same bandwidth.

In other words, interfering noise which is equal to system noise before the compressor will also be equal to system noise after the compressor.

3.3.8.9 The effect of Pulse Compression on a CW waveform

The exact form of interference is not known. However, if phase or frequency shift coding is used, then the waveform will look like short bursts of a continuous wave signal and the effect of pulse compression will be quite different to the effect on noise, pulse compression spreads unwanted signals by the uncompressed pulse length.

Figure 3.3.8-10 shows the output of a pulse compressor to a correctly coded pulse. In this example, the compressor has a compression ratio of 19dB. Figure 3.3.8-11 shows the output of the compressor when the input is a CW pulse of the same length as the matched pulse. Comparing the height of the outputs shows that the CW pulse is reduced, compared to the coded pulse, by about 13dB. However, since the gain of the matched pulse is 19dB, this shows that a CW pulse also receives some gain through the compressor, in this case about 6dB.

The result is that the effect of bursts of CW will be worse than if the interfering signal is white noise.

Figure 3.3.8-10 Output of Pulse Compressor to Coded Input Pulse

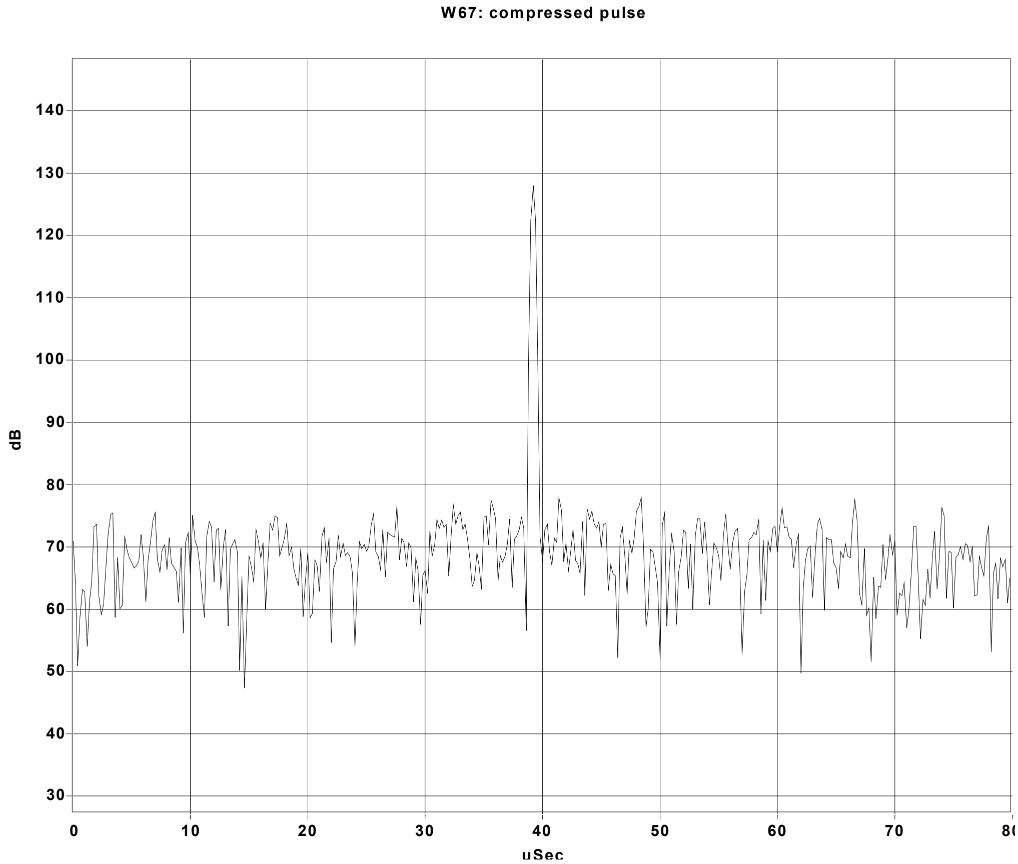
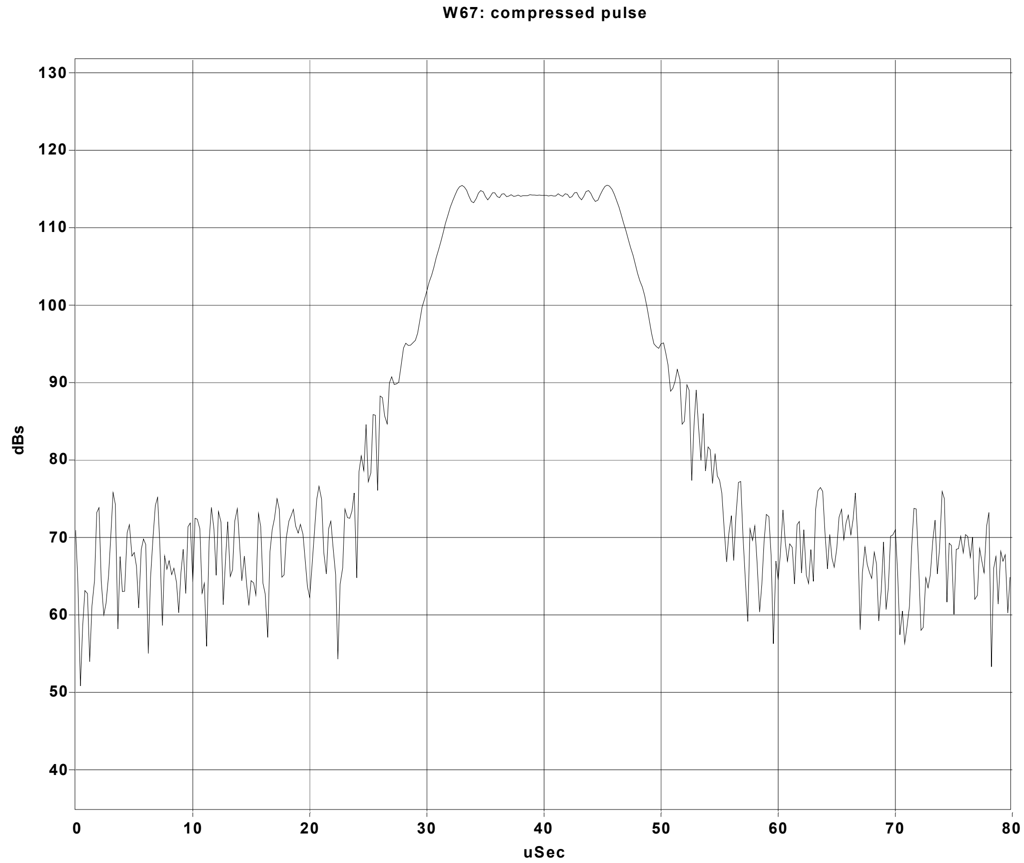


Figure 3.3.8-11 Output of Pulse Compressor to CW Input Pulse



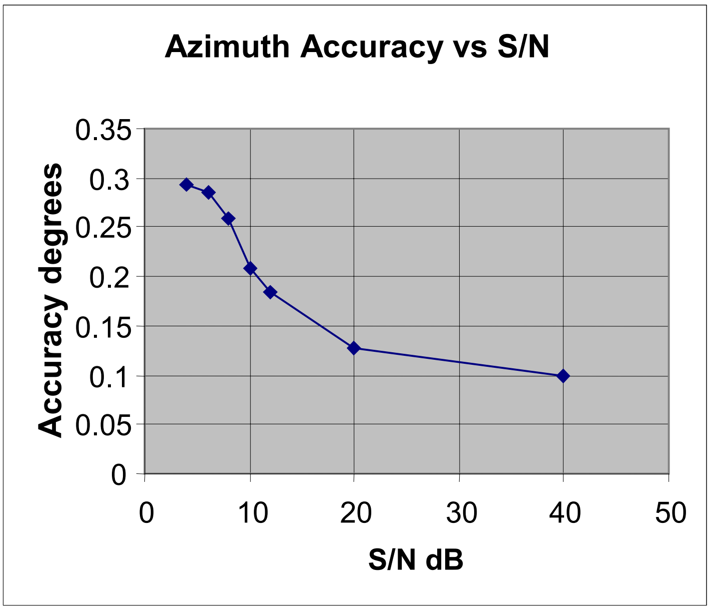
3.3.8.10 Azimuth Accuracy

Many radars use a beam centroiding technique to calculate the azimuth position of the plot output. This method essentially works by measuring the azimuth angle at which the target is first detected within the beam, and the angle at which the target is detected to have fallen out of the beam. The true target position is estimated as the mean of these two angles.

The interfering signals affect these angular measurements and the effective reduction in S/N causes the azimuth errors to increase. The exact effect is dependent on the design of the radar signal processing and the detection thresholds set.

Figure 3.3.8-12 below shows a curve of the Signal to Noise ratio against the azimuth accuracy for a typical ATC radar.

Figure 3.3.8-12 Effect of S/N on Azimuth Accuracy



As can be seen in Figure 3.3.8-12, the accuracy degrades as the S/N ratio falls; the S/N ratio is related to the P_d . Table 3.3.8-1 shows the relationship between P_d and S/N. The coverage predictions in this section are based on the traditional figure of 80% with a 1 x 10^{-6} P_{fa} for ATC calculations.

At 80% the S/N is approximately 9 dB, a 1 dB reduction due to interference would result in a reduction of accuracy from 0.23 degrees to 0.26 degrees. To put this into context most users would expect to see azimuth errors of less than 0.2 degrees for P_d of around 90%. Weak targets at lower P_d and under conditions of interference at the minimum protection level, (6 dB below SNL), could considerably exceed these limits.

This however assumes that all the detections across the beam are degraded in a similar fashion. Most systems use frequency diversity. If the interference selectively degrades the radar at only one of these diversity frequencies then severe distortion of the beam could occur. This could give rise to errors of the order of 1/4 of the effective beam width. The effective beam width being defined as the region over which the returns exceed the detection threshold. This could result in errors greater than 0.5 degrees even on larger targets with a high P_d. The actual error experienced on each scan is related to the timing of the PRI with respect to the start of the detection process and will vary every scan.

Table 3.3.8-1 Relationship of P_d to S/N at a P_{fa} of $1x10^{-6}$

P_d	S/N
%	dB
80	9
90	12
95	14
98	16
99	18

3.3.9 Statistical Variation of S/N

It may be worth considering some statistical variations that can occur in the radar detection process. Consider the noise-limited performance based on the basic single-pulse radar detection equation:

$$S/N = PG^2\lambda^2\sigma/(4\pi)^3\,r^4\,kTBNL.e^{-\mu r} \qquad \text{Equation 3.3.9-1}$$

Where the symbols have the meanings as defined in Table 3.3.8-1 below.

Table 3.3.9-1 Meanings of Symbols

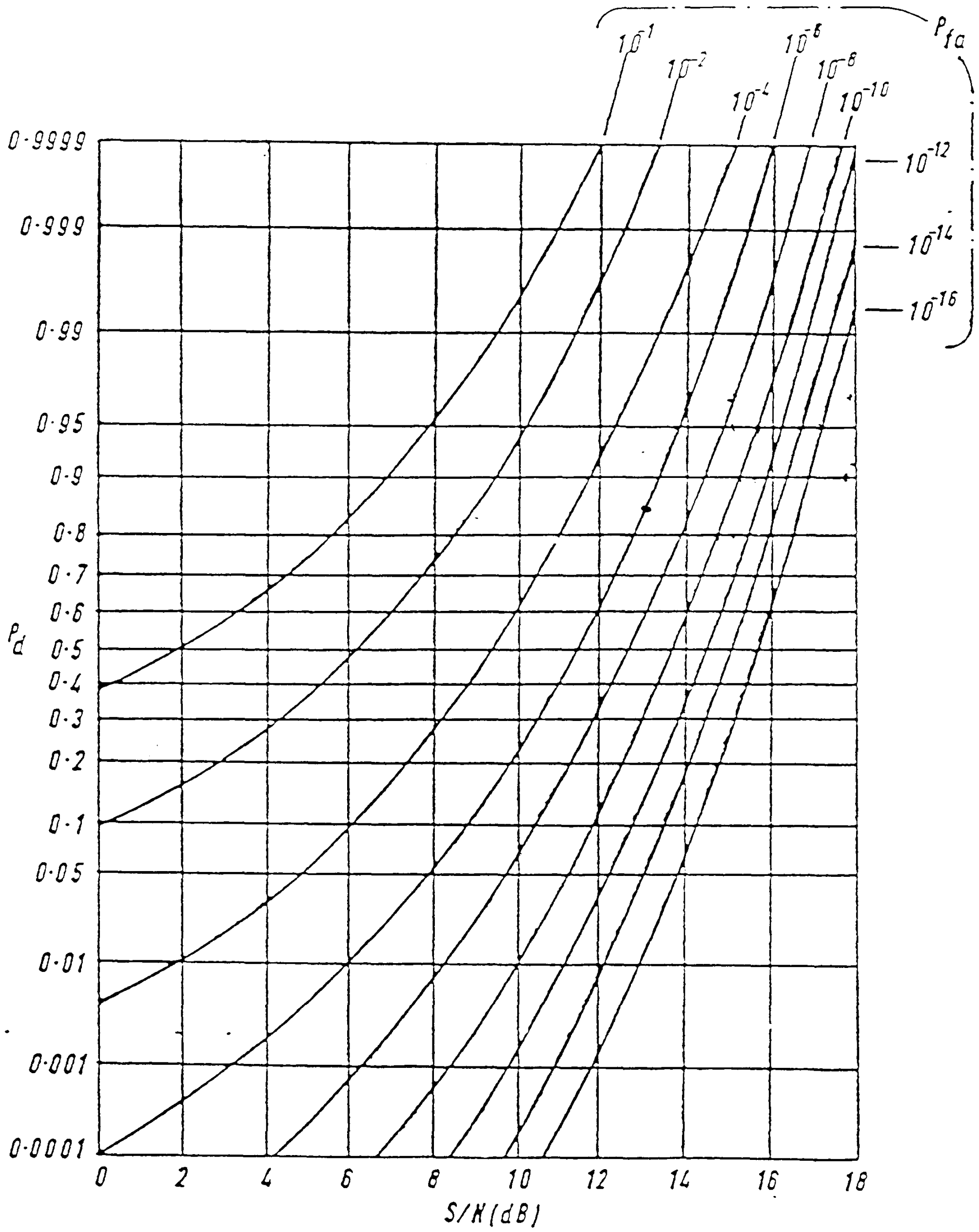
Symbol	Meaning	Typical rms uncertainty	
P	Transmitter Power	0.5dB	
G	Antenna Gain	0.2dB	
λ	Wavelength	0	{nominal value}
σ	Target RCS	2dB	
r	Range	0	{dependent variable}
k	Boltzmann's constant	0	
T	Effective noise temperature	0	
B	Receiver bandwidth	0.05dB	
N	Receiver noise figure	0.5dB	
L	Receiver and processor losses	0.5dB	
μ	Atmospheric attenuation	0.5dB	{e.g. in clear air over 200 km in L-Band}
S/N	Signal to noise ratio	2.3dB	{derived value}

The uncertainty is thus dominated by the uncertainty in the RCS of the target, without which the uncertainty in the performance of the actual radar is only about 1dB rms.

3.3.10 Relationship between S/N, P_d and P_{fa}

Figure 3.3.10-1 illustrates how the design aims of Probability Detection and Probability of False Alarms for a radar system effectively defines the Signal to Noise Ratio required within a Radar Receiver.

Figure 3.3.10-1 Graph Displaying the Relationship between S/N, P_d and P_{fa}



3.3.11 Comparison of Broad-band and Narrow-band Noise

The purpose of this analysis is to determine the amplitude of a Narrow-band signal that is required to have the same Power Spectral Density (PSD) as its Broad-band counterpart, over a given bandwidth.

This is demonstrated in the following example:

- It is assumed that a given Broad-band noise signal occupies a bandwidth of 60 MHz, where its Power Spectral Density is -50 dBW/Hz. (Arbitrarily chosen)
- It is assumed that the Narrow-band signal resides in the same bandwidth as the Broad-band signal.
- It is assumed, for simplicity, that the Narrow-band noise signal approximates to its ultimate form. i.e. that of a single sinusoidal carrier.
- It is possible to calculate the magnitude of the Narrow-band signal that will produce the same Power Spectral Density as the Broad-band signal, using the steps below:

The first step is to convert the Power Spectral Density of the Broad-Band signal from dBW/Hz to W/Hz:

$$PSD_{Narrow-band\,(dBW/Hz)} = PSD_{Broad-band\,(dBW/Hz)} = -50dBW/Hz$$

Equation 3.3.11-1

$$PSD_{Narrow-band\,(W/Hz)} = 10^{\frac{-50}{10}}$$

$$\therefore PSD_{Narrow-band\,(W/Hz)} = 10\mu W/Hz$$

If the PSD is multiplied by the required bandwidth the product is the required Narrow-band amplitude:

$$\therefore P_{Narrow-band\,(W)} = 60MHz \times 10\mu W/Hz$$

$$\therefore P_{Narrow-band\,(W)} = 600W$$

The final step is to convert this value into its dB equivalent:

$$\therefore P_{Narrow-band\,(dBW)} = 10Log_{10}(600W)$$

$$\therefore P_{Narrow-band\,(dBW)} = 27.8dBW$$

This shows that a broadband signal of 10μW/MHz (-50dBW/MHz) in a 60MHz bandwidth generates the same within-channel power as a narrow band signal with a power of 600W (27.8dBW).

3.3.12 Comments On Specific Considerations Regarding Sharing Between GPS RNSS / GLONASS Services Allocated On A Co-Primary Basis In The 1215 – 1300 MHz Band

3.3.12.1 Introduction

Currently Radiolocation/radionavigation radars operate on a co-primary basis with satellites of the Radio Navigation Satellite Service (RNSS) in the band 1215 to 1300 MHz. These radars are subject to the protection requirements defined in ITU-R Recommendation M.1463 "Characteristics and protection criteria for radars operating in the radiodetermination service in the frequency band 1215 to 1400 MHz" covering radars of the radiolocation and aeronautical radio navigation services.

ITU-R Recommendation M.1463 specifies a protection requirement of I/N of -6 dB. Work reported in Working Party documents 8B/64, 8D/93 and 8D/18 indicate that a worst case power flux density of [-133] dBW/m^2/MHz can be present at the radar antenna from satellites of the RNSS. Using published radar characteristics, (ITU-R Recommendation M.1463), it is possible to calculate that in the worst case, using a Power Flux Density (PFD) of -133 dBW/m^2/MHz, the resulting I/N ratio is approximately 22 dB, some 28 dB greater than the current -6 dB I/N protection level.

Currently, the band 1215 to 1260 MHz is shared inter alia between the RNSS and radiodetermination service, and papers report that no interference has been observed between them. Working Party document 8B/148 (also 8D/185) carries out a simplified analysis on the likely effect of these levels of interference on the probability of detection (P_d) and probability of false alarms (P_{fa}). It concludes that whilst the performance of the radar would be seriously degraded in the direction of the satellites, that operationally, this is not significant. It is not known whether there are papers that carry out an operational analysis on the degradation of performance to assess the effect of such a reduction in performance on the safety of an air-traffic control (ATC) system using such radars.

Based on these reported lack of interference effects and the simplified analysis, it is proposed to replace the protection criteria required for RNSS signals over the band 1215 to 1260 MHz to [-133] dBW/m^2/MHz and to extend this new protection requirement over the band 1260 to 1300 MHz.

To this end, modified Conference Preparatory Meeting text was proposed in Attachment 16 of the Chairman's report of the 11th meeting of ITU-R Working Party 8D.

This section comments on these proposals and raises concerns, in that the operational analysis may not be complete. Section 3.3.12.8 comments on the analysis method used.

3.3.12.2 Effect of interference

The effect of interference on the radar system depends on the level of the interference, how the interference is processed within the radar and what effect the output has, on the operation of the system.

3.3.12.3 Level of Interference

The level of interference from the RNSS seen by a radar depends on the number of satellites in the radar beam at any one time and their position within the antenna's radiation pattern. As the radar beam is narrow in azimuth and the satellites are well spaced, it is likely that only one satellite will appear at a specific azimuth. Satellites low on the horizon will appear close to the peak of the antenna's main beam. The antenna's elevation pattern and azimuth side-lobes will suppress others in view. Each satellite will produce a maximum PFD of -133 dBW/m^2/MHz. As the antenna scans, the level of interference will rise and fall depending on the elevation of the individual satellites.

The signal level received will also depend on the width of the radar receiver's IF filter. The wider the filter bandwidth, the more signal will be received, until the filter becomes wider than the bandwidth of the interference. Using the figures provided in the references, the interfering signal could be up to 22 dB above the noise using the maximum figures quoted for GLONASS (-133 dBW/m^2/MHz) and the most sensitive radar type (received PFD level producing I/N of –6dB, PFD_{-6dB}) of approximately -161 dBW/m^2/MHz.

3.3.12.4 How the interference affects the radar

The effect that the interference has on the radar depends on the type and structure of the interfering signal. Depending on the signal, the effect will be either to reduce the detection ability of the radar or produce false detections (false alarms) or a mixture of both. Analysis of the type of signals used by RNSS satellites would indicate that the interference of the type produced by satellites in the RNSS is likely to be noise-like and hence will predominantly result in loss of detections.

3.3.12.5 Effect of interference on the operation of the system

High levels of loss of detection results in the inability to detect targets or a loss of tracks on previously detected targets. False targets can have several effects; they can produce false plots or tracks and high levels of these can contribute to operator workload and fatigue. A very high number of false plots can overload the radar's data processing and data links.

Dependent on the bearing of the satellite, the loss of detection could persist for many scans resulting in an azimuth sector of reduced sensitivity. Experiments with noise-like interference at this level, on essentially a fixed bearing, have shown that there is a loss of the ability to detect targets in the sector containing the interference, see section 3.3.12.9. The levels shown in this section are comparable with the worst case figures based on the requested protection level of [-133] dBW/m^2/MHz at the antenna.

Some measurements have been made on an in service system. The to-date unpublished results conclude that for the radar type under consideration the probability of detection of the radar starts to degrade at I/N values of –11 dB (1 MHz reference bandwidth) for narrow-band RNSS signals. For wide-band RNSS signals the P_d starts to degrade not below an I/N value of -3 dB (1 MHz reference bandwidth). These limits would keep the loss of P_d below 1% and the increase of noise as well as the increase of the minimum detectable signal power to below 1 dB. The measured I/N values corresponds to PFD values of -164 dB(W/m²) in any 1 MHz for narrow-band RNSS signals and of -151 dB(W/m²) in any 1 MHz for wide-band RNSS signals respectively.

3.3.12.6 Operational issues

Operationally, the acceptability of any interference can only be decided on by those charged with operating the system, the requirements placed on the integrity of the radar data, and the back up systems such as SSR etc. It is not possible in this report to make that judgement for the operators. However, requirements placed on radar manufacturers for design proving, system optimisation in the area of false alarms, P_d and missed plots etc, would not seem consistent with the degradation predicted in Working Party document 8B/148.

Operationally, interference of this type would result in sectors of low P_d . As the satellites move, the bearing of this sector will move in azimuth.

Working Party document 8B/148 shows sectors with the range reduced to 70% of normal range, or conversely, a loss of larger targets at maximum range and a loss of smaller targets at shorter ranges on the same bearing. It should be noted that these results are calculated using GPS interference levels of -142 dBW/m^2/MHz and -147 dBW/m^2/MHz which are well below the worst case protection requirements (-133 dBW/m^2/MHz for GLONASS) which would result in ranges being reduced to approximately 30%.

Working Party document 8B/148 also uses in the example, a radar of PFD_{-6dB} approximately equal to -155 dBW/m^2/MHz. This is some 7 dB worse than the most sensitive radar quoted. Observation of Figure 2 of Working Party document 8B/148 shows that even at the GPS level of –142 dBW/m^2/MHz quoted, the range would be approximately at the 50% figure for the more sensitive radars quoted.

Assessments of the nature of the interfering signal have led to the belief that it will cause the CFAR clutter map circuits to seriously reduce the sensitivity of the radar in the direction of the satellite, the absolute effect depending on the elevation angle. The worst effect will occur for low elevation satellites near the peak gain of the antenna's elevation pattern, typically 2 degrees to 7 degrees. The nature of the relatively slow motion of the satellite will mean that the reduction in P_d will be of an insidious nature that may not be noticed by operators or automatic tracking systems.

3.3.12.7 Why interference may not be seen

The submissions requesting the change in the current protection level make much of the issue that no interference from RNSS has been reported. Maybe this could be for several reasons, see ITU Working Party 8D document 8D/137 for more details.

3.3.12.7.1 The signal is not causing interference

Currently RNSS operates in the band 1215 to 1260 MHz. It is possible that administrations are limiting their radiolocation/radionavigation radars to the band 1260 to 1300 MHz or at least avoiding the RNSS frequencies. Thus the radars will not be co-channel with the RNSS signals and the selectivity of the radar receiver and the spectral limit of the RNSS signal will provide protection. This is the case in the UK where the majority of radars operate above 1260 MHz. In Germany the band 1250 to 1260 is used but only one radar station at 1251 MHz has a potential clash of frequencies and that is with the GLONASS channels 10,11 & 12 i.e. frequencies 1250.375, 1250.813 & 1251.250 MHz and of these 11 & 12 have not been operational.

3.3.12.7.2 The interference exists but is not observed or reported

It may be that the interfering signal is lower than predicted (10 dB margin) or it may be that the effects are occurring as described, but that operators do not observe the interference. This may be due to many factors; the position of the satellites relative to air traffic areas for example, or the fact that the interference is in narrow sectors. It may be that the use of tracked outputs is coasting missing detections so that they are not noticed. The only way to check this is to specifically look for the interference. A possible method may be to record data from the PSR (Primary Surveillance Radar) and the SSR (Secondary Surveillance Radar) and correlate this with the satellite positions. The number of lost primary detections could then be measured directly as could the satellite's PFD.

However the fact that the interference is not obvious does not mean it does not exist and that it is not having an effect on the radar's P_d and its SIL (Safety Integrity Level).

3.3.12.8 Specific comments on method of calculation and results given in Working Party document 8B/148

The paper refers to a 'Safety Margin'. It is thought that this means that the maximum PFD can be XdB greater than the minimum PFD. This 'Safety Margin' changes from 10dB to 5dB, thus making the interference less severe. There does not seem to be any justification for making this assumption.

The paper goes on to use this 5dB safety margin in the calculations and show that the performance of the radar is reduced in such a way that the range for a given P_d is reduced by 30% (to a value of 70%). This constitutes notable degradation but the paper has not considered what the value would be if the 10dB safety margin had been used. The result would be even worse. The illustration also uses figures quoted for GPS, however the GLONASS numbers would be 11 dB higher. It also calculates the effect on the least sensitive radar. Taking this into account the reduction in range would be approaching 70% i.e. a detection range of 30%. The ranges are also all referenced to the PFD_{-6dB} that assumes an inherent degradation to start with, although they should be referenced to the no interference case.

Although a $P_{fa} = 10^{-5}$ is used, generally for ATC systems, we tend to consider a $P_{fa} = 10^{-6}$. Figure 6 of 8B/148 should be plotted on a log scale for P_{fa} to show the real extent of the change.

The paper comments that the increase in P_{fa} is small and not noticeable by the operator. However, the operator is quite likely to notice that many more false alarms appear on the screen, however this may not be noticeable if only a narrow azimuth sector is affected.

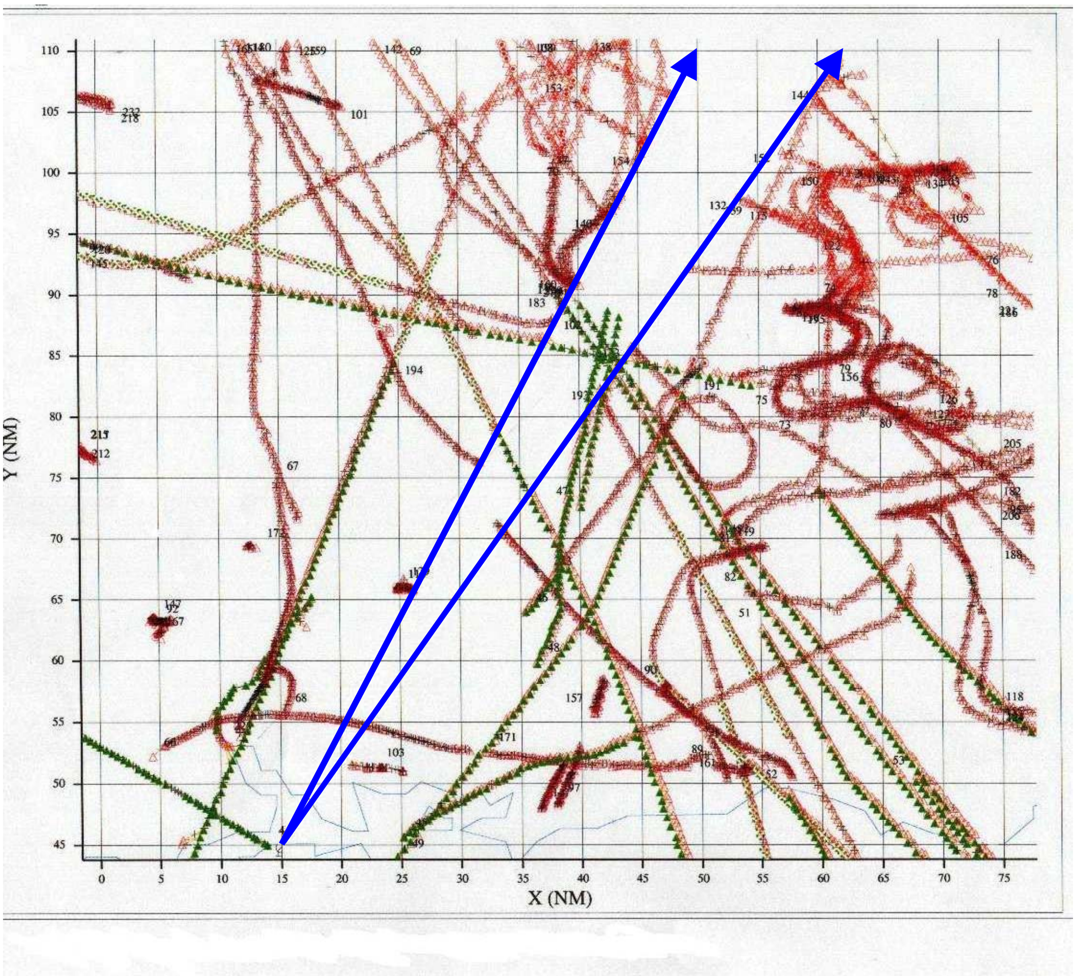
The paper notes that the operators do not seem to notice the reduction in P_d/range performance. This is not surprising since it is much more difficult to notice a target that is not displayed than false ones that are. The source of this subjective information is unclear. It is not known in this case how the PSR and SSR data is fused, but it would be useful to compare the number of times a secondary reply is not matched with a primary target return. This would give some indication of what is occurring to the PSR's range performance.

Working Party document 8B/148 makes a judgement of what is acceptable. To a radar designer, reduction to 70% range would seem severe but it is not the radar designer's decision but the decision of the user. The ATC community may have some concerns. It is assumed that the requirements on the radars are defined from an operational requirement and if there is a requirement for detecting a given target at a given range with a given P_d, then reducing that range to 70% or less would undoubtedly lead to not meeting the requirements.

The interference originates from the satellites. As the paper illustrates, it may be coming from a number of directions. To the ground based radar these satellites appear to move slowly so that this interference will appear in the same Azimuth for some time. Thus, if a target is at long range in the same azimuth as the satellite and is travelling towards the radar then it will be invisible for a long time - this seems unacceptable.

3.3.12.9 Example of the measured effect of Noise-like Interference

Figure 3.3.12-1 Example of the effect of Noise Interference I/N 19 dB



Key:- Red triangles - Primary Radar Detections

Green (distinct) triangles - Secondary Radar Detections

The recording was made by superimposing the output of a Primary radar with a Secondary Surveillance Radar (SSR). The two radars were not physically in the same place and their coverage regions did not overlap completely. There are no secondary detections in the north-east half of the figure because the aircraft in this region are out of range. The lack of secondary detections on some aircraft in the south-west half of the figure is due to their being below the radar horizon of the SSR which was situated 180 km south-west of the primary radar.

This recording shows a sector of simulated satellite noise interference of approximately 8 degrees at a level of 19 dB above the system noise injected into the primary radar. The secondary radar was unaffected by the interference. The level of interference was set to within the 10 dB range of Max/Min PFD ratio (see document 8B/64) of RNSS interference being proposed and less than the maximum of [-133] dBW/m^2/MHz. In the case of RNSS interference, this sector would correspond to the radar antenna's azimuth beamwidth plus a reduced level of interference in the beamwidths either side. The interference is thus likely to affect a sector of a few beamwidths in azimuth.

Note the specific lack of primary tracks within the sector.

3.3.13 Worked Examples & Calculations

3.3.13.1 Single Pulse Radar Range Equation and Example

The single pulse radar range equation (as below) was used to demonstrate the effect of I/N on the maximum range of the victim radar:

$$R\max^4 = \frac{P_t.G^2.\sigma.\lambda^2}{(4\pi)^3.N.(S/N).L_{tot}}$$ Equation 3.3.13–1

The radar parameters are as follows:

Peak Transmitted Power, P_t	=	200 kW
Transmitted Pulse Width, τ	=	10 μs
∴ Receiver Bandwidth,B = 1/ τ	=	0.1 MHz
Antenna Gain, G	=	30 dB
Target Radar Cross-Section, σ	=	10 dB m^2
Centre Frequency, f_c	=	1.3 GHz
∴ Wavelength, λ = $c/f_c = 3\times10^8 / 1.3\times10^9$ m		
	=	0.2308 m
System Loss, L_{sys}	=	7 dB
Loss Due to Interference, $L_{I/N}$	=	0 dB
Total System Loss, $L_{tot} = L_{sys} + L_{I/N}$	=	7 dB
Noise Figure, NF	=	3 dB
Signal/Noise Ratio, S/N	=	13 dB

To calculate the equation it is usual for all parameters to be in dB:

P_t (dBW)	=	10 log$_{10}$ (200x10^3)	=	53.01
G^2 (dB)	=	2 x 30	=	60
λ^2 (dB)	=	20 log$_{10}$ (0.2308)	=	–12.73
$(4\pi)^3$ (dB)	=	10log$_{10}$ (1.9844x10^3)	=	32.98
Noise, N	=	$kT_0B + NF$		
B	=	100kHz		
kT_0B	=	(1.38x10^{-23}).(290).(10^5)	=	400.2x10^{-18}
N (dB)	=	10log$_{10}$ (400.2x10^{-18}) + 3	=	-150.98
R_{max}^4 (dB m^4)	=	$P_t + G^2 + \sigma + \lambda^2 - L_{tot} - (4\pi)^3 - N - S/N$		
R_{max}^4 (dB m^4)	=	(53.01) + (60) + (10) + (–12.73) - (7) – (32.98) – (–150.98) – (13)		
R_{max}^4 (dB m^4)	=	208.28		
R_{max}^4 (m^4)	=	$10^{208.28/10}$	=	672.98x10^{18}

R_{max} = $\sqrt[4]{672.98 \times 10^{18}}$ m = 161.06 km

Now calculate the influence of I/N on Total System Loss.

Conversion from I/N to actual Loss, in dB:

(For derivation see Section 3.3.4)

Example to show the calculation of the value $L_{I/N}$:

I/N (dB) = –6 dB, I/N = $10^{-6/10}$ = 0.251

Therefore, $L_{I/N}$ = $10\log_{10}(1+I/N)$ = $10\log_{10}(1.251)$ = 0.973 dB

This shows that an I/N of –6 dB can be expressed as an additional loss of almost 1 dB. Table 3.3.13-1 and Table 3.3.13-2 below show the loss incurred for a varying I/N.

Table 3.3.13-1 The loss incurred for a varying I/N - (I/N = 20 to 0 dB)

I/N (dB)	I/N	$L_{I/N}$(dB)
20	100	20.043
19	79.433	19.054
18	63.096	18.068
17	50.119	17.086
16	39.811	16.108
15	31.623	15.135
14	25.119	14.170
13	19.953	13.212
12	15.849	12.266
11	12.589	11.332
10	10	10.414
9	7.943	9.515
8	6.310	8.639
7	5.012	7.790
6	3.981	6.973
5	3.162	6.193
4	2.512	5.455
3	1.995	4.764
2	1.585	4.124
1	1.259	3.539
0	1	3.010

Table 3.3.13-2 The loss incurred for a varying I/N - (I/N = -1 to -20 dB)

I/N (dB)	I/N	$L_{I/N}$ (dB)
-1	0.794	2.539
-2	0.631	2.124
-3	0.501	1.764
-4	0.398	1.455
-5	0.316	1.193
-6	0.251	0.973
-7	0.199	0.790
-8	0.158	0.639
-9	0.126	0.515
-10	0.100	0.413
-11	0.079	0.332
-12	0.063	0.266
-13	0.050	0.212
-14	0.039	0.170
-15	0.032	0.135
-16	0.025	0.108
-17	0.020	0.086
-18	0.016	0.069
-19	0.013	0.054
-20	0.010	0.043

The values listed as $L_{I/N}$ are added to L_{sys} in the overall calculation of R_{max} to form a modified L_{tot}.

This enables the influence of I/N on maximum range to be modelled as it increases and decreases. This is as shown in Table 3.3.4-1 in Section 3.3.4.1.

3.3.13.2 Required Jamming Power Equation and Example

Using the single pulse radar range equation, an alternative equation can be formed to calculate the jamming power (P_j dB)needed to inflict a specific I/N at the victim radar receiver, the equation is as below:

$$P_j(dB) = W_r + 20\log(4\pi R) - G_j - G_r - 20\log(\lambda) + L_{tot} \quad \text{Equation 3.3.13–2}$$

The Jamming parameters are as follows:

Jamming Antenna Gain, G_j	=	0 dB
Receiving Antenna Gain, G_r	=	30 dB
Centre Frequency, f_c	=	1.3 GHz
Total System Loss, L_{tot}	=	7 dB
Range of Jammer to Victim, R	=	161.06 km
Power at Victim Receiver, W_r For an I/N value of -6dBs	=	–156.98 dBW

To calculate the equation it is usual for all parameters to be in dB:

Total Antenna Gain G (dB)			=	30
Wavelength, λ	=	$c/f_c = 3\times10^8/1.3\times10^9$ m	=	0.2308 m

Therefore:

λ^2 (dB)	=	$20\log_{10}(0.2308)$	=	–12.73
$(4\pi)^2$ (dB)	=	$20\log_{10}(12.57)$	=	21.98
R^2 (dB)	=	$20\log_{10}(161.06\text{x}10^3)$	=	104.14

Power at Transmitter, $P_j\,dB$ = $(W_r) + (4\pi)^2 + (R^2) - (G) - (\lambda^2) + (L_{tot})$

Therefore, P_j (dB) = (–156.98) + (21.98) + (104.14) – (30) – (–12.73) + (7)

Therefore, P_j = –41.13 dBW

= 77 μW

This equation can be modified to calculate the Power at the transmitter for varying distances from the victim receiver. In the main report, the distances of 161 km and 1 km are displayed.

3.3.13.3 Calculations for Transposed Radar Range Equation Used to Calculate S/N

The radar range equation (as below) was used to demonstrate the effect of I/N on the maximum range of the victim radar:

$$S/N_{dB} = P_t + (G_{tot}) + 10\log_{10}(\sigma) + 20\log_{10}(\lambda) - L_{tot} - 30\log_{10}(4\pi) - N - 40\log_{10}(R_{max})$$

Equation 3.3.13-3

The radar parameters are as follows:

Peak Transmitted Power, P_t			=	53 dB
Total Antenna Gain, $G_{tot} = G_t + G_r$			=	60 dB
Radar Cross-section, σ			=	10 dB m^2
System Loss, L_{sys}			=	7 dB
Loss Due to Interference, $L_{I/N}$			=	0 dB
Total System Loss, $L_{tot} = L_{sys} + L_{I/N}$			=	7 dB
λ^2 (dB)			=	–12.73
$(4\pi)^3$ (dB)			=	32.98
Noise, N (dB)	=	kT_oB + NF		
kT_oB	=	$(1.38\text{x}10^{-23}).(290).(0.1\text{x}10^{-6})$	=	$400.2\text{x}10^{-18}$
N (dB)	=	$10\log_{10}(400.2\text{x}10^{-18}) + 3$	=	–150.98 dBW
$R_{max}{}^4$ (dB m^4)			=	208.28

The required value of S/N for the ideal scenario is found to be:

S/N (dB) = $(P_t) + (G_{tot}) + (\sigma) + (\lambda^2) - (L_{tot}) - (4\pi)^3 - (N) - (R_{max}{}^4)$

∴ S/N (dB) = (53) + (60) + (10) + (–12.73) – (7) – (32.98) – (–150.98) –(208.28)

∴ S/N (dB) = 13dB

To calculate the S/N that takes into account the effect of the I/N value, simply recalculate the total loss, L_{tot}, to incorporate the value $L_{I/N}$. This results in the values displayed in Section 3.3.4.3 in Table 3.3.4-2.

3.3.14 Summary

It is understandable that radar systems must endure a certain amount of external interference. However, the recent upsurge in mobile and personal communications has exacerbated the current interference situation. With many interference sources appearing in close proximity to the pre-defined radar bands, causing cross-modulation throughout, and thus introducing increased levels of broad-band noise.

The increase in broad-band noise can cause undesirable effects, such as, reduction in maximum detection range and an increase in the number of false alarms generated. Coupled with this are the complexities associated with pulsed interference sources and the signals produced. Both types of interference signal are difficult to remove.

Radar systems do employ certain protection methods, which reduce the probability that an interference signal will cause corruption, but these are not 100% effective and in some instances are expensive to introduce into an older system.

The radar community is always making significant technological gains, especially with the development of the Phased Array Radar and its improved immunity to any possible interference signals and sources. These gains do come at a price, and with current economical restraint a Phased Array is an expensive option.

Interference effects need to be fully analysed and correctly specified, as each interference scenario may cause a reaction that is system dependent. This phenomenon will mask the interference effect when applied to one system and amplify its effect when applied to another. The multitude of radar systems available makes the process of definition and specification a difficult one.

The one overriding factor that cannot be ignored is the effect that interference may have on Safety Of Life services. If any future spectral allocations involve the possibility for a potential interference source to be generated, then its full effect must investigated on the applicable systems and measures introduced to mitigate the effect.

Work has shown how noise-like interference will degrade radar coverage. However, it is unlikely that all interference will match the noise-like model. It has also been shown that there is a likelihood of increased false alarms when the interference deviates from noise-like. Also, it is shown that pulsed CW interference can degrade the radar more than noise interference due to the action of pulse compression on CW signals.

Future work should include developing an understanding of both the frequency and temporal nature of interference in order to assess accurately the effect on radar systems.

The effect of 1 dB loss equivalent to interference 6 dB below system noise can start to produce degradation to the radar detection. 3dB loss is seen to produce a significant reduction in the coverage. The radar still achieves detection out to the full-instrumented range but both low-level cover and high level cover have been eroded. Civil aircraft usually have relatively large radar cross-sections and many will have areas much larger than the 1 square metre assumed in the previous analysis; the problem comes in detecting small uncontrolled targets such a some military or general aviation aircraft (which may not have or do not chose to use SSR).

The effect of 1dB and 3dB loss can, when added to the effects of the clutter residue after processing, say a combination of heavy ground and rain clutter, be shown to erode the radars coverage.

As well as the reduction in cover it would be expected that the signals from mobile communications would be highly non-homogeneous in time as telephones and base stations transmit randomly. It would therefore be expected that the radars CFAR circuits would perform badly when subjected to this form of interference and would produce large numbers of false alarms. This can produce high levels of operator nuisance and if large enough can lead to an overload of the radar plot extraction and filtering functions, possibly resulting in target loss.

At the required levels of P_d, a 1 dB reduction due to interference would result in a reduction of azimuth accuracy by approximately 10%. Weak targets at lower P_d and under conditions of interference at the minimum protection level, (6 dB below SNL), could considerably exceed these limits. Selective interference on one frequency of a two-frequency diversity radar can have more drastic effects that result from the corruption of a complete block of pulses on one of the frequencies being used.

Measurements on several radar systems have now been carried out and the effect on the average P_d has been determined. Using this as a measure of the detection performance reduction, the results suggest that if interfering signals are of a noise-like nature and are at, or around, the current ITU protection levels of I/N = -6 dB that this gives a measurable and significant reduction in radar performance. The evidence suggests that for SOL services a -12 dB I/N must be adopted.

There are other possible effects such as false alarms and false tracks; these effects are related to the temporal or spectral properties of the interference. Methods to reduce these can only reduce the effective sensitivity of the system.

In pulse compression systems, for signals that do not appear noise-like the I/N needs to be considered at the output of the pulse compressor thus the effective compression ratio of the interfering signal needs to be ascertained.

Consideration has been given to the effects of RNSS signals on L-Band systems, measurements have shown that such signals have very similar effects as the noise-like signals studied on the S-Band systems. The possible reasons that no effects have been observed are mainly due to the fact that radars currently have the ability to avoid operating close to RNSS frequencies. This would change if extra Glonass frequencies come into use and if the Galileo (European SatNav) is given frequencies above 1260 MHz. The current levels of protection requirements being proposed for use over the complete radar band are unacceptable at this time as they could give rise to significant loss of detection. The issue of what protection requirements if any, should be defined for this band, still needs further investigation to finally resolve what the interference mechanism is, and to account for its apparent non-appearance to users.The paper in Annex 3 of this report replicates a recent UK paper on the subject of RNSS interference. However, the implication to date is that a PFD limit is required on RNSS satellites in the band 1215 to 1300 MHz.

One approach to mitigating the effect of interference is to design the radar assuming that the interference is present, effectively increasing the S/N requirement for a given P_d. In older radars it may be possible to reduce the system noise level by replacing or adding a lower noise front end[20]. However, in modern radars where low noise front ends are already fitted, the only option is to increase the transmitter power. This seems perverse if the overall aim is to make better use of the spectrum. Increase transmitter power will result in more interference and longer reuse distances.

[20] Assuming the protection criteria is observed for the lower level of system noise.

3.3.15 Recommendations

The following recommendations are made with respect to Protection Requirements:

- The protection level of SOL systems be set to I/N of -12 dB and that specific sharing studies be carried out to confirm the adequacy.
- The protection level for other radars is studied further to ascertain if -6 dB I/N is adequate.
- The I/N level is specified at the input to the detector, not the receiver and that the issue of spectral power densities and relative bandwidths is clarified.
- If the -12 dB I/N protection level is exceeded, then further studies are required to ascertain if any mitigation measures can be applied.
- The protection for RNSS to ARNS radars in the L-Band (including that from RNSS) is increased to -12 dB from the current -6 dB recommended in ITU-R Recommendation M.1463.
- A PFD limit is applied to RNSS satellites in the band 1215 to 1300 MHz.

The following recommendations are made in respect of general receiver design:

- The system should use the maximum values of IF and RF selectivity subject to the operational requirements of the design.
- The appropriate mitigation options as defined in this report should be included subject to the required operation and cost of the radar.

Section 3.4

An Assessment of the Measurement Techniques described in ITU-R Recommendation M.1177-2

Contents:

Figures:

Tables:

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3.4 An Assessment of the Measurement Techniques described in ITU-R Recommendation M.1177-2

3.4.1 Introduction

This section discusses the current status and proposed changes to ITU-R Recommendation M.1177-2. The document ITU-R Recommendation M.1177 was initially intended as a method of measuring Spurious Emissions (SE) from marine radars. In its current form ITU-R Recommendation M.1177-2 (00/05) "Techniques for measuring unwanted emissions from radar systems" is intended to measure more than the original spurious emissions, covering all unwanted emissions from the full range of radar types.

ITU-R Recommendation M.1177-2 has the status of a recommendation however it is referenced in the following ITU documents.

- Appendix 3 of the Radio Regulations.
- ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain"
- ITU-R Recommendation SM.329-9 "Spurious emissions"

This document is heavily relied upon for guidance procedures by the Radio Regulations and other approved Recommendations.

This section considers the proposed current text for the revised version of ITU-R Recommendation M.1177-2 contained in Attachment 8 to ITU Working Party 8B, document 184-E "Preliminary Draft Revision of Recommendation ITU-R M.1177".

The proposed text describes "Techniques for measurement of unwanted emissions of radar systems". It details three methods, two based on direct (or "off-air") measurements and one based on a combination of separate measurements of the antenna and transmitter parameters.

- The direct methods require Equivalent Isotropically Radiated Power (EIRP) and spectral power density measurements to be carried out on an installed radar system, during its normal operation, using a measuring antenna and receiver to sample the radiation.
- The indirect method requires measurements of the transmitter output emissions followed by separate measurements of the antenna gain at the required frequencies. These results are then combined to provide a calculation of the far-field levels.

The two direct methods are referred to as the 'manual method' and the 'automatic method'. The manual method makes use of a swept receiver while the automatic method makes use of a computer controlled stepped receiver.

Practical work has been completed as part of this study to confirm the details of the automatic direct method as described in ITU-R Recommendation M.1177-2. This work consisted of a series of measurements of in-service radar systems together with one marine radar measured at the QinetiQ Funtington test range.

The initial parts of this section address a series of more philosophical issues that are apparent with the current methods as described in document ITU-R Recommendation M.1177-2 and in the proposed revision of the document as given in 8B/184-E. This is followed by a section detailing the practical results obtained from the implementation of the automatic direct method. These are then compared with the theory, and with the recommendations in document ITU-R Recommendation M.1177-2 and 84/184-E. Finally, a series of observations and recommendations are made for inclusion in the next issue of ITU-R Recommendation M.1177.

The following ITU-R Recommendation M.1177-2 issues are dealt with in this section:

- Measurement bandwidth in relation to Out of Band Emissions (OOB) and Spurious Emissions (SE) measurements;
- Interpretation of measurement results in the light of the specifications for OOB and SE;
- Unwanted emission limit levels;
- Radar modes of operation and practical issues;
- Appropriateness of the indirect method.

3.4.2 Definition of Bandwidths

Several terms have been used in the past in ITU and other documents to refer to the bandwidth of a measurement receiver. These include: receiver bandwidth, measurement bandwidth, resolution bandwidth, IF Bandwidth 3 or 6 dB, measurement system bandwidth. In some cases they have been specifically defined, in other cases not.

ITU-R Recommendation M.1177-2 uses the terms "Receiver IF bandwidth", "IF bandwidth", "measurement bandwidth" and "measurement IF bandwidth" for the same parameter. It makes no distinction between the frequency and impulse response of the system. The proposed up-date 8B/184-E uses the same terms and uses the abbreviation B_R: receiver 3 dB bandwidth (Hz) which is equivalent to the IF bandwidth.

This section of the report refers to a number of different bandwidths. The main ones are defined as follows:[1]

B_{pep} PEP Bandwidth -the bandwidth required to accurately measure the Peak Envelope Power (PEP) of a pulse. In this report $B_{pep} = 1/\tau$

RBw Receiver Bandwidth equal to the 3dB IF bandwidth of the measuring receiver.

B_{res} Resolution Bandwidth - the impulse response of the measurement receiver and for the receiver used in this study = *1.5 x RBw*

B_{ref} Reference Bandwidth - the bandwidth in which the spurious emission level is defined.

3.4.3 Measurement of Unwanted Emissions

The document ITU-R Recommendation M.1177-2 describes a method for measuring "Unwanted Emissions" from radar systems; unwanted emissions comprise two distinct types of emissions, Out of Band Emissions (OOB) and Spurious Emissions (SE)[2]. There is however an essential difference between the data that is required in these two measurements and hence the measurement parameters used.

OOB measurements are related to measuring the transmitted spectrum of the fundamental radar emission to ascertain if the energy is contained within specified limits of amplitude and frequency, essentially between the Necessary Bandwidth (NB) region and the Spurious Emission (SE) region. The requirements of this measurement are to accurately ascertain the shape of the transmitted spectrum close to the "carrier". For some radar types, in particular fixed frequency radars operating in dedicated radar bands, the shape of the spectrum may

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[1] The latest proposed revision of the document 8B/270-E PRELIMINARY DRAFT REVISION OF ITU RECOMMENDATION ITU-R M.1177-2 produced 4th September 2002 uses the terms B_m and B_{if}. In terms of this report $B_m = B_{res}$ and $B_{if} = RBw$

[2] For the latest requirements for these see: ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain" and ITU-R Recommendation SM.329-9 "Spurious emissions".

not be of great importance as the OOB limits only apply at the band edge and there is some leeway in the recommendations on how the OOB mask is applied. However for frequency hopping radars and particularly those that may have to operate in shared bands, the shape of the spectrum is a key parameter. The accurate measurement of the spectrum is also important at the OOB/SE boundary in respect that OOB emissions could be classified as SE emissions. These measurements are specified as Peak Power (dB_{pp}).

The requirement to measure spurious emissions is more related to measuring the total radiated power of emissions in the spurious domain, generally well removed from the fundamental frequency. It is normally only the Peak Envelope Power (PEP) of the emission that is of interest. However, In some cases of interference the shape of the harmonic spectrum may be of importance.

Generally the frequency range for spurious emission (SE) measurements for radars operating between 600 MHz and 5.2 GHz is from 30 MHz to 26 GHz. For radars with waveguide feeds, the lower limit is increased to 0.7 of the waveguide cut-off frequency. The current version of the Radio Regulations Appendix 3 states:

> *"The frequency range of the measurement of spurious emissions is from 9 kHz to 110 GHz or the second harmonic if higher"*

However, reference is made to ITU-R Recommendation SM.329-9 "Spurious emissions" which states:

> *"Limits on spurious domain emissions for radio equipments are considered here to be applicable to the range 9 kHz to 300 GHz.*
>
> *However, for practical measurement purposes only, the frequency range of the spurious domain may be restricted. As guidance for practical purposes, the following frequency ranges of measurement, as given in Table 1, are normally recommended."*

These limits are reproduced in Table 3.4.3-1 below. Those of interest to this study are emboldened.

Table 3.4.3-1 Required range for SE measurements

Fundamental frequency range	**Frequency range for measurements**	
	Lower limit	**Upper limit (The test should include the entire harmonic band and not be truncated at the precise upper frequency limit stated)**
9 kHz-100 MHz	9 kHz	1 GHz
100 MHz-300 MHz	9 kHz	10th harmonic
300 MHz-600 MHz	30 MHz	3 GHz
600 MHz-5.2 GHz	**30 MHz**	**5th harmonic**
5.2 GHz-13 GHz	**30 MHz**	**26 GHz**
13 GHz-150 GHz	30 MHz	2nd harmonic
150 GHz-300 GHz	30 MHz	300 GHz

Spurious emissions are specified in terms of Peak Envelope Power (dB_{pep}).

There is a major difference between the resolution bandwidths and hence the receiver IF bandwidth required to measure the shape of the OOB response and the SE levels.

3.4.3.1 Radar Transmitted Spectra

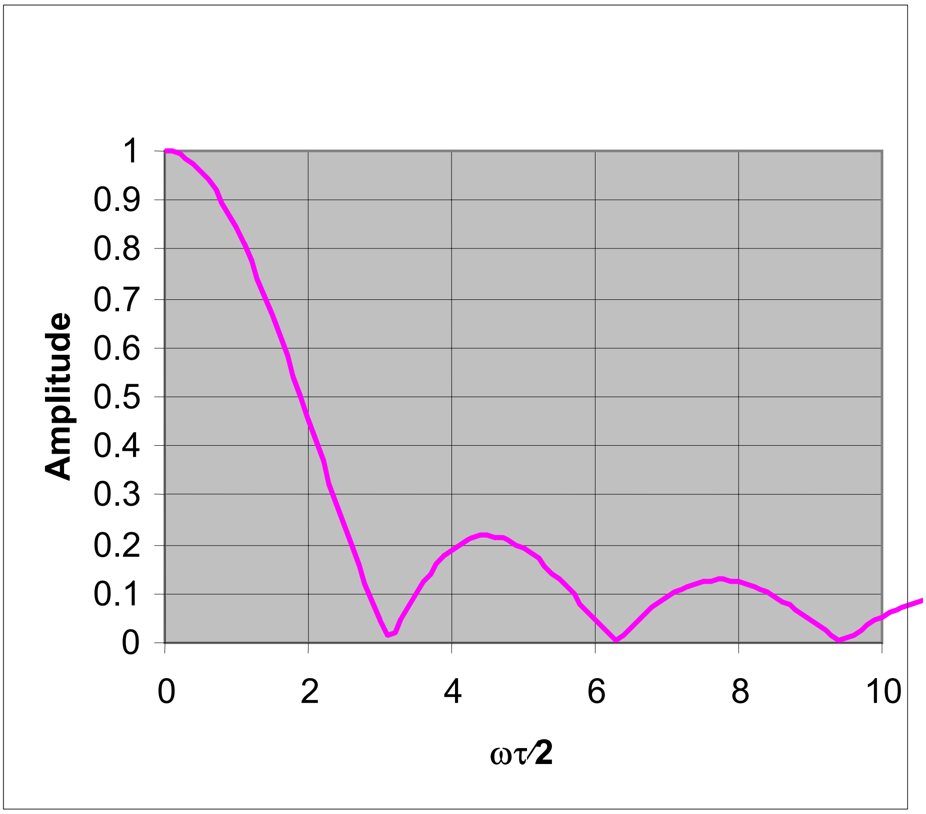
Radar transmissions typically[3] consist of a series of RF pulses repeated at a regular interval known as the Pulse Repetition Rate (PRR) (or the Pulse Repetition Frequency). This is related to the time between the pulses or the Pulse Repetition Interval (PRI) (or Pulse Repetition Period), by the simple formula PRI = 1/PRR. In many systems, modulation such as Phase Chipping or FM is added to pulses to facilitate pulse compression.

If we consider the spectrum of a simple unmodulated pulse radar, this is the spectrum of a series of repetitive pulses. This spectrum consists of a series of spectral lines separated by a frequency equal to the PRR and with an envelope shape dependent on the shape of the pulse.

The simplest pulse to analyse, although very rarely generated in practice,[4] is the pure rectangular pulse. Figure 3.4.3-1[5] shows the envelope of the spectrum of a rectangular pulse. In this case the spectrum takes the form of the classic Sin(X)/X function.

These are shown in Figures 3.4.3-1 and 3.4.3-2 plotted on the normalised frequency axis $\omega\tau/2$.

Figure 3.4.3-1 Envelope of the Spectrum of a Rectangular Pulse

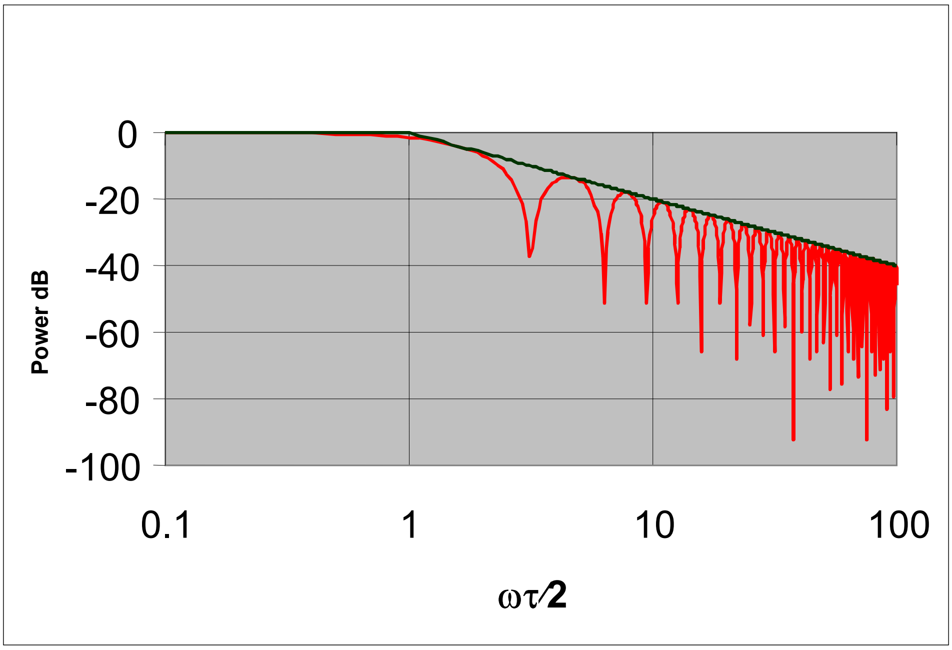


[3] For pulsed systems.

[4] The generation of fast edges is generally avoided.

[5] These are plotted for normalised frequency variable $\omega\tau/2$ where $\omega = 2\pi f$, τ = pulse length and f = offset frequency.

Figure 3.4.3-2 Envelope of Spectrum of a Rectangular Pulse Train Log/Log



In many cases relating to OOB issues, it is the envelope of the spectrum that is considered. If this is plotted on a Log power vs. Log frequency display, the envelope is described as a trapezium whose top is equal to 0.64/τ and whose sides roll off at 20 dB/decade. See Figure 3.4.3- 2.

The parameters of this spectrum are.

Spectral Line Spacing	= 1/T
Main-lobe Width[6]	= 2/τ
Main-lobe $Width_{3dB}$	= 0.9/τ
Main-lobe $Width_{20dB}$	= 1.84/τ
Envelope $Width_{0dB}$	= 0.64/τ
Envelope $Width_{20dB}$	= 6.4/τ (approximately the necessary bandwidth)
Envelope $Width_{40dB}$	= 64/τ

Where:

T = PRI

τ = Pulse Length

There are several important parameters of the spectrum that may be required to be measured. These include:

- Peak Power (PP)
- Peak Envelope Power (PEP)
- Shape of the Spectrum
- Spectral Power Density
- Shape of the spectrum envelope

[6] Defined as the frequency between the two nulls.

3.4.4 Measurement of the Shape of the Transmitted Spectrum

Consider first the measurement of the "shape" of the spectrum. This is required to ascertain (generally in relative terms) how fast the signal amplitude falls off outside the Necessary Bandwidth[7] (NB) region.

There are two approaches that can be taken to measure the shape of the spectrum. One approach is to attempt to measure the individual spectral lines and to reconstruct the spectrum from the individual lines. The other approach is to measure the envelope of the spectrum directly.

3.4.4.1 Line Spectrum Response (Fourier Series Spectrum)

To measure the spectral lines directly, the receiver needs a resolution bandwidth much less than the spacing between the lines. This would require a receiver with a resolution bandwidth of much less than 1/T (where T is the pulse repetition interval). In order to resolve such a spectrum accurately, a good rule of thumb is that the resolution bandwidth (B_{res}) should be less than 0.3/T and preferably 0.1/T. This allows measurement of the true Fourier series spectrum. The spectral envelope can then be constructed by plotting the individual measured lines or displaying them on a cathode-ray tube display, if a swept measurement is being made.

Civil radars use PRRs varying from 150 to 8000 Hz. This would necessitate measurement receiver IF bandwidths RBw from 10 Hz to 533 Hz [8]. At the higher PRRs the radars tend to operate with narrower pulses giving rise to a wider spectrum.

This method has several disadvantages, it:

- Does not measure the peak power (PP) or the peak envelope power (PEP) directly.
- Requires very narrow resolution bandwidths, (B_{res}), hence many steps.
- Cannot be used with variable waveform radars as the spectral lines move in time[9].

If the bandwidth of the receiver is widened, the point is reached when B_{res} = 1/T, and at this point the receiver is starting to measure more than one spectral line. The resolution bandwidth B_{res}, is now equal to the PRR. This is the transition between a true Fourier series spectrum, where each line is a response representing the energy contained within a harmonic, and a "pulse" or Fourier-transform response.

In a swept receiver system, the "spectral lines" now displayed are not frequency components but lines generated in the time domain by the single pulses of the signal.

3.4.4.2 The Pulse (Fourier-Transform) Response

3.4.4.2.1 Theoretical Consideration of Measurement Bandwidth

If the receiver resolution bandwidth, B_{res}, is increased to be greater than the PRR, then the receiver will lose the ability to resolve the individual spectral lines. The measured peak power will also increase due to the fact that the receiver is sampling a broader region of the spectrum each time, and collecting power from more than one spectral line.

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[7] Necessary Bandwidth (NB) is defined in S1.152 as the minimum bandwidth required to transmit a signal with an acceptable level of error (or distortion). For the sake of this section the NB will be defined as the -20 dB spectral envelope points.

[8] B_{res} approximately equals 1.5 x RBw - see 3.4.5.2

[9] This may be an issue if the radar is operating in more than one mode or has jitter applied.

This case is referred to as the "Pulse" spectrum or Fourier Transform response. If however the receiver's resolution bandwidth is much less than the width of the spectral envelope[10], then the shape of the envelope can be resolved.

In a swept[11] system (e.g. Spectrum Analyser) the resultant real time display is not a true frequency domain response but a combination of a time and frequency display. It is a frequency display of the spectral envelope and a time display of the pulse lines since each line is displayed when a pulse occurs regardless of the instantaneous frequency of the receiver. The spacing of the lines is thus related to the sweep time of the receiver and the PRR. By knowing the sweep rate, the PRR can be measured directly from the line spacing.

For a stepping system[12] where the sweep rate is effectively 0 Hz, no lines are displayed, and the result is that only the frequency envelope can be recovered.

In order to accurately measure the pulse spectrum, resolving the shape of the main-lobe and the level and shape of the side-lobe peaks and nulls, a resolution bandwidth B_{res} of between $0.1/\tau_{eff}$ to $0.03/\tau_{eff}$ is required, or less than 0.05 (5%) of the main-lobe width (τ_{eff}, the effective pulse length, is defined as the width of a rectangular pulse with the same impulse bandwidth as the pulse being measured). For a rectangular pulse $\tau = \tau_{eff}$.

The narrower the resolution bandwidth of the receiver the better the fine structure of the spectrum that can be resolved. Generally however, 5% ($0.05 * 2/\tau_{eff} = 0.1/\tau_{eff}$) of the main-lobe width is considered adequate to give good resolution of the shape of the spectrum.

If the IF bandwidth of the receiver RBw is increased, the peak power measured by the receiver will increase typically at 6dB/octave of bandwidth. This is a property of a peak detector and is referred to as pulse desensitisation. That is, double the bandwidth gives a 6 dB increase in amplitude. This relationship is true whilst the resolution bandwidth B_{res} does not exceed $0.2/\tau_{eff}$, above this bandwidth the rate of increase in peak power with bandwidth decreases. When the bandwidth B_{res} equals $1/\tau_{eff,}$ the receiver measures practically the full peak power of the signal (showing that it is covering nearly all the significant spectral components). Further widening of the bandwidth thus does not result in a significant further increase in peak power. For a rectangular pulse $1/\tau_{eff}$ equals half the width of the main-lobe, $2/\tau_{eff}$, and is significantly wider than the 0 dB envelope bandwidth of $0.64/\tau_{eff}$ [13]. In this case, however, the receiver has lost the ability to resolve the true shape of the spectral envelope.

As an illustration, consider Figure 3.4.4-1, a rectangular spectrum is measured using a receiver with a rectangular pass band of half the main-lobe width. The result of the measurement is a distortion of the spectrum shape and a considerable widening of the bandwidth. If a narrower filter is used, the shape of the spectrum is much better preserved.

There is a limit, however, on how narrow the resolution bandwidth can be. As the bandwidth is decreased, the power received reduces. This is due to the pulsed nature of the measurement (see section 3.4.5). The system must respond to each pulse independently; the effect of one pulse must decay before the next pulse arrives. Assuming the IF amplifier decay time constant is approximately 0.3/B, giving 5 time-constants to decay to -40 dB level, gives the rule that the resolution bandwidth B_{res} must be greater than 1.7 x PRR. In practice however it is the system dynamic range that sets the limit on the narrowest filter before this theoretical limit is reached. As the resolution bandwidth reduces, the peak power measured falls at a rate of "$20\log(B_{res})$ " however the system noise floor only falls as "$10\log(B_{res})$". Thus the total dynamic range of the system, the difference between the peak and the noise, falls at a rate of "$10\log(B_{res})$".

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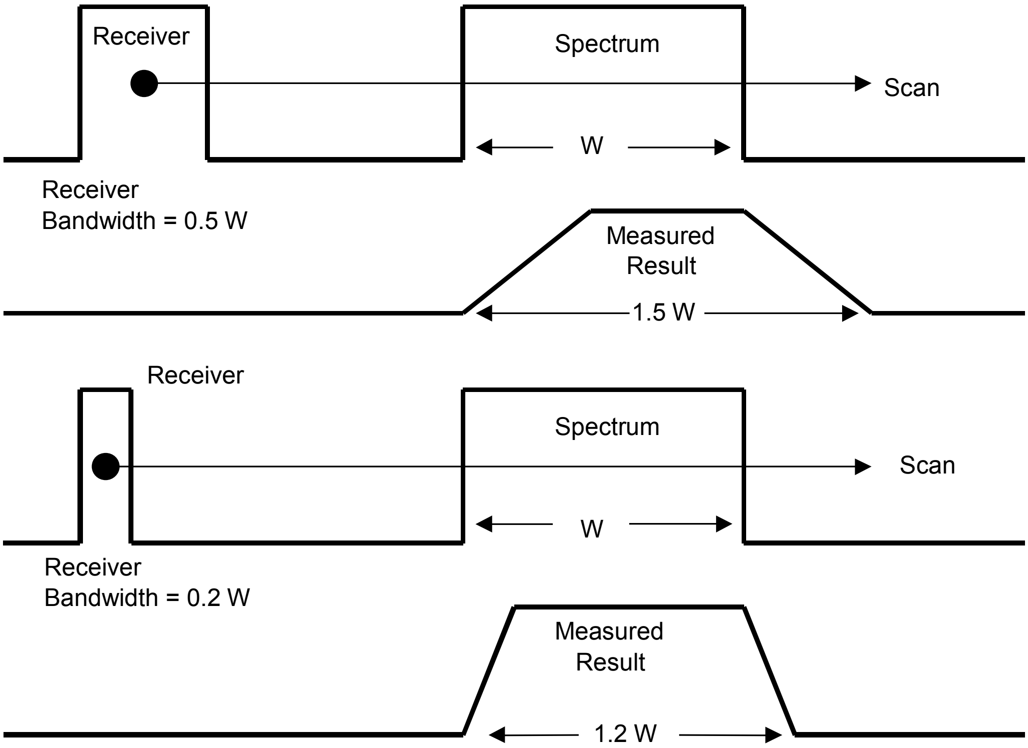
[10] Generally the width is described by the width of the main spectral lobe null to null. This part of the spectrum generally contains the majority of the power.

[11] Manual System

[12] Automatic system

[13] See Figure 3.4.3-2

Figure 3.4.4-1 Effect of Measurement Bandwidth on shape of spectrum



3.4.5 Pulse measurements.

When making measurements on pulse systems, it is necessary to consider the impulse response of the measurement receiver and the effect of "pulse desensitisation". The expression "pulse desensitisation" relates to the reduction in measured peak power seen in a pulsed system.

The act of pulsing a CW waveform results in its power being spread over a number of spectral components, main-lobe and side-lobes or frequency spreading. Each of these components contains only a fraction of the total power. The expression "pulse desensitisation" relates to the reduction in measured peak power seen in a pulsed system compared to the same power if measured as a CW signal in the same receiver bandwidth.

The term is thus somewhat misleading, as the reduction in measured power is not due to the sensitivity of the receiver system changing.

3.4.5.1 Fourier Spectrum

It can be shown that for a Fourier Spectrum (i.e. B_{res} less than 0.1 PRR) measurement, the factor that relates the measured peak power to the true peak power (α_l) is only related to the pulse width and the duty cycle by the equation:

$$\alpha_l = 20\log_{10}(\tau \times PRR) \qquad \text{Equation 3.4.5-1}$$

3.4.5.2 Pulse Spectrum

In the pulse spectrum mode, the response of the receiver to each RF input pulse is effectively the pulse response of the IF amplifier.

Given that the response is basically independent of pulse shape and PRR, the formula for α_p can be written as:

$$\alpha_p = 20\log(\tau_{eff} \times B_{res}) \qquad \text{Equation 3.4.5-2}$$

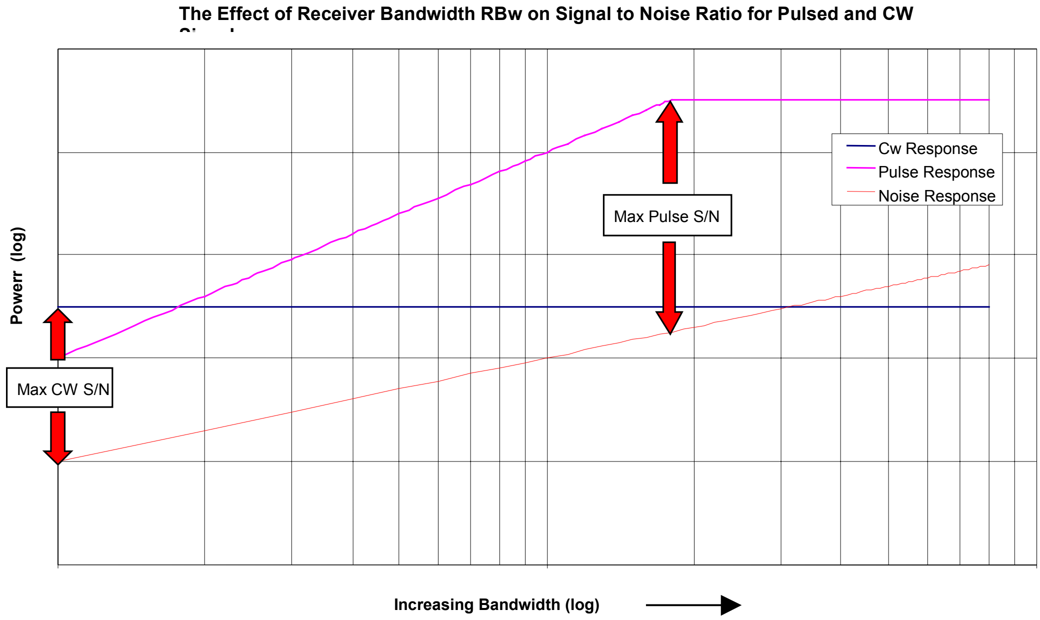
Since the resolution bandwidth is not the same as the 3 dB IF receiver bandwidth, the two can be related by the formula:

$$K = \frac{B_{res}}{RBw} \qquad \text{Equation 3.4.5-3}$$

Where *K* is a parameter dependent on the parameters of the receiver. For many spectrum analysers K is approximately 1.5. For other systems K would have to be derived and there are methods published for doing this. When using swept methods, other factors such as scan width and sweep time can affect the display. The rules for using these are either published in application notes or pre-programmed into more modern systems.

As has been stated, pulsing a CW waveform results in the total power being spread over a number of spectral components including the main-lobe and side-lobes seen in a pulsed spectrum.The measured peak power of a CW signal is independent of receiver bandwidth and therefore when measuring a CW signal it is typical to use a narrow receiver bandwidth to improve the Signal to Noise ratio (S/N). However when attempting to measure the peak power of a pulsed signal, the receiver bandwidth must be sufficient to capture all, or certainly the majority of the energy within the pulse. Figure 3.4.5-1 below is a graph which demonstrates the effect of receiver bandwidth on different input signals. The graph highlights that both the CW and pulsed signals have optimum bandwidths (maximum S/N) for accurate measurement, however they are very different. The knee of the signal curve occurs at the point where B_{res} equals $1/\tau$.

Figure 3.4.5-1 The effect of receiver bandwidth RBw on the measurement of different input signals



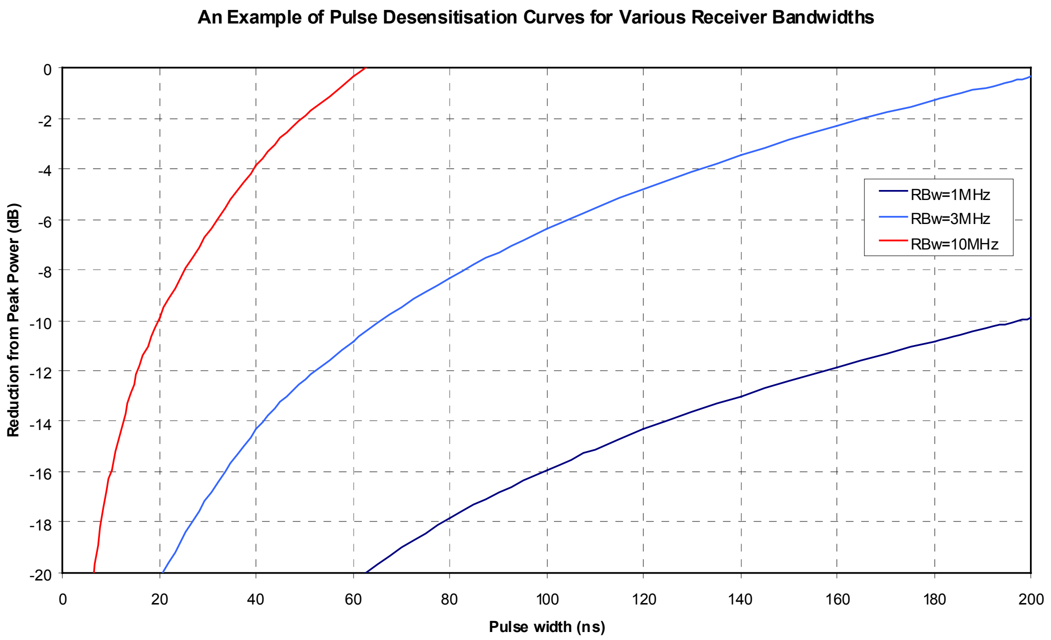
As a pulsed signal is impulsive in nature, the pulse desensitisation factor (α_p) is related to the Bw_m of the receiver system by the equation:-

$$\alpha_p \approx 20\log(\tau \times 1.5 \times RBw) \qquad \text{Equation 3.4.5-4}$$

Typically for spectrum analysers as those used in the measurement campaign, the B_{res} is 1.5 to 1.6 x RBw.

Figure 3.4.5-2 below shows a graph of example desensitisation curves for various receiver bandwidths calculated for different pulse widths.

Figure 3.4.5-2 Example plots of desensitisation curves for various RBw and pulse widths



The equivalent equation for a chirped pulse is given as[14]:

$$\alpha_p \approx -10\log(Bc/(\tau(1.5 \times RBw)^2)) \qquad \text{Equation 3.4.5-5}$$

Where Bc is the bandwidth of the chirped pulse.

14 Attachment 8 to 8B/184-E "Preliminary Draft Revision of Recommendation ITU-R M.1177." Appendix 1 to Annex 1.

3.4.6 Peak Power Measurements

In order to measure the peak power of the waveform directly with a reasonable degree of accuracy it is necessary to widen B_{res} from that which is just needed to resolve the true shape of the spectrum. For rectangular unmodulated pulses, a B_{res} of $1/\tau$ gives an acceptable result. This value of B_{res} is defined as B_{pep}, the minimum bandwidth required to measure PEP. A B_{res} of $2/\tau$ would be more accurate as it would capture all the power in the main spectral lobe - the difference however is small and not considered relevant, this however may not be true for other waveforms. It may also be argued that the errors associated with a B_{res} of as low as $0.75/\tau$ could be acceptable in some applications where accuracy is not the paramount consideration.

The practical method to ascertain the value of B_{pep} would be to widen B_{res} until there is no detectable change in measured peak value. Alternatively the true Peak Power (PP) could be calculated from knowledge of the pulse desensitisation factor if the receiver does not have a wide enough bandwidth.

When using this method, care however should be taken not to overload the receiver system front-end. Overload can be masked by the effects of the α pulse desensitisation factor, and can lead to damage occurring.

3.4.6.1 Very Narrow Pulses

For very narrow pulses it may not be possible to widen the resolution bandwidth enough to achieve a B_{pep} of $1/\tau$ notwithstanding that a B_{pep} of $1/\tau$ is required to give an accurate result. In this case it is necessary to obtain the peak power from measurements of peak power taking into account the pulse desensitisation factor.

For example a 0.09µs pulse requires a B_{res} bandwidth of greater than or equal to B_{pep} of 11.1 MHz to measure the true peak power.

Pulse desensitisation will also effect the dynamic range of the measurement that can be achieved.

Conventional spectrum analysers are limited to about 5 MHz IF bandwidths, although the more specialised can achieve up to 50 MHz. Above 50 MHz specialised receivers are required. The efficacy of these types of devices has not been considered in this study. The issue however with these devices will relate to the balance between the acceptable pulse desensitisation and the resulting dynamic range. Potentially a 50 MHz RBw would allow the accurate measurement of the peak power of 0.013µs pulses.

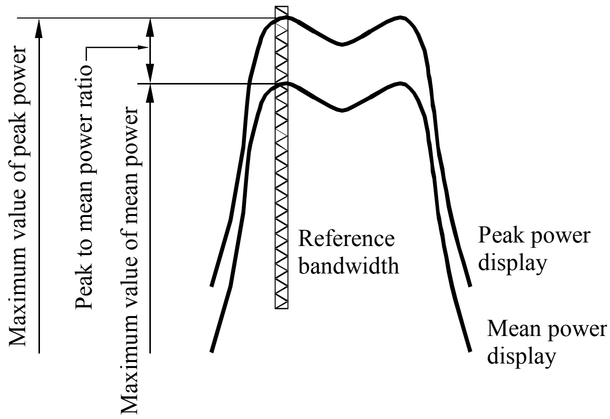
3.4.6.2 Peak Envelope Power

The ITU requirements on spurious emissions are specified in terms of PEP "Peak Envelope Power". PEP is a measurement of the average power in one cycle of the carrier whose amplitude is equal to the peak of the modulation envelope. It is a "time" based measurement and can only be carried out with a wide-band detector. For a truly rectangular pulse it is equal to the peak power of the pulse which is equal to the energy in the pulse divided by the pulse width. If the pulse is not rectangular, then the relationship between the power in the pulse and the PEP becomes more complex. For the measurements of SE, provided the bandwidth is wide enough to capture the majority of the spectrum ($1/\tau$), then the PEP approximates to the PP.

3.4.6.3 Decibels relative to maximum power density (dB_{pp})

dB_{pp} are decibels relative to the maximum value of the spectrum, measured with the reference bandwidth within the occupied bandwidth. The in-band peak power is expressed in the same reference bandwidth as the OOB peak power, see Figure 3.4.6-1. Both the in-band and the unwanted emissions are evaluated in terms of peak values. For radar systems, the reference bandwidth is selected according to ITU-R Recommendation M.1177-2.

Figure 3.4.6-1 0 dB_{pp} reference, maximum value of peak power



3.4.6.4 Maximum Spectral Level P_t (dBm/kHz)[15]

This is measure of the mean power divided by the bandwidth occupied by the signal. The equation for the calculation of P_t includes the duty cycle of the radar hence P_t is in units of mean power/kHz. It has some useful applications when considering interference with some types of receivers.

[15] MIL STD 469 Radar Engineering Interface Requirements Electromagnetic Compatibility

3.4.7 Practical Measurement Considerations

3.4.7.1 Receiver Bandwidths

The correct configuration of the various receiver system bandwidths is fundamental to the accurate measurement of radar transmitted spectra. The various bandwidths within the receiver system must be considered before making a measurement (i.e. the RF bandwidth, the IF bandwidth and the video bandwidth).

The IF bandwidth of the receiver system is the most significant contribution to the overall system bandwidth. The other contributions, (i.e. video bandwidth, etc) are normally set sufficiently wide so as not to influence the overall receiver system bandwidth RBw.

3.4.7.1.1 RF Front-end Bandwidth

In most cases the bandwidth of either the RF front-end of a spectrum analyser or any external tuneable filters is much greater than required for the assessment of the pulsed spectrum from the majority of radar systems. However some areas of radar usage are tending towards very short pulse widths, for example marine navigation radars can have pulse widths of 50 to 60ns in short pulse mode and Airport Surface Detection Equipments (ASDE) can have pulse widths less than 40ns. In the case of the ASDE, the RF bandwidth would preferably have to exceed $1/\tau$, 25MHz, which becomes comparable to some pre-selection filters used on RF front-ends. Therefore when considering measuring short pulse radars that occupy large bandwidths, the RF front-end devices must be considered.

3.4.7.1.2 Resolution Bandwidth

The required resolution bandwidth (B_{res}) for measuring a particular radar will depend on the type of measurement being made. For the measurements of SE, the requirement is for a bandwidth sufficient to measure peak power across the measurement band (over the SE domain) particularly the fundamental emission. For the case of an OOB domain measurement, where it may be required to resolve the shape of the transmitted spectrum in more detail, then the bandwidth may need to be much narrower.

For the assessment of an installed radar it is necessary to perform a peak power measurement over the fundamental region first in order to ascertain the peak level of the fundamental. This will need to be performed using a sufficiently wide bandwidth, i.e. $B_{res} = 1/\tau$ for non-modulated pulsed radars. If it is not possible to obtain or measure the pulse parameters, then the required B_{res} needs to be determined from measurements of the spectrum rather than by calculation. This method consists of putting the spectrum analyser into manual mode and while measuring the fundamental emission reduce the receiver's bandwidth until the measured power begins to decrease. The bandwidth obtained in this way will be the optimum resolution bandwidth (B_{res}) for accurate assessment of the SE domain without having to know the detailed characteristics of the pulse or modulation used. This technique is described in the proposed revision 8B/184-E of ITU-R Recommendation M.1177-2 as the "(1/T) method". This "(1/T) method" has also to be adopted when the radar is operating in a multi-mode manner where pulse width and modulation is continually varying.

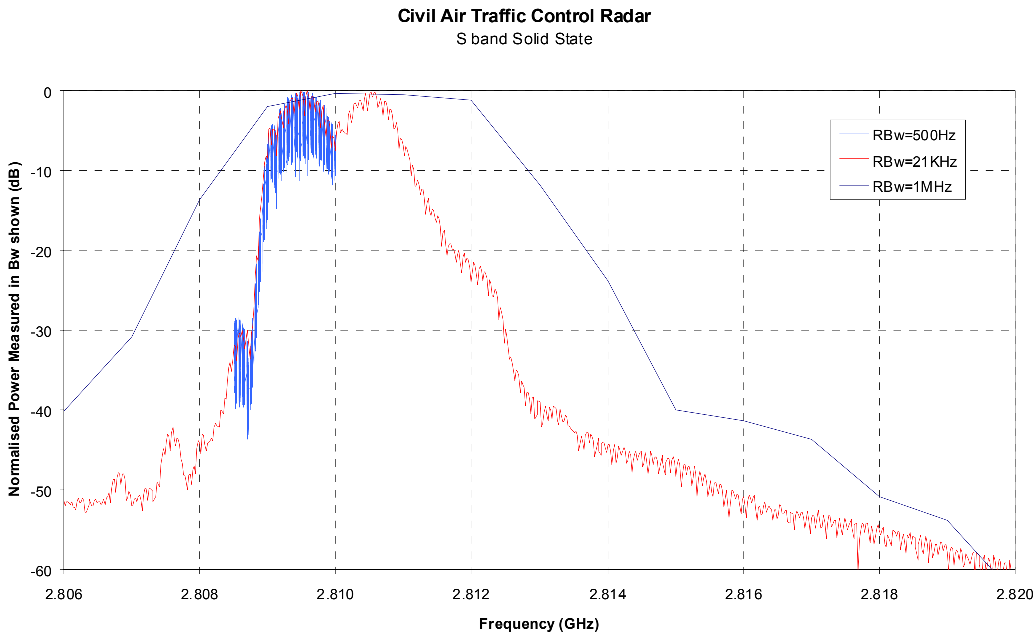
Following the determination of the peak power of the fundamental, the same B_{res} can then be used to measure the signal over the complete Unwanted Emission (UE) band of interest.

The initial results of this measurement run can then be analysed to see if it is necessary to perform a higher resolution measurement run for the assessment of the OOB emissions. If the data measured in the OOB domain comfortably falls within the required mask, then it may not be deemed necessary for a higher resolution run[16]. However because a wide resolution

[16] The demonstration that the measured data falls well below the mask would be sufficient to demonstrate a pass against a specification limit but may not be adequate for a more detailed engineering investigation. The failure to meet a spectrum mask may not be considered an issue for say a high level investigation such as a spectrum occupancy survey.

bandwidth produces a measured spectrum shape distorted by the filter shape with a wider main-lobe etc., the measured spectra may not fall within the limit mask. The broader main-lobe may restrict the movement or placement of the mask, a method used in type approval measurements to optimise the result. The initial survey run will also allow the judgement of the required band over which to measure with a narrower filter to be made. It is not necessary to measure across the whole OOB region if the spectrum drops off well below the mask at frequencies away from the fundamental. This may be the case in either radars with filters in the transmit path or with radars with very well controlled rise and fall times. Figure 3.4.7-1 below shows the measured spectrum of a solid state ATC radar which has a very slow rise time compared to other output device radars. The resulting spectrum is very well contained. This spectrum contains two fundamental signals with two pulse types a 1μs uncompressed pulse and a 100μs pulse with a 1 MHz of chirp Bc giving a compressed pulse length of 1μs. The two pulse lengths alternate frequencies within a burst and hence the measured level of the long pulse dominates the measurement results in each case.

Figure 3.4.7-1 [17] The measured spectrum of the solid state ATC radar with different RBw



The 1MHz (1/τ) IF bandwidth RBw, was used to measure the peak power while the other IF bandwidths 21 kHz and 500 Hz were used to resolve the spectrum shape. It is clear that the wide bandwidth (1/τ) does not allow the two transmit frequencies to be resolved, as they are so close in frequency. Also the wide bandwidth causes considerable broadening of the two main-lobes. It is thus necessary to use a narrower resolution bandwidth to resolve the true shape of the spectrum. It would not be considered necessary to use the very narrow measurement bandwidths illustrated to resolve the spectrum shape but in practice a B_{res} of 100 kHz (0.1 Bc) would be suitable leading to a lower pulse desensitisation loss and a better signal to noise.

This result also illustrates the limitation of using a step size that is too large. The 1 MHz filter has failed to measure the peak of the lower of the two frequencies. This phenomenon is discussed in section 3.4.7.2 later in this report.

[17] Source Annex 2 of this report

Figure 3.4.7-2 and Figure 3.4.7-3 below show the resulting spectrum measured with different IF bandwidths RBw of a 3GHz pulsed signal with a pulse width of 1μs. The five plots shown equate to approximately 2.5% (0.05/τ, 51 kHz), 10% (0.2/τ, 215 kHz), 20% (0.4/τ, 422 kHz), 30% (0.6/τ, 619 kHz) and 50% (1/τ, 1 MHz) of the main-lobe width (2/τ). The 2.5% (51 kHz, 0.05/τ) RBw measurement is provided as a benchmark for the spectrum shape. Figure 3.4.7-2 shows the spectrum as a log power vs frequency plot and highlights the distortion of a measured spectrum shape when using the wider bandwidths. Figure 3.4.7-3 is a log power vs log frequency plot and highlights the broadening of the main-lobe with bandwidth. The measurement bandwidth of approximately 10% (0.2/τ) main-lobe width, (i.e. the 215kHz RBw), shows results with very little distortion of both the main-lobe width and the side-lobe levels. The nulls of the spectrum are however not well defined.

Figure 3.4.7-2 Plots of a pulsed spectrum from a synthesiser measured in different RBw bandwidths

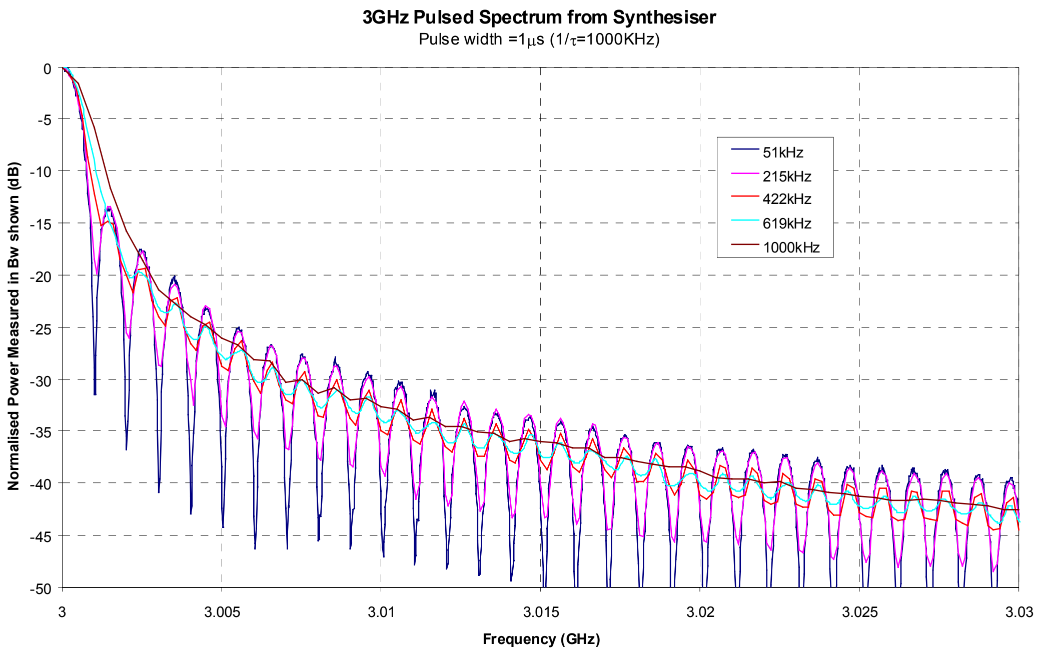
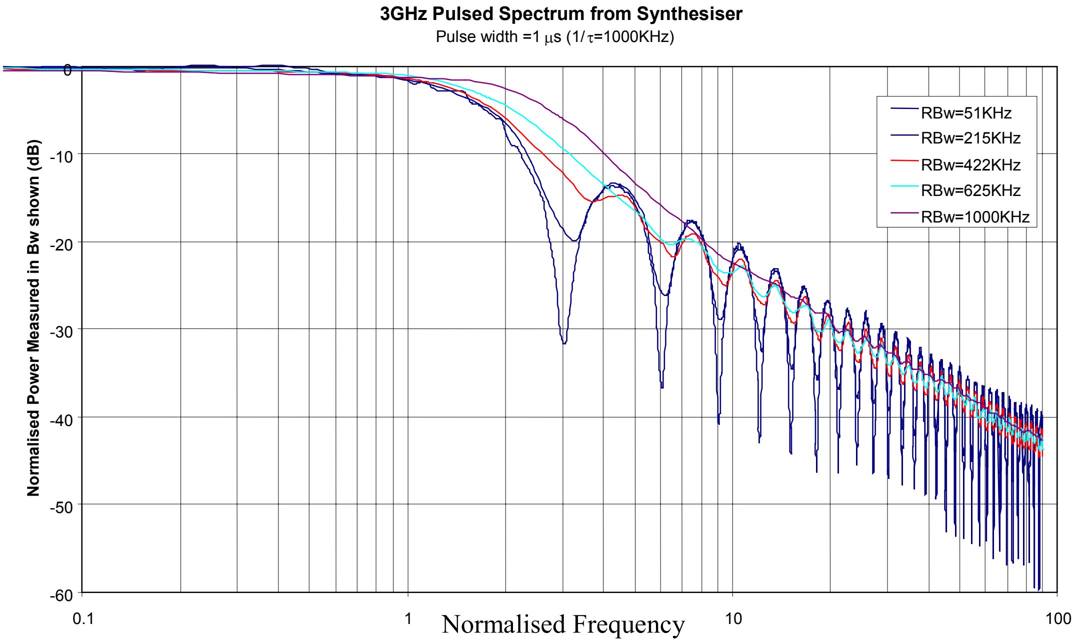


Figure 3.4.7-3 Plots of a pulsed spectrum from a synthesiser measured in different RBw bandwidths



3.4.7.1.3 Video Bandwidth

The video filter is a low pass filter that is located after the envelope detector and before the analogue to digital converter. The filter is used to average or smooth the trace displayed on the screen. As the cut-off frequency of the video filter is reduced to the point at which it becomes equal to or less than the resolution bandwidth selected, the video system can no longer follow the more rapid variations of the envelope of the signals passing through the IF chain. The result is an averaging or smoothing of the displayed signal.

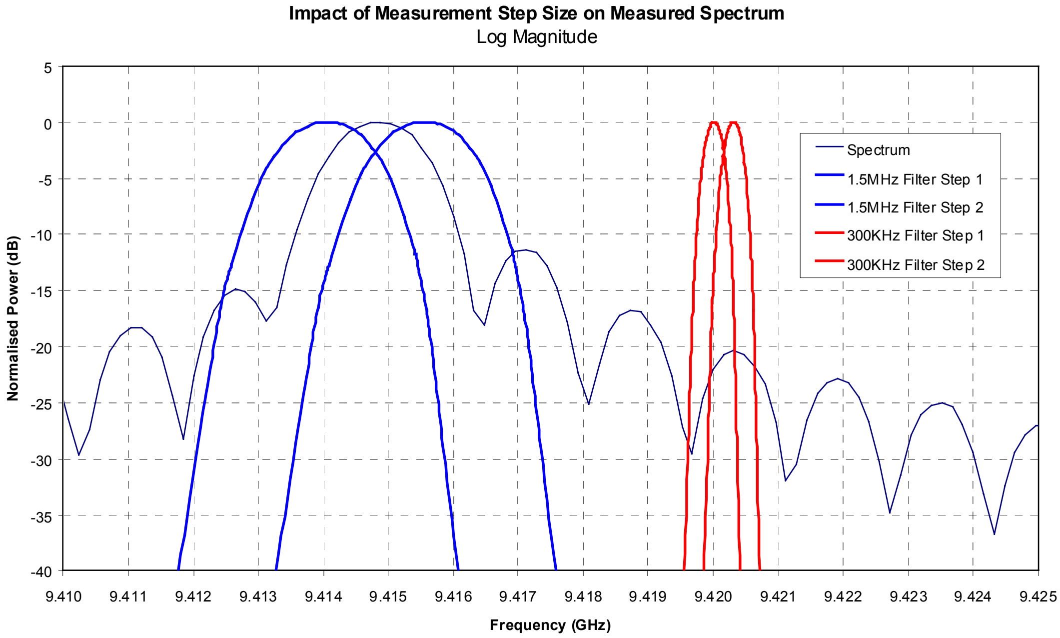
Altering the video bandwidth does not alter the average noise and therefore does not improve the noise floor of the system when narrowing the filter. However, the peak variation of the noise is altered by changing the video bandwidth. When using a spectrum analyser in positive peak mode, as in the case of unwanted emission measurements, the effect of narrowing the video bandwidth is that the apparent noise floor is lowered, however it is only lowered towards the average noise of the system. Therefore when measuring the noise-like signals, particularly in the spurious domain, the video bandwidth will change the measured values if it is narrower than the RBw filter.

The setting of the video bandwidth is also an important consideration when measuring the pulse spectrum. The video filter will influence the impulse response and hence the resolution bandwidth (B_{res}) of the receiver system as the displayed signal will depend on the filter's ability to respond to a pulsed signal i.e. one of an impulsive nature. To ensure that the peak power, or indeed the shape of the spectrum, is not influenced to an unacceptable level, the video bandwidth should be set greater than the RBw or indeed to the maximum available on the spectrum analyser.

3.4.7.2 Measurement Step Size

The recommended measurement step size in ITU-R Recommendation M.1177-2 is equal to the bandwidth chosen for the measurement. This would provide continuous data across the entire frequency band of interest. However when measuring the peak power of the transmitted spectrum for assessment of SE, it is possible to underestimate the peak power if the IF filter does not coincide with the peak of the radar fundamental or indeed any other signal. Figure 3.4.7-4 and Figure 3.4.7-5 below highlight the effect.

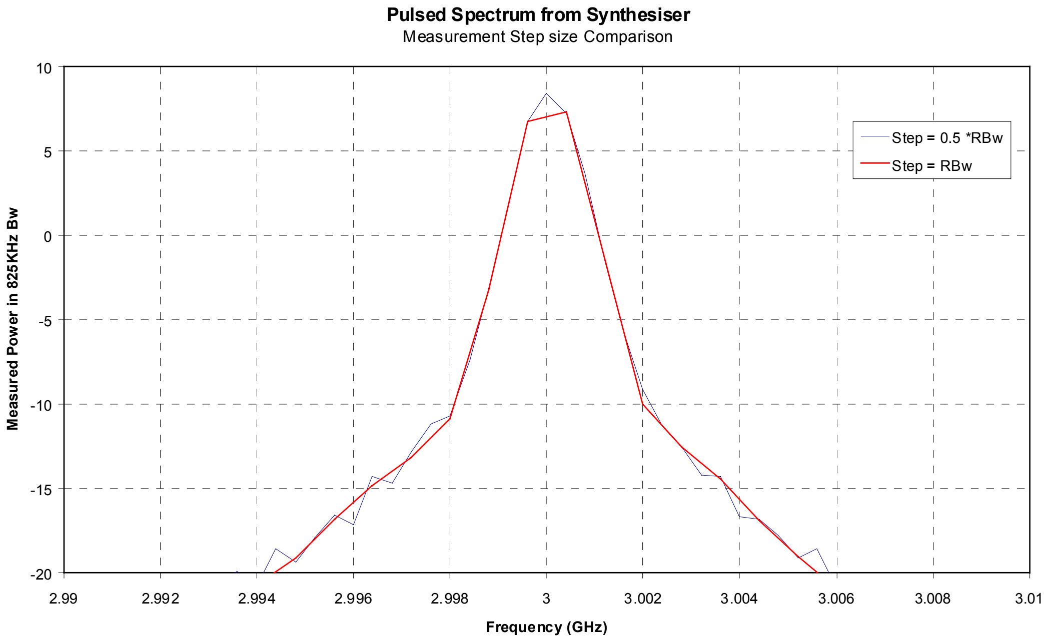
Figure 3.4.7-4 Example radar spectrum with two different RBw IF filters overlaid at the M.1177-2 recommended step size[18]



The 1.5MHz filter shown on the plot will not adequately measure the peak power because it does not line up with the peak of the spectrum whereas the 300 kHz filter, with its smaller step size, will measure the peak power of each lobe. Although the area under the curve that is not measured appears insignificant, it can lead to differences of 2 or more dB in the measured peak power which could be considered an unnessessary addition to the measurement uncertanties. Figure 3.4.7-5 below is an example of two plots, one measured with the step size equal to RBw, the the other RBw/2 . The RBw in this case is such that $B_{res} \approx 1/\tau$ (B_{pep}). Thus the step sizes are approximately the recommended B_{res} and $B_{res}/2$. The signal source in this case is a microwave synthesiser. The difference in measured peak power is clearly apparent. Measuring a broad frequency band with half the recommended step size will double the measurement time and may not be viable depending on the accuracy required. In some cases where the exact values of SE are not required, for example general spectrum occupancy surveys, the wider step size may be appropriate. However in the case of type approval measurements performed at QinetiQ, the additional uncertainty is not acceptable and therefore the measurements are performed at half the recommended step size of RBw.

[18] Measured data from this figure taken from Annex 5 of this report. (A5-3)

Figure 3.4.7-5 An example of measured spectra with different step sizes



This effect does not occur when measuring the shape of the pulse spectrum using the narrow IF filters needed to resoilve the true shape, as shown above in Figure 3.4.7-5. Therefore for the assessment of the OOB region, the step size is recommended to be equal to the B_{res}.

3.4.7.3 Measurement time

The measurement time for either an OOB or a SE measurement is dictated by a combination of the radar characteristics, measurement step size and the frequency range to be measured. The measurement step size is directly related to resolution/measurement bandwidth as discussed above. This section discusses the results of the measurement campaign.

The dominant parameter for measurement time is the rotation rate of the radar antenna as it is important to ensure the antenna has completed at least a whole revolution before stepping the spectrum analyser to the next frequency. The measurement time is then quite simply the number of steps multiplied by the rotation rate. In some cases a radar may switch modes on a rotation basis and therefore it could be necessary to wait for a revolution at every radar mode before stepping to the next frequency.

Table 3.4.7-1 below provides a list of measurements performed on a S-Band TWT ATC radar with the associated measurement parameters and measurement times. The total time is only an indication as the measurements were performed as part of the research package with a couple of additional runs at higher resolution. Also the total measurement time does not include set-up time for the measurements or time to configure the equipment before each run or the calibration runs. The dominant measurement time is for the assessment of the SE with the run being broken into 5 parts with a total run time of 14.2 hours. The long run was broken up to allow storage and backing up of the measurement data to prevent loss in the event of power or computer failure. The required measurement of the spectrum shape amounted to approximately 5 hours because the radar transmitted on multiple frequencies and pulse modes.

Table 3.4.7-1 Measurement runs and times for the S-Band TWT ATC radar

Run	Date	Run Title	Run Type	RBw (KHz)	Step (KHz)	Start Freq (GHz)	Stop Freq (GHz)	Duration (Hrs)
1	10-Dec-01	ATC S band TWT SE 3MHz survey	SE	3000.000	3000.00	2.0000	4.1500	0.8
2	11-Dec-01	ATC S band TWT SE 1MHz part 1	SE	1000.000	1000.00	2.0000	2.7000	0.8
3	11-Dec-01	ATC S band TWT SE 1MHz part 2	SE	1000.000	1000.00	2.7000	4.0000	1.5
4	11-Dec-01	ATC S band TWT OOB 1 125KHz	OOB	125.000	125.00	2.6000	3.0000	3.6
5	11-Dec-01	ATC S band TWT OOB 2 10KHz	OOB	10.000	10.00	2.7620	2.7680	0.7
6	12-Dec-01	ATC S band TWT SE 1MHz part 3	SE	1000.000	1000.00	4.0000	5.0000	1.1
7	12-Dec-01	ATC S band TWT SE 1MHz part 4	SE	1000.000	1000.00	5.0000	12.0000	8
8	12-Dec-01	ATC S band TWT SE 1MHz part 5	SE	1000.000	1000.00	12.0000	14.5000	2.8
9	12-Dec-01	ATC S band TWT OOB 3 2-61KHz	OOB	2.610	2.50	2.8820	2.8880	2.7
10	12-Dec-01	ATC S band TWT OOB 4 2-61KHz	OOB	2.610	2.50	2.7620	2.7632	0.5

Total Time	22.5

3.4.8 Comments on Results of the Investigation

The results of the investigation undertaken, both practical and theoretical, during this study can be summarised as follows:

3.4.8.1 Resolution Bandwidth for Spectrum Shape

The theory presented in section 3.4.4 suggests that to accurately resolve the shape of the spectrum of an unmodulated pulse in the OOB region, a resolution bandwidth of less than 5% of the main-lobe width of $2/\tau$, that is a bandwidth of equal to, or less than $0.1/\tau$ is required. However the requirement of this measurement is to accurately resolve the envelope of the spectrum including the nulls. Measurements suggest that in the case currently being studied here, where it is only required to measure the envelope of the spectrum and not the nulls, then a resolution bandwidth of 10% of the main-lobe width (i.e. $0.2/\tau$) is a good approximation. Such a resolution bandwidth would result in a desensitisation α of 13.9 dB[19] resulting in more than adequate dynamic range.

If we consider a chirped pulse, then the main-lobe width approximates to the chirp bandwidth. Thus the resolution bandwidth can be approximated to 10% of the chirp bandwidth (Bc) (i.e. 0.1 x Bc). The longer the pulse, the more accurate this approximation becomes. The long pulses however mean that the desensitisation is reduced and that the dynamic range of the measurement increases.

3.4.8.2 Resolution Bandwidth for Spurious Emissions

Spurious emissions require the measurement of peak power in the reference bandwidth to be compared to the PEP measured in the appropriate bandwidth. In order to resolve spurious emissions, a resolution bandwidth of $B_{res} = 1/\tau$ gives satisfactory results, and is recommended for use where it is achievable .

If it cannot be achieved then a B_{res} of between $0.75/\tau$ to $1/\tau$ is a reasonable compromise, for the assessment of SE of an unmodulated pulsed radar depending on the accuracy required of the measurement. At a B_{res} of $0.75/\tau$, this does not strictly allow the accurate measurement of peak power, however in relative terms across the frequency band of interest, it will result in satisfactory measurement results. The pulse desensitisation of the peak power would be approximately -2.5 dB[20]dB for a receiver of the same type as used in the QinetiQ facility.

This would apply to the spectrum throughout the OOB region. However the measurement of the signals other than harmonics or other time related signals, in the spurious domain could be reduced by up to 1.25dB[21] [22] as discussed in 3.4.8.4. This results in a maximum difference of around 1dB in the relative levels for both types of signals that would not be a significant contribution to the overall errors.

For measurements in bandwidths much less than $0.75/\tau$ the error becomes unacceptable and correction factors need to be applied all the time for the measurement of PEP and signals in the SE region if the B_{res} differs from the B_{ref} defined for SE.

---

19 $\alpha = 20 \log(\tau \times \frac{0.2}{\tau}) \approx -13.98\, dB$

20 $20 \log\left(\tau \times \frac{0.75}{\tau}\right) = -2.5\, dB$

21 $10\log\left(\tau \times \frac{0.75}{\tau}\right) = -1.25 dB$

22 Harmonics and time related signals will suffer the same desensitisation as the fundamental frequency

3.4.8.3 Example of General Spectrum Measurements

Figure 3.4.8-1 below shows an example radar spectrum measured with three different measurement bandwidths. The data has been normalised to demonstrate the effect of the shape of the measured result with different bandwidths. The radar had a nominal pulse width τ of 1μs and would therefore require a resolution bandwidth of B_{pep}. 1MHz ($1/\tau$) to measure the peak power and a resolution bandwidth of 200kHz ($0.2/\tau$) or less to resolve the shape of the pulse spectrum envelope. In this example an IF filter of $0.1/\tau$ ($B_{res} = 0.15/\tau$) was used to resolve the spectrum shape.

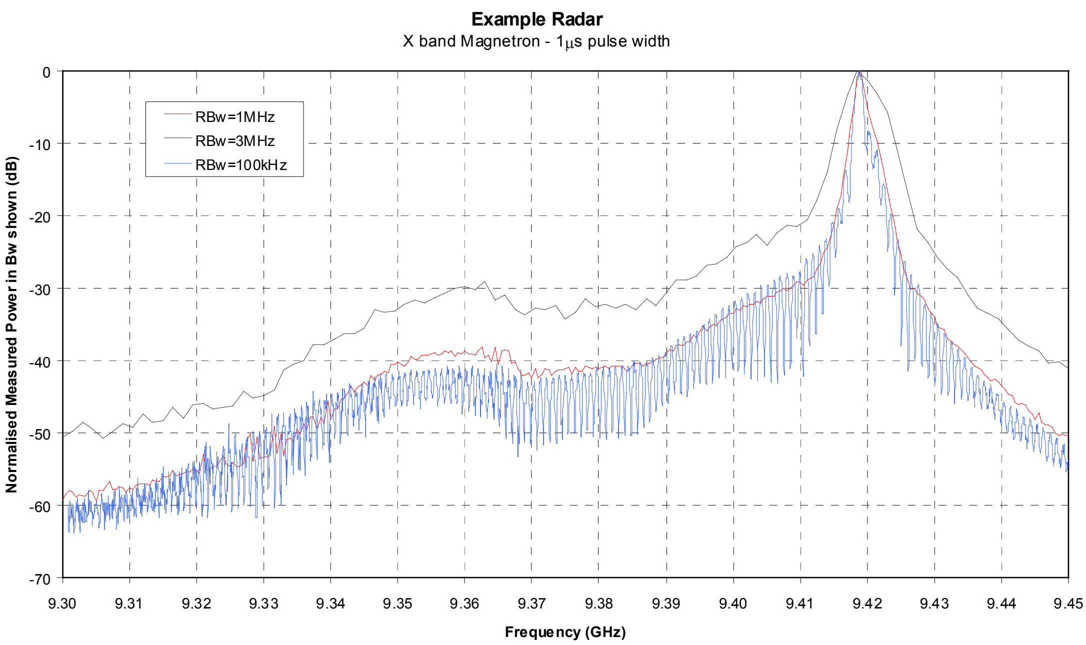
As can be seen in Figure 3.4.8-1, the $0.1/\tau$ receiver filter ($0.15/\tau$ resolution bandwidth) resolves the fine detail of the spectrum side-bands, the desensitisation loss (α) is approximately 16.5[23] dB which is still acceptable, in that it still provides an adequate dynamic range.

In practice a wider filter with a resolution bandwidth of $0.2/\tau$ (200 kHz) would still have given acceptable results with a desensitisation loss of 14 dB, and would have resulted in fewer measurement steps.

The $1/\tau$ IF filter gives rise to a measurement error in the shape of the spectrum of the order of 2 to 3 dB.

The plots highlight that although it is important to have sufficient bandwidth to measure peak power, it is equally important not to have too wide a bandwidth. In this case a 3MHz ($3/\tau$) RBw results in the spectra away from the fundamental emission increasing due to more energy falling within the filter bandwidth while at the fundamental there is no more energy to measure.

Figure 3.4.8-1 Example radar spectrum measured with three different bandwidths



3.4.8.4 Composite Spectra

As well as the fundamental signal and its harmonics, radar systems may emit other types of unwanted emissions or may emit more than one form of the fundamental emission.

23 $$\alpha = 20\log(\tau \times 1.5 \times \frac{0.1}{\tau}) \approx -16.5\,dB$$

Depending on the type of system being measured, some of the unwanted emissions may not occur in the same time relationship as the main pulses. Some systems may emit continuous noise-like signals, CW signals or very short-lived signals related to the rise-time of the radar pulse. The use of different measuring bandwidths helps to resolve the differing time responses of these unwanted emissions. Changing the resolution bandwidth and understanding the relationship between the measured peak signal level, the desensitisation and the noise level can aid the identification of the signals.

Some radars operate with different multiple pulse patterns. If the change in pulse length is associated with a change in frequency, then it may be possible to resolve the two signals in the frequency domain. If the pulses are on the same frequency, then they cannot be distinguished in the frequency domain. However the measured result is more complex than the simple overlaying of the two spectra.

The following examples illustrate some of the issues:

The measurement of composite spectra is complicated for four reasons:

- The Impulse bandwidths of the pulses are different, hence the desensitisation is different;
- The spectrum levels may need to be compared against P_t, which is the mean power spectral density;
- The measurement system measures peak power;
- The B_{res} required to resolve the shapes of the individual spectra is different.

When comparing unwanted emissions to the peak of the spectrum, because they are relative, the measurements can be expressed directly in dB relative to the fundamental peak. However when comparing two different spectra or resolving composite spectra, the absolute levels of the spectra being measured must be used to allow the relative levels of the signals to be calculated.

This can be done by comparing either the peak power of the spectrum or, in some cases, the spectral power densities. When comparing peak power levels then due account needs to be made of the different pulse desensitisation resulting from the resolution bandwidth that has been used. This is the case when the radar can only be used in a multiple waveform mode and the different pulse spectra are displayed simultaneously.

As well as containing the different pulse spectra of the fundamental emissions, the SE spectrum can also contain other types of emissions.

If we consider two examples of different types of composite spectra. The first is the output spectrum of a magnetron type radar using a 50 ns pulse, (see Figure 3.4.8-2 below) this spectrum consists of three particular features of interest:

a) A continuous spectrum associated with the fundamental emission from the pulse extending from about 2.4 GHz to 3.9 GHz

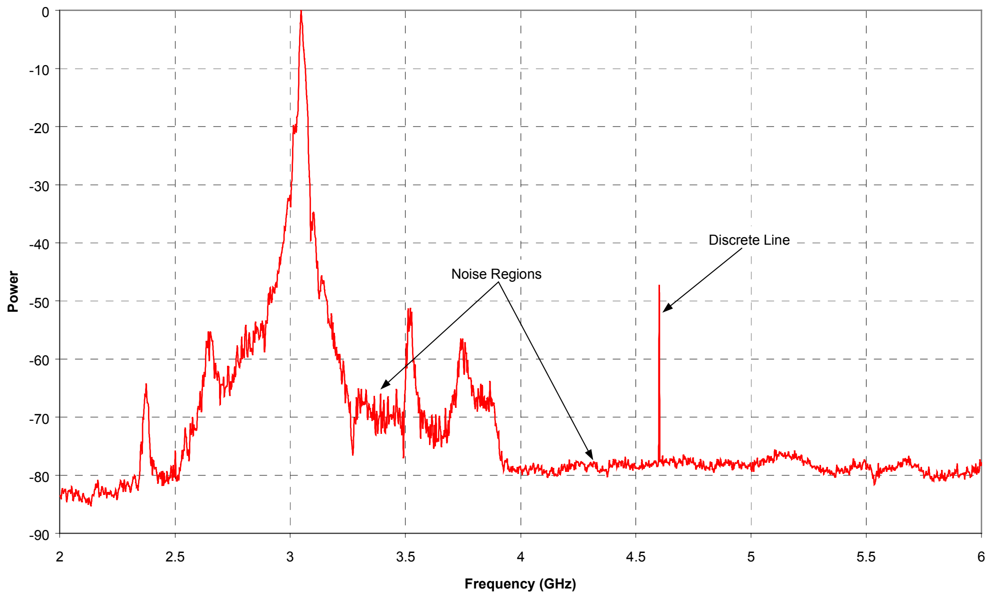
b) Noise-like regions, typically at just above –80dB, and possibly in other regions such as from about 3.3 GHz to 3.5 GHz.

c) A discrete spectral line at around 4.6 GHz.

The $1/\tau$ resolution bandwidth for a 50 ns pulse is 1/50 ns or 20 MHz. However, the spectrum has been measured with a receiver with a maximum 3 MHz IF bandwidth (B_{res}= 4.5 MHz), which is the widest bandwidth available on some receivers.

In order to interpret the results it is necessary to consider the effect of the reduced bandwidth on these three regions. In the continuous spectrum region, increasing the measurement bandwidth (RBw) to greater than the 3 MHz will cause the measurement of the peak spectral power density to increase in line with the desensitisation formula, that is, increase as 20 $\log_{10}(RBw/3)$[24].

Figure 3.4.8-2[25] Measurement using 3 MHz RBw



In the noise regions, increasing the measurement bandwidth increases the measured noise power by 10 $\log_{10}(RBw/3)$[26].

For discrete spectral lines, increasing the measurement bandwidth does not result in any increase in the power measured.

If the measurement IF bandwidth were increased to 20 MHz, then the peak would increase by 16.5 dB[27], and the noise by 8.24 dB[28] giving a net relative reduction of 8.24 dB. The CW tone would not change but would suffer a net 16.5 dB reduction compared with the peak of the fundamental. A representation of what the changes would look like is given in Figure 3.4.8-3 below.

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[24] $20\log(RBw \times 1.5 \times \tau) - 20\log(3 \times 1.5 \times \tau) = 20\log\left(\frac{RBw}{3}\right)$

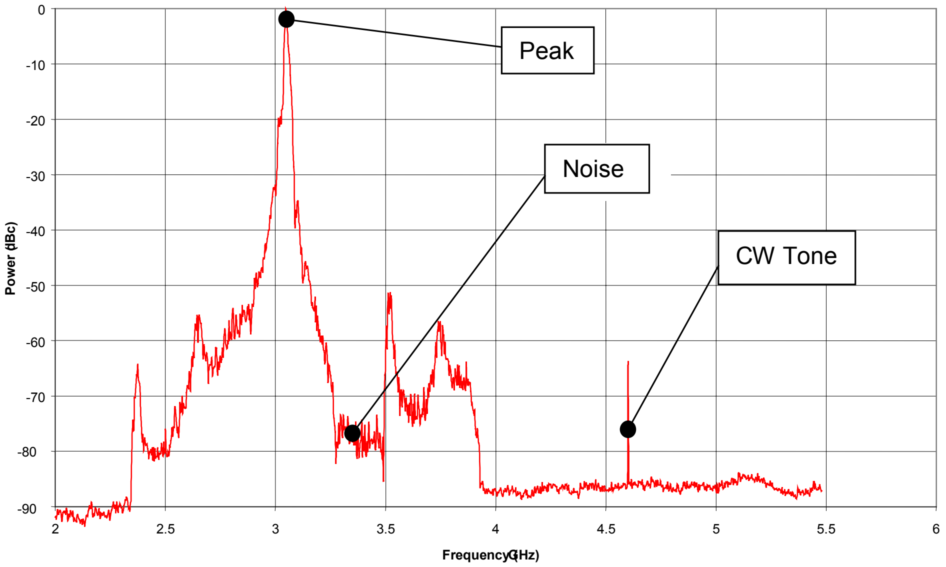
[25] Source Private Communication

[26] In these regions the signals are noise and not correlated with the pulsed fundamental, their level changes with bandwidth as the classical 10 log rule for increasing measured noise power.

[27] $20\log(20/3) = 16.5\,dB$

[28] $10\log(20/3) = 8.24\,dB$

Figure 3.4.8-3 Representation of Measurement using 20 MHz RBw[29]



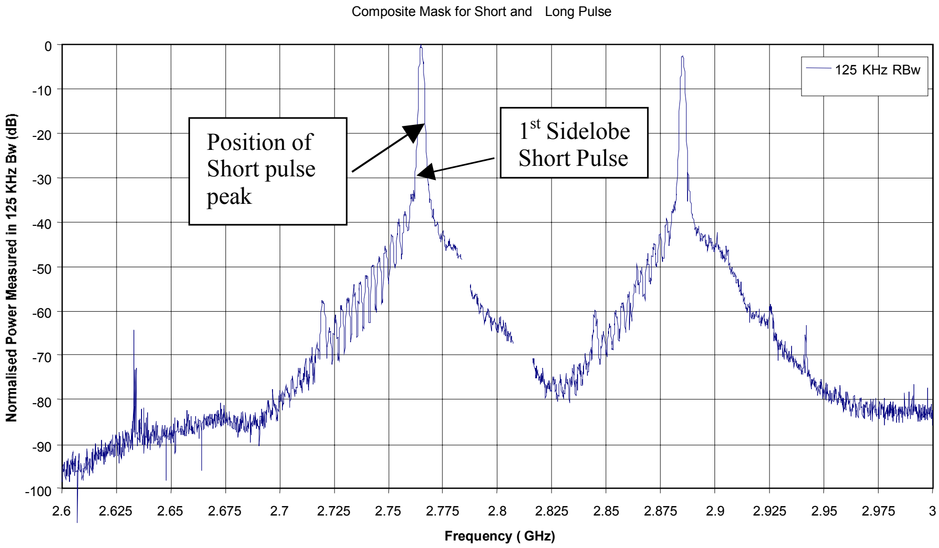
An alternative form of composite spectrum that is considered is one that comprises a mixture of pulses of different lengths and/or type using the same fundamental frequency. When considering the measured spectrum that would result, the following factors need to be addressed:

- The width of the spectrum;
- The difference in desensitisation values.

Figure 3.4.8-4 shows the spectrum of a two-frequency radar operating on alternate short and long pulses on both frequencies. The measurement is made with a RBw of 125 KHz.

[29] Source Private Communication

Figure 3.4.8-4 Composite Spectrum[30]



The short 0.33 µs (as measured) pulse has a sinx/x type spectrum with first side-lobes at approximately 13 dB below the peak. This pulse undergoes a pulse desensitisation of 23.6 dB[31]. The long pulse of 19.3 µs (as measured) with 2.5 MHz of chirp has a narrower spectrum with no apparent side-lobes, with a pulse desensitisation of 5.1dB[32] the difference in the desensitisation being 18.5 dB. The receiver in this case utilises a peak power detector and records using a "peak-hold" function. Thus the peak of the short pulse would be displayed at 18.5 dB below the 0dB level referenced to the long pulse peak but is not visible because it is masked by the long pulse. At the level of the first sidelobe of the short pulse 13+18.5 = 31.5dB below the displayed peak, the two spectra have similar widths and the 1st sidelobes of the short pulse cannot be clearly distinguished. The short pulse spectrum is wider than the long pulse in the region below the first side-lobes and hence this can be clearly seen emerging from the long pulse spectrum at around the level of the second sidelobes, 16+18.5 = 34.5 dB (16 dB being the approximate level of the second short pulse sidelobes) below the composite peak. Outside this region, the sidelobe structure constitutes that of the short pulse spectrum. These lower side-lobes now consitute the "peak-hold" level and are consequently displayed by the reciever. Thus when using the peak detector, the top of the displayed spectrum is that of the long pulse, whilst at the lower levels it is the shape of the short pulse spectrum which is displayed.

The spectra for the different pulse types can also be compared on levels relative to the maximum of the spectral power density. In this case it is thus necessary to calculate the difference in the two spectral power densities (P_t)[33].

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30 Source Annex 5 of this study

31 $20\log(\tau \times 1.6 \times 125\ kHz) = -23.6\,dB$ in this case the measured K factor of the receiver is 1.6

32 $-10\log\left(\frac{Bc}{(1.6 \times 125\ kHz)^2\,\tau}\right) = -5.1\,dB$

33 When calculating power received by a victim receiver P_t is a useful parameter to consider.

The maximum spectral power density (P_t) is normally defined in dBm/kHz and is calculated from the following formula[34]:

$$P_t = P_p + 20\log(\tau) + 10\log(PRR) - PG - 90 \qquad \text{Equation 3.4.8-1}$$

Where :

P_p = *Peak power in dBm*

τ = *Pulse Length in µs*

PG = *10log(d) where d is compression ratio*

PRR = *Pulse Repetition Rate in Hz*

This expression can be rewritten in the following form:

For uncompressed pulses :

$$P_t = 10\log(P_p \times PRR \times \tau^2) = 10\log(\frac{P_m}{Bw}) \qquad \text{Equation 3.4.8-2}$$

For compressed pulses :

$$P_t = 10\log(P_p \times PRR \times \tau \times \tau_c) = 10\log(\frac{P_m}{Bw}) \qquad \text{Equation 3.4.8-3}$$

Where:

τ_c = *Compressed pulse length in μs*

P_p = *Peak Power in mW*

P_m = *Mean Power in mW*

Bw = *Bandwidth in kHz*

This however is an approximation (albeit a frequently used one), as it takes no account of the shape of the spectrum defining it in terms of bandwidth only.

For example, a rectangular spectrum should have a higher value of P_t than that of a SinX/X spectrum essentially due to the energy contained within the side-bands. Notwithstanding this caveat, it is common practice to use the formula above.

It should be noted that this comparison cannot be made between direct measured data as the receiver measures peak power for comparison purposes, the measured data would have to be corrected for the difference in the duty cycle and bandwidths before comparison.

3.4.8.5 Measurement of the Magnetron Π_{-1} Mode

One particular unwanted emission of interest is the one associated with the so-called Magnetron Π_{-1} Mode, see Figure 3.4.8-5. This mode can lead to major non-compliancies of some Magnetron systems against the current ITU OOB and SE limits. It has been argued that although it is above the limit, its ability to cause interference is limited due to the temporal nature of the signal.

The spectrum and level of the Π_{-1} mode is related to the fundamental or Π mode of the Magnetron .

The normal oscillating mode of the Magnetron is called the Π mode. In this mode each vane or cavity is in anti-phase (180°) with its neighbour, that is Π radians. The Π mode is reinforced in some systems by "strapping" alternate vanes at an equipotential. The mode

[34] NTIA Document Radio Spectrum Engineering Criteria Chapter 5 Section 4.1

number η associated with the Π mode depends on the number of cavities in the magnetron. However other modes are possible within the cavity and can occur depending on variations in the modulator drive.

The mode with a mode number of η-1 (called the Π_{-1} mode), is an asymmetrical mode and hence cannot be maintained in a symmetrical structure, but can be present for short times particularly under certain drive conditions.

The mode number of the Π_{-1} is less than that of the Π mode so it would be expected that the lower mode number would result in a resonant frequency lower than that of the Π mode. The Π_{-1} mode however is seen at a frequency higher than the fundamental. This is because of the capacitive effect of the strapping of the vanes. The effect of the capacitance depends on the mode number and de-tunes the Π mode by more than the Π_{-1} mode resulting in the Π_{-1} mode resonance being at a higher frequency than the Π mode.

The mode can occur for short times during the rise and fall of the drive pulse or be present at low levels throughout the main pulse. Magnetrons can also miss pulses and it is possible that during these missed pulses only the Π_{-1} mode may be present. This gives rise to several issues:

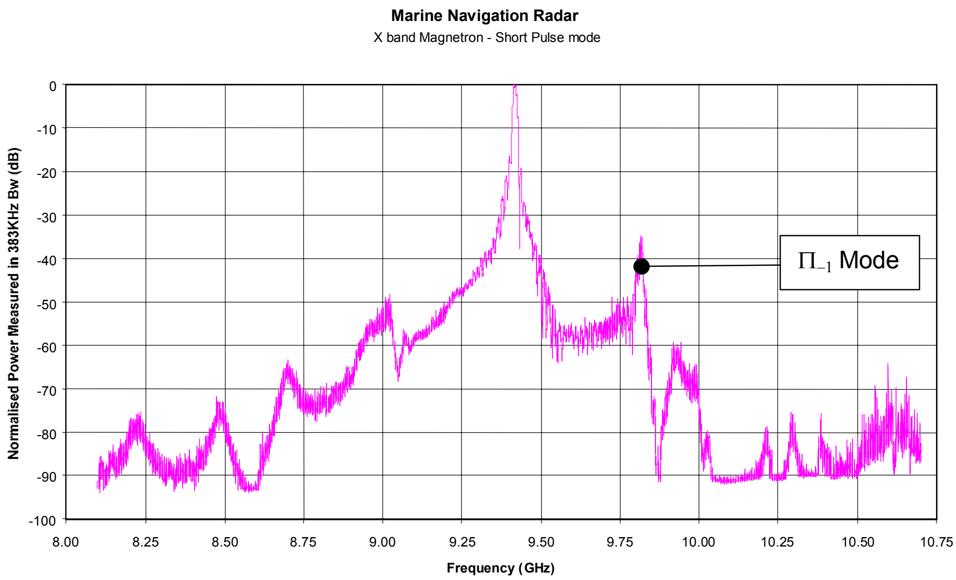
- What resolution bandwidth should be used to measure emissions from this mode, especially if the resonance occurs within the OOB region ?
- How long should the measurement interval be in order to confirm the existence of this mode ?

If the Π_{-1} mode is short lived, then a wide bandwidth filter will be needed so as not to be desensitised.

The only approach that can be taken to investigate the Π_{-1} mode is to use various resolution bandwidths to investigate the rate of change between the emission being investigated and the peak of the fundamental. The problem might be that if the pulse is very narrow, the receiver may not have an adequate resolution bandwidth to fully investigate the phenomena and the peak of the Π_{-1} emission may never reach a limit condition with the changing bandwidth and hence an accurate measurement of the level may not be possible.

The measurement interval should, strictly speaking, be long enough to capture a missed pulse however in practice the total energy in any Π_{-1} mode associated with a missed pulse will be extremely small. Thus in practice the measurement interval associated with the SE measurement (i.e. the order of 1s or greater) should be more than adequate to measure the Π_{-1} emission.

Figure 3.4.8-5[35] Π_{-1} mode emission



3.4.8.6 Low Frequency Radars

In the current proposed update of ITU-R Recommendation M.1177-2, contained in draft document 8B/184-E there is an Annex 2. This annex is related to a version of the direct method for measuring low frequency radar, in particular HF and VHF radars.

The resolution bandwidths specified are an order of magnitude lower than those recommended in Annex 1 of the document 8B/184-E. As the bandwidths are related to the parameters of the pulse they should be made equal to those specified in Annex 1. This of course is subject to the ability, if required, to use narrower bandwidths in the OOB region.

[35] Source this study

3.4.9 Application of findings of the study to ITU-R Recommendation M.1177-2

The following comments relate to the three methods described in ITU-R Recommendation M.1177-2 and relate to issues of resolution bandwidth, step size and measurement time. They are essentially related to the receiver and apply equally to direct and indirect measurements.

3.4.9.1 Appropriate Measurement Bandwidth for ITU-R Recommendation M.1177-2

ITU-R Recommendation M.1177-2 is entitled "TECHNIQUES FOR MEASUREMENT OF UNWANTED EMISSIONS OF RADAR SYSTEMS". It thus covers measurements of both the OOB and SE domains. This document is being reviewed and the proposed revisions are contained at Attachment 8 to 8B/184-E "Preliminary Draft Revision of Recommendation ITU-R M.1177".

The document recommends the measurement bandwidths that should be used in Annex 1. It recommends the use of $0.5/\tau$ for an un-coded pulse and $0.5*\mathrm{sqrt}(B/\tau)$ for a chirped pulse both the abbreviations B and Bc are used in this document to denote the chirp bandwidth. When considering the required resolution bandwidth to be used it is necessary to decide whether Spurious Emissions or Out-of-Band Emissions are being measured and whether the pulse is chirped or not.

The measurement of OOB emissions is required to demonstrate that the spectrum falls below the defined spectral mask. For radars operating in "radar only" bands, this spectral mask only strictly applies at the band edge.

For the measurement of SE it is required to measure the PEP of emissions relative to the PEP of the fundamental frequency.

The following sections address ITU-R Recommendation M.1177-2 in the light of the theoretical and practical results presented in the study.

3.4.9.1.1 Recommendations on Out of Band Emissions of non-chirped pulses

The measurement of OOB emissions is essentially the measurement of the shape of the spectrum. Strictly speaking the recommended limit applies between the -40 and the -60 dB points relative to the peak spectral power density measured in dB_{pp}.

In ITU-R Recommendation M.1177-2 it is not explicitly stated which method (Fourier Spectrum or Pulsed Spectrum) is being employed. The resolution bandwidths being quoted however imply that it is the pulse spectrum, as do the limits described in ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain" and ITU-R Recommendation SM.329-9 "Spurious emissions".

Currently only one bandwidth is recommended, that being optimized for the measurement of SE, and no consideration is given to the fact that there are essential differences between the measurement of SE and OOB domains.

With a rectangular pulse the recommended B_{res} for SE is $1/\tau$. This would be approximately 33% of the main-lobe width and does not fulfil the criteria for resolving the spectrum envelope i.e. a B_{res} of less than 5% ($0.1/\tau$) of the main-lobe width. The use of a $1/\tau$ B_{res} bandwidth will result in an approximate 3 dB error in the measured shape of the envelope of the spectrum over the -40 to -60dB region. The experimental work has also shown that to accurately resolve the shape of the spectrum envelope within the OOB region, a resolution bandwidth B_{res} filter of $0.2/\tau$ is needed and is recommended.

For pulses with slower rise times than rectangular, using a B_{res} equal to $1/\tau$ in the OOB domain makes the results worse. Such pulses have significantly reduced spectral width compared to the rectangular case and are subject to more error if a B_{res} of $1/\tau$ is used as the measuring filter is wider in relative terms compared to the spectrum being measured . This difference comes about because for non-rectangular pulses $\tau \neq \tau_{eff}$.

Take for example a τ equal to a 1μs wide pulse with τ_r equal to 200 ns rise and fall times. Comparing the 20dB envelope points, (necessary bandwidth), this gives a theoretical 20 dB bandwidth of approximately $1.79/sqrt(\tau*\tau_r)$ = 4 MHz, compared to a bandwidth of 6.4 MHz for the rectangular pulse.

The initial measurement of the OOB domain should be made using the same resolution bandwidth as for the SE domain. If it is necessary to achieve the truer representation of the OOB region then the recommendation for the current update of ITU-R Recommendation M.1177-2 is to use 0.2/τ as the resolution bandwidth. However for pulses with very slow rise times it may be necessary to reduce the resolution bandwidth to B_{res}= 0.1/τ. .

The appropriate value however can be determined in practice by measuring the OOB region with differing bandwidths and determining at what point the shape of the spectrum stops changing.

3.4.9.1.2 Recommendations on Out-of-Band Emissions of Chirped Pulses

The recommended B_{res} for swept frequency (FM or Chirp) is given in ITU Working Group 8B document 184-E as "Bw = 0.5*sqrt(Bc/τ)", where Bc is the chirp bandwidth[36].

Thus for example, a radar with say 5 MHz of chirp, a 10 μs pulse width and 0.1μs rise time, would have a specified resolution bandwidth of approximately 353 kHz, compared with a NB of $2*Bc+1.79/sqrt(\tau*\tau_r)$ = 11.8 MHz.

This would give a ratio of the resolution bandwidth (B_{res}) to NB of 11.8 MHz/353 kHz = 33.

If the pulse length were 100μs instead of 10μs, this would reduce B_{res} to 112 kHz for a necessary bandwidth of 10.6 MHz, giving a ratio of 95.

This formula for B_{res} gives the minimum bandwidth that can be used to measure the PEP of a chirped pulse with no desensitisation. The use of this bandwidth to resolve the shape of a chirped spectrum initially seems inappropriate as increasing the time bandwidth product makes the spectrum more "rectangular". In chirped pulses with Bc fixed, the spectrum shape and hence the Bw_{-20dB} tends towards a constant value (approx. Bc) as the pulse length increases. The B_{res} should reflect this by itself tending to a constant value. However in the formula, increasing the time bandwidth product leads to a narrower and narrower B_{res} bandwidth. This approach would lead in the end to an ever increasing number of sample points being used hence extending the measurement time.

To illustrate the point Figure 3.4.9-1 and Figure 3.4.9-2 below show the spectra for a 100 μs and a 40 μs pulse both with 5 MHz chirp. If the 20 dB widths are considered, then for the 40 μs pulse the 20 dB width is 6 MHz, for the 100 μs pulse the 20 dB width is less than 6 MHz. As the time bandwidth product increases further, the 20 dB width tends towards 5 MHz (i.e. the value of the chirp Bc). Thus the spectrum gets more "rectangular" as the time bandwidth constant increases.

[36] Please note in the early versions and proposed revisions of ITU-R Recommendation M.1177 the distinction between measurement and resolution bandwidth was not made. Later revisions developed and proposed in August/September 2002 have made this distinction.

Figure 3.4.9-1 Calculated spectra 100 µs Pulse with 5 MHz Chirp

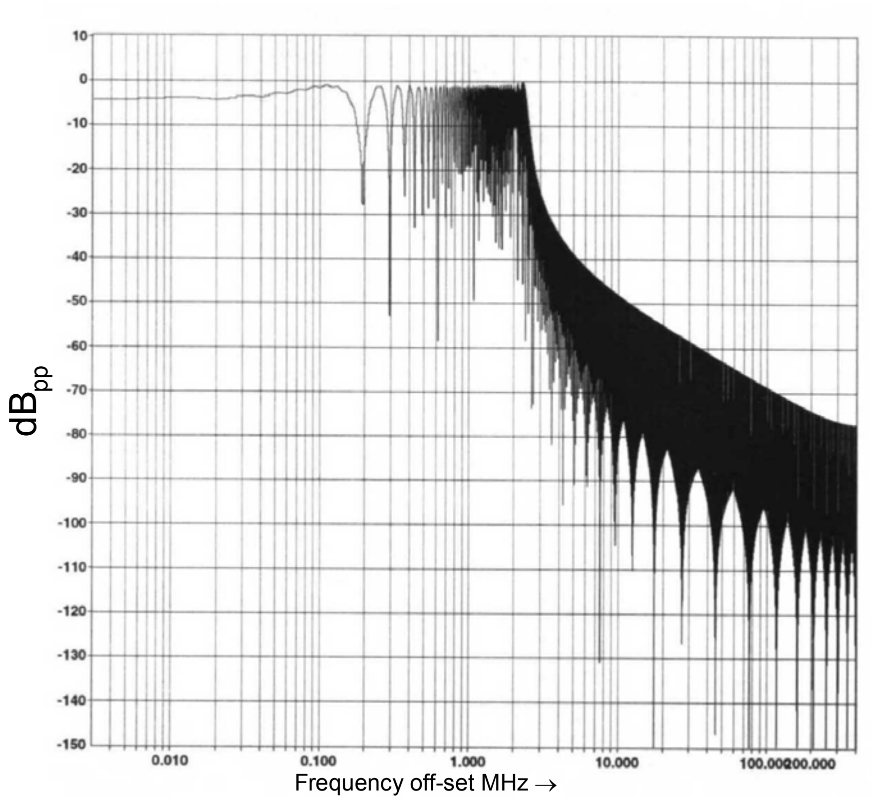
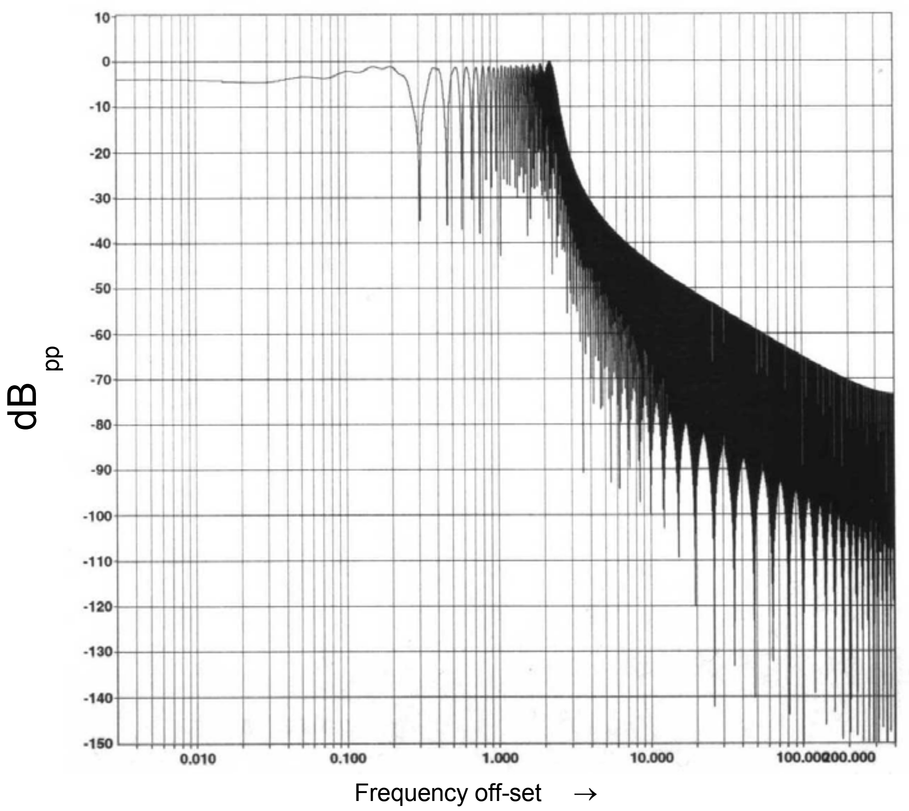


Figure 3.4.9-2 Calculated spectra 40 µs Pulse with 5 MHz Chirp



In this study however, it has been determined by analysing measured and calculated spectra that an appropriate B_{res} figure to use to measure chirped waveforms is 0.1 x Bc. In the case being illustrated this would result in a B_{res} of 500 kHz. Table 3.4.9-1 shows a comparison of the current ITU Working Group 8B document 184-E recommendation against the simple 0.1 x Bc rule for Bc= 5 MHz of chirp.

Table 3.4.9-1 Comparison of recommendations - Chirp 5 MHz

Chirp	Pulse Length	Bw (8B/184)	Bw (0.1Bc)
MHz	**Micro Sec**	**MHz**	**MHz**
5	10	0.354	0.500
5	20	0.250	0.500
5	40	0.177	0.500
5	50	0.158	0.500
5	100	0.112	0.500
5	200	0.079	0.500
5	300	0.065	0.500

This shows that in all cases the 0.1 x Bc resolution bandwidth is greater than that proposed in the latest revision.

Table 3.4.9-2 shows a comparison of the recommendations for Bc = 1MHz of chirp. At low time bandwidth products, 0.1 x Bc is less than the current recommendation. It can be seen that the cross over is at a time bandwidth product of approximately 30.

Table 3.4.9-2 Comparison of recommendations - Chirp 1 MHz

Chirp	Pulse Length	Bw (8B/184)	Bw (0.1Bc)	The greater Bw
MHz	**Micro Sec**	**MHz**	**MHz**	**MHz**
1	10	0.158	0.100	0.158
1	20	0.112	0.100	0.112
1	40	0.079	0.100	0.100
1	50	0.071	0.100	0.100
1	100	0.050	0.100	0.100
1	200	0.035	0.100	0.100
1	300	0.029	0.100	0.100

A pragmatic solution would be to calculate both resolution bandwidths and use the larger value. In practice this would mean using the 0.1 x Bc for time bandwidth products greater than approximately 30. There are however reasons why measuring in a bandwidth between the two might give an advantage.

The recommendation is thus:

If 0.1Bc is greater than 0.5*sqrt(Bc/τ) then a resolution bandwidth between the two values should be used.

If 0.1Bc is less than 0.5*sqrt(Bc/τ) then a resolution bandwidth of 0.1Bc should be used.

If however it is required for other practical reasons, then carrying out measurements using a bandwidth of less than that recommended is acceptable[37] subject to the requirements of dynamic range.

3.4.9.1.3 Recommendations on Spurious Emissions of Non-Chirped Pulses

In order to measure spurious emissions, it is necessary to use a bandwidth that is capable of capturing the PEP, i.e. the majority of power at the fundamental and the SE frequencies. This requires a resolution bandwidth B_{res} of 1/τ or greater. If bandwidths of less than 1/τ are used due to measurement equipment limitations, then the results will require correction for pulse desensitisation.

The recommendation for measurements of the SE domain and initial OOB domain measurements is a 1/τ resolution bandwidth.

3.4.9.1.4 Spurious Emissions of Chirped Pulses

In order to make SE measurements it is necessary to make an accurate measurement of PEP. Experience shows that the minimum resolution bandwidth required to measure the PEP of a chirped pulse with no loss is[38];

$$B_{res} = \sqrt{(Bc/\tau)}$$ Equation 3.4.9-1

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[37] In discussions with those who regularly make the measurement this issue does not seem as yet to have been recognised as an issue for great importance probably because radars measured to date have had only moderate time bandwidth products. The issue may achieve grater prominence as new radars using very long compressed pulses come on line.

[38] Attachment 8 to ITU Working Group 8B document 184-E "Preliminary Draft Revision of Recommendation ITU-R M.1177. Appendix 1 to Annex 1".

If B_{res} is made equal to the chirp, *Bc,* then this equation reduces to:

$$Bc^2 = \frac{Bc}{\tau}$$ Equation 3.4.9-2

$$1 = Bc \times \tau$$ Equation 3.4.9-3

Thus the criteria is fulfilled if the "time x bandwidth" product is greater than or equal to 1 or that the compression ratio is greater than 1. This criterion is always fulfilled in pulse compression radars by definition. Thus using a resolution bandwidth equal to the chirp will always result in an accurate measurement of PEP.

Practical measurements made in this study suggested that a resolution bandwidth between 0.5 & 1 times the chirp gives acceptable results for measurements of PEP when the time bandwidth product is much larger than 1.

Using a resolution bandwidth equal to the chirp will, however, result in a resolution bandwidth that is much wider than the reference bandwidth in which the SE levels are defined and will require corrections to the measured data to be applied over the full SE domain. The use of such a B_{res} could also lead to problems with measurement dynamic range, particularly if there are noise-like areas in the spectrum.

The larger the time bandwidth product, the larger is the discrepancy between the resolution bandwidth and the specified reference bandwidth if B_{res} = Bc.

The advantage however in using this wider bandwidth is that it results in a much reduced number of steps compared with those calculated from the minimum theoretical values. The latest proposed revision of ITU-R Recommendation M.1177-2 (8B/184-E) recommends the use of a measurement bandwidth RBw:

$$RBw = 0.5 \times \sqrt{(Bc / \tau)}$$ Equation 3.4.9-4

which is half the minimum value and results in twice the number of measurement steps and will give rise to an error in measuring PEP.

It is recommended that for future revisions of ITU-R Recommendation M.1177 that a bandwidth of:

$$B_{res} = \sqrt{(Bc / \tau)}$$ **Equation 3.4.9-5**

is used for chirped radars.

This will still result in more steps than that result from using B_{res} = Bc, but discussions with those making or commissioning the measurements have not raised this as an issue. This is because the measurement times are dominated by the setting to work and not the step size. In addition the use of a resolution bandwidth equal to the reference bandwidth will result in no post measurement corrections being required.

If the B_{res} used to measure the SE domain is less than 0.1 Bc, and the same bandwidth is used to measure the OOB domain, this will result in a continuous limit mask at the SE/OOB boundary and give an accurate representation of emissions in both domains.

3.4.9.2 Total Measurement Times

In a previous section the measurement times encountered in the study campaign were reported, this section discusses the general case and recommends a strategy to minimise the measurement time.

3.4.9.2.1 Direct Method

The measurement time is a combination of the frequency range being covered, the time to make an individual measurement and the step size being used.

Generally the requirement is to measure from about 10% below the radar carrier frequency up to the 5th harmonic or about 26 GHz whichever is the lower. Taking for example C-Band radars operating at just above 5 GHz, this would result in a required scan region of 4.5 to 25 GHz, a total of 21.5 GHz.

The time taken to make the measurement depends on the rotation rate of the radar antenna. The automatic method, in theory, should be capable of making a measurement in the order of one scan period. The swept method may take up to three scan periods, due to the un-synchronised nature of the analyser sweep to the rotation of the radar. It should be remembered however that the swept measurement cannot generally achieve the ultimate dynamic range of the stepped automatic method. In some electronically scanning radars however it may take longer than one azimuth scan period depending on the time needed for the radar to perform all its tasks and for the measurement system to capture the worst case.

The step size used depends on the method used. In the automatic method the step size is recommended to be equal to the half resolution bandwidth. The work carried out in this study shows that in order to accurately characterise the PEP at the fundamental frequency, the reference level for SE measurements, these should be made in a step size of 0.5 x resolution bandwidth in order not to miss the peak. In the manual swept method it is the analyser frequency scan width which constitutes the step size. In practice in order to expedite the measurements efficiently, it is necessary to decide what step size is required over which frequency range(s). Narrow steps may be required for characterising the fundamental frequency OOB region. Wider steps for surveying and finding the harmonic frequencies of interest (and for eliminating interference). This may then be followed by selective narrower band scans of harmonic radiation if required.

Thus, depending on what the measurement set up is and the radar that is being measured, measurement times in excess of many hours may be required. As an example, consider the C-Band radar described above. To carry out a high dynamic range stepped measurement using a 500 kHz resolution bandwidth ($1/\tau$ where τ = 2μs) and a step size of $0.5/\tau$ 250 KHz over 21.5 GHz with a measurement time of of say 2 seconds per step would take 24 hours. Section 3.4.7 (Table 3.4.7-1) reported on a measurement time of 22 hours for an S-Band ATC radar.

In practice however, these numbers are to some extent of limited use, apart from indicating that the measurement time is not short, since the measurement time is made up of many other factors. Examples of these are setting to work, site surveys, number of radar modes being measured, local interference conditions and how much control over the radar can be exercised. Obviously much of this time can be saved if measurements are made at a dedicated site where electromagnetic conditions are better controlled.

The following method is proposed in order to minimise the measurement time.

- **Carry out a wide band site survey to ascertain the electromagnetic conditions. If possible this should be carried out with the radar to be tested turned off. This minimises the time required to eliminate any signals not emanating from the system under test. This survey should be carried out with a step size equal to the resolution bandwidth.**
- **Carry out a measurement over the full UE domain using a resolution bandwidth (B_{res}) as previously recommended and a step size of 0.5 B_{res}.**
- **Identify any SEs that need investigation and re-measure, if needed, with improved accuracy taking into account issues such as pulse desensitisation, noise floor etc.**
- **If necessary, measure the OOB region with a narrower resolution bandwidth suitable to resolve the shape of the spectrum to the fidelity required.**

Based on experience, Table 3.4.9-3 shows the estimated overall measurement times for several types of radar.

Table 3.4.9-3 Estimated Measurement Times[39]

Measurement Time Days		
Type	**In-situ**	**On Range**
ATC 2D	3	n/a
Civil Marine	2	1
Air Defence 3D	4	n/a
VTS	3	1
Airborne Weather	n/a	1
PAR	2	n/a
Ground weather	2	n/a
ASDE	2	1

3.4.9.2.2 Indirect Method

The indirect method does not use a rotating antenna, hence the measurement time of the transmitted signal will only be limited by the stepping rate and the number of steps required.

The antenna gain characterisation at each of the frequencies identified could be a long process, possibly taking many minutes at a time to align the antenna and make the measurement. It would thus seem inappropriate to use this method to attempt to characterise in detail the OOB emissions or the spectral shape of any SE radiation that requires fine frequency steps.

[39] Does not include travelling time to site.

3.4.10 Specific Comments on the Indirect Method

The indirect method described in ITU-R Recommendation M.1177-2 has several practical limitations which make its use limited to very few radar types. In addition, the document does not provide a detailed budget for measurement uncertainties, so it is not possible to verify the claims for the accuracy made for the method as described.

However the following practical limitations do exist with the method:

- It requires the antenna to be detached from the radar and placed on the near-field range to have its gain characterised. This may not be appropriate for large antennas or antennas where the transmitting and radiating function are combined, such as in active antennas.
- It requires the use of a special absorptive filter to attenuate the fundamental and allow the spurious emission to pass through. Such a filter is not practical for use with high power radars.
- The method also makes the tacit assumption that the antenna gain figure can be added to the measured transmitter power level to ascertain the EIRP over all the SE domain. It assumes no interaction between the antenna and feed and the transmitter. This may be true in the OOB domain but is much more uncertain in the SE domain particularly at harmonically related frequencies.

ITU-R Recommendation M.1177-2 documents the two sources of uncertainty in the measurements as:

- Near-field gain measurement uncertainty with the applied correction factors;
- Measurement uncertainty in a waveguide.

The following sources of error over and above the errors associated with the measurement uncertainties described above have been identified. These issues do not seem to have been addressed in ITU-R Recommendation M.1177-2 or its proposed revision. These comments pertain to the use of the method to measure emissions in both the OOB and SE domains including harmonic emissions:

- The use of a special filter and a matched receiver will provide essentially a matched load at the harmonic frequencies. In practice the transmitter will see a mismatched antenna and feeder system at the harmonic frequency. The level of the harmonic power produced will thus vary with the amplitude and phase of this miss-match. As well as affecting the level of harmonic power generated, the amount of power coupled to the antenna will also vary. This poor antenna match will also affect the accuracy of the power measurement depending on the directivity of the measurement coupler. These effects need consideration when calculating the error of the far-field power. Allowance needs to be made for the change in power and miss-match loss. It is not possible to calculate these changes for a general system as they depend totally on the layout of the microwave components and the sensitivity of the individual transmitter types to miss-matches in the OOB and SE domains. Experience has shown that changes resulting from these effects could be of the order of 10dB at harmonic frequencies.
- The gain of the antenna at the harmonic frequencies and the position of any harmonic beam formed will depend on the mix of modes excited in the feed systems and radiators, especially in feed systems that comprise waveguides. The mode mix at the harmonic frequencies will depend on the type and position of all the feed components. ITU-R Recommendation M.1177-2 makes light of this effect speculating that the higher order modes will be trapped in coaxial to waveguide transitions. Whilst it is true that if these components are present within the feed they can act as mode filters, they

however can also generate higher order modes themselves depending on the plane of symmetry within the transition, also not all radar feed systems have such a transition or use coaxial cable. Thus the Equivalent Isotropically Radiated Power (EIRP) of the harmonic beam will depend on the exact arrangement of the feed. This effect is not replicated in the direct method and will add further errors.

- The equation used to calculate the "near-field" transmit antenna gain is based on the FRIIS transmission equation. This equation is only valid for antennas spaced at a distance greater than $2D^2/\lambda$ where D is the largest dimension of the two antennas. A further term to correct for the gain of the probe antenna is thus required. The lower the gain of the receiving antenna the less this effect will be, as the far-field distance for an antenna increases with the gain of the antenna. The probe antenna will also suppress energy from off axis due to its gain pattern shape; any transform needs to include this "probe correction" factor.

- The near-field to far-field gain transformation assumes uniform illumination. This will be in error when antennas with significant edge tapers are measured. The transform described is a single point near to far-field transform, the accuracy of which is unproven. Particularly for large antennas, the near-field is complex and must be sampled over the full extent of the aperture, azimuth and elevation, in order to get a good estimate of the far-field gain by the use of a transform. Errors relating to the transform should be included. It is not possible to calculate the error in the transform without detailed knowledge of the antenna under test.

- A further issue is that of antenna to antenna interaction. It is also possible to set up a standing wave between the antenna under test and the probe antenna; this effect can result in fluctuation in the received power in the boresight as a function of range. The effect can be checked by moving the probe antenna towards and away from the antenna under test and observing any variations or ripples.

- Harmonic radiation may not be radiated coincident with the fundamental frequency, so the effective aperture at these frequencies will not be the same as at the fundamental. Harmonic radiation can also radiate in more than one beam simultaneously due to the wide spacing of the array elements at harmonic frequencies. If there are higher order modes in the waveguide feed, then harmonic radiation can be radiated out of the horizontal plane. This all means that at harmonic frequencies the effective aperture can depart significantly from the physical aperture used. Thus the aperture used in the transform from the near to far-field will be in error.

- Harmonic radiation is likely to occur in significant amounts in a form cross-polarised to the fundamental frequency radiation. The method needs to look for the position of any cross-polar beams to ascertain the peak in terms of co-polarised radiation.

- The arrangement shown in ITU-R Recommendation M.1177-2 gives a depression angle of approximately 18° to the ground plane. The effect of multi-path needs to be considered. The effect the multi-path will have depends on the elevation beamwidth of the Tx and Rx antennas and the reflectivity of the ground plane. Small antennas designed for use on un-stabilised marine platforms have wide elevation beamwidths (25 to 30°); methods need to be employed to reduce the effect of multi-path. The use of a ground plane only enhances the problem. The practice of adjusting the test antenna height prior to measurements would tend to maximise the multi-path error. An attempt should be made to attenuate the multi-path and confirm this by ensuring that the received signal is essentially multi-path free. This can be carried out by using the measurement antenna to sample the received power in the elevation plane by moving it up and down. The variation in this plane can then be reduced by the application of absorptive material to the ground between the antennas. The use of a high gain receive antenna will reduce the ripple by suppressing the reception of the multipath signal but will increase the errors associated with the gain measurement.

3.4.11 Specific Comments on Direct Method

The following areas need consideration when using the direct method. If not controlled they can detract from the efficacy of the method and lead to an increase in errors.

- The receiver antenna needs to be situated such as to be able to receive sufficient power so as to allow the full potential dynamic of the receiver systems range to be achieved.
- Elevation multi-path effects can be minimised by using a highly directive receive antenna. Careful positioning of the measurement antenna can also be used to minimise any azimuth multi-path taking into account reflections from buildings etc.
- Weather can also effect the measurement. Atmospheric absorption except in extreme precipitation conditions is highly unlikely to have a significant effect on the measurement, however water condensing on the measurement antenna, particularly on the windows of feed horns, could have an effect at frequencies above X band.
- Strong winds could effect the stability of the measurement particularly if high gain antennas are being used. In certain conditions scintillation due to hot weather may also be seen causing the results to fluctuate. These types of weather affects can only be managed on a day to day basis. It is necessary for those making the measurement to satisfy themselves that the weather conditions are within acceptable bounds.
- One error that can be present with the direct method is caused by the modulation of the radar beam being measured with frequency. If the measuring antenna is not aligned with the peak of the radar beam in the elevation plane, then the coupling between the two antennas will vary as the radar beam narrows as the frequency increases. The attenuation will increase as the receive antenna "runs down the side of the radar beam" that couples energy from further and further away from the peak of the transmitting beam. The received amplitude will thus vary as the beamwidth changes. The measuring antenna thus needs to be positioned as close to the peak of the transmitting antenna beam as possible in the elevation plane.
- At harmonic frequencies, the peak of the SE beam (or beams), produced may not occur in the same elevation plane as that of the fundamental signal, The position of the harmonic beam is a function of the detailed construction of the antenna.

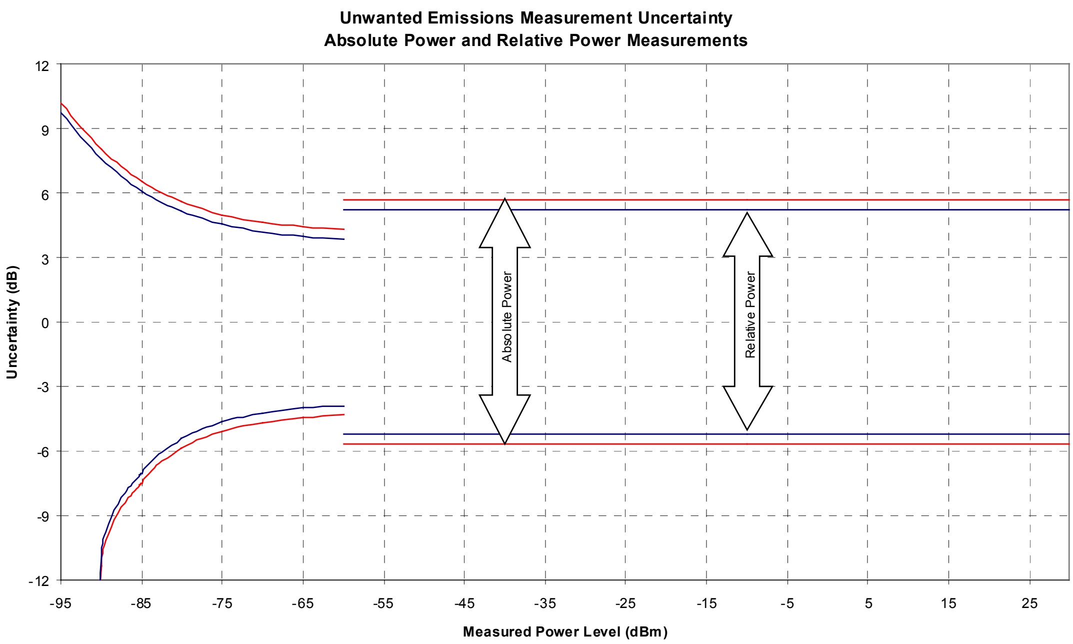
3.4.12 Accuracy of the Measurements

3.4.12.1 Direct Method

ITU-R Recommendation M.1177-2 states "Experience with these techniques has yielded repeatability of ±2 dB at any given frequency and under the condition of agreed fixed measurement parameters when the spectrum of any particular radar unit is repeatedly measured". This is a statement of repeatability, not accuracy. If measurements are to be made for comparison with specified limits or between systems then it is required to provide an error budget for the system.

Section 3.1.3 of this report gives an estimate of the errors that can be achieved when using the direct method. This is shown graphically in Figure 3.4.12-1 below.

Figure 3.4.12-1 Measurement Uncertainty Direct Methods



The majority of the errors are dominated by the errors in the receiver.

3.4.12.2 Indirect Method

There has been no published error budget for the indirect method, however two figures are quoted in ITU-R Recommendation M.1177-2:

"Near field gain measurement uncertainty with the applied correction factors

The worst-case measurement uncertainty can be calculated to be ±6 dB, which includes, uncertainties due to a spectrum analyser, test horn gain, cable loss and source and site imperfection. Total uncertainties with a confidence level of not less than 95% can be calculated to be ±4.2 dB.

The derivation of the correction factors for these distances assumes the AUT radiating aperture to be constant at all frequencies."

"Measurement uncertainty in a waveguide

The system has a measurement accuracy of ±1.3 dB across the frequency band 2 to 18.4 GHz for the waveguide port. Total uncertainties with a confidence level of not less *than 95% can be calculated to be ±3.4 dB for the waveguide port including the spectrum analyser."*

If we take the Root of the Sum of the Squares (RSS) of the two 95% figures quoted 4.2 and 3.4 dB we achieve ±5.4dB, however unpublished sources indicate that in practice the errors using this method could be as large as 20 to 30 dB.

Considering each of these uncertainly statements in turn:

3.4.12.2.1 Measurement uncertainty in a waveguide

The errors come from several sources:

- Receiver Errors
- Component losses
- Miss-match Errors[40]

These issues do not seem to have been fully addressed in the published uncertainties as the uncertainties attributed to the waveguide set-up are quite small, however no full breakdown is given. This measurement as defined in ITU-R Recommendation M.1177-2 requires a measurement of absolute power of UEs. In order to ascertain the level relative to the PEP, as required by the Radio Regulations, either the power of the transmitter has to be measured directly or the loss of the system has to be characterised at the fundamental frequency for the reference level to be obtained. The level of the UEs relative to the fundamental or an absolute reference, cannot be obtained in one measurement due to the set-up being used..

This will require a further measurement, which itself will have similar errors to the first. In order to avoid having to measure the PEP directly, (which would involve the use of high power attenuators) it would be better to characterise the loss of the system to the fundamental frequency (including the notch filter) at low power. This measurement will have a similar set of uncertainties to that of the first measurement made of the level of the UEs. This extra level of uncertainty will need to be added to the overall uncertainty figure.

It is also unclear in the method as presented how the systems losses at harmonic frequency are accounted for, as it is not possible to simply calibrate out the losses given the fact that the input and output waveguide are of a different size, extra tapers would be required to do this. Alternatively each component could be measured separately and the results added, but then their individual miss-match errors would need to be allowed for in the overall uncertainty.

3.4.12.2.2 Near-field gain measurement uncertainty with the applied correction factors

Errors associated with the characterisation of antenna result from:

- Gain transform errors
- Multi-path errors
- Polarisation errors
- Beam pointing errors
- Power Measurement Errors[41]

ITU-R Recommendation M.1177-2 gives an uncertainty of ± 6 dB max or ± 4.2 dB @ 95% for the gain correction factor, and again no breakdown is given of the constituent parts. In particular it is not clear what errors have been associated with the near to far-field transform, which is known to be a gross over-simplification.

[40] Resulting from the variation in measured signal due to the return loss of the measurement systems.

[41] This is the power measurement made to allow the uncorrected antenna gain to be determined.

The uncertainty will be dominated by the errors associated with the characterisation of the antenna, in particular the determination of the antenna gain.

The receiver errors associated with the "Power Measurement" needed to calculate the gain prior to correction are similar to those achieved by using the direct method, or by the UE power measurement in the first part of the indirect method. These are quoted at 95% value of ± 3.5 dB. If the overall result of ± 4.2 dB is assumed to be an RSS of the uncertainty obtained from the power measurement, i.e. ± 3.5 dB, plus that obtained from the transform and the other errors quoted, then this results in an uncertainty value of ±1.4 dB[42] to cover for the transform and the other errors quoted. This figure of ± 1.4 dB seems low when all the simplifications and limitations of the transform are considered. This would seem to indicate that the quoted maximum value of ± 6 dB is an underestimate of the uncertainties involved in this measurement.

When considering these errors, it must not be forgotten that there are still the interaction uncertainties associated with the good match seen by the transmitter by the use of the "special" filter and the effect of the feed components at harmonic frequencies.

If the error in the gain measurements could be reduced, then the overall uncertainty would be reduced. In order to fully characterise the test antenna, and to overcome the limitations described, a wide angle characterisation of the antenna pattern over the required frequency range is needed. Figure 3.4.12-2 shows a facility capable of making such a measurement. The operation of this facility is described in paper "High-precision outdoor cylindrical near-field antenna test facility"[43]. The use of such a facility should be referred to in the upgrade of ITU-R Recommendation M.1177-2

This is not the only facility in the UK that could produce the type of results required. There are several others based on cylindrical or spherical scanners, including some indoor based facilities.

Such facilities can achieve an absolute characterisation of the transmitting antenna main beam gain of ±0.5 dB and on a -50 dB side-lobe of ± 3 dB. Measurements of this accuracy would significantly reduce the estimated uncertainty in the indirect method.

Whilst such facilities are automatic, considerable time would still be required to characterise the antenna over the very wide frequency band required.

Given that such an approach is adopted, to reduce the measurement uncertainties associated with the measurement of the gain, then there are still unknowns that are not accounted for in the use of the indirect method. Such errors are related to the interactions between the antenna and the transmitter, which are highly dependent on the feed arrangement, particularly if the feed is implemented using waveguide. Coaxial feeds are more predictable if the coaxial line can be constrained to a Transverse ElectroMagnetic wave (TEM) mode.

[42] In linear units of power

$$2.6 = \sqrt{\left(x^2 + \left(10 ^ \left(\frac{3.5}{10} \right) \right)^2 \right)}$$

where x is the uncertainty of the transform.

Solving for x in dB gives x = 1.5 dB

[43] Electronics & Communication Engineering Journal, June 1995, J.R.Holloway & A.H.I M^c^Cormick

Figure 3.4.12-2 High-precision Cylindrical Near-field Test Facility

The cylindrical near-field test facility at Cowes, Isle of Wight

3.4.13 Comparison of Direct and Indirect Methods

ITU-R Recommendation M.1177-2 does not recommend any single method of those described. In order to compare the methods it is necessary to understand the requirements of the measurement compared to the measurement accuracy that can be achieved.

ITU-R Recommendation M.1177-2 is referenced as the method of choice in other ITU documents dealing with issues such as radar OOB or SE limits. It is likely that ITU-R Recommendation M.1177-2 would be required to be used as the basis of a type approval exercise. It is also likely to be used for monitoring in-service performance, wideband spectrum surveys, interference investigation and conflict resolution.

It is thus necessary to use methods that are accurate, repeatable and practical; the direct methods seem to meet these requirements subject to the ability to achieve the required dynamic range[44]. Problems with dynamic range, resulting from a lack of received signal, are however generally clearly apparent to the operator as the measurements are being taken, as the received signal is seen approaching the system noise and measures can be taken to rectify the problem if it occurs.

Neither method described in ITU-R Recommendation M-1177-2 specifies what receive polarisation is to be used. For measurements at and around the fundamental frequency, the polarisation should be matched to the radar polarisation. At harmonic frequencies, it may be required to measure in two orthogonal polarisations. Alternatively, if the source is linearly polarised, a circular polarised receive antenna could be used, noting that this will introduce a loss of 3 dB to any form of linear polarisation.

The indirect method as described however has severe limitations with keeping the measurement uncertainties to an acceptable level, because of both its practical limitations and its measurement accuracy. It is of limited use, given that it can only be used on a specific test site and that it can only be used for certain types of radars. An improved indirect method is available with the use of more accurate near-field systems, however the time and complexity increase significantly.

Even if the method was to be improved by using a more accurate method of measuring the antenna gain. It is unlikely, that the measurement time and cost would be reduced to below that of the direct method. This is true for both direct measurements made either on a dedicated range or in-situ.

The indirect method does however have two advantages over the direct method:

- The measurement of the transmitter is made in a "closed" environment and is not subject to interference.
- If the improved near-field measurement is made, then this can potentially give a full hemispherical polarimetric characterisation of the antenna over all frequencies.

It may be that its use should be restricted only to a "type approval" method for small civil marine radars. It may have some applicability as a "transfer" method where, with the use of a well characterised test antenna, results can be compared with those taken using the direct method. This could allow variants of transmitters to be tested without recourse to the direct method. In this case it is repeatability more than its absolute accuracy that may be more important for comparative testing. It needs, however, to be established that users who elect to use the direct method for type approval are not disadvantaged compared to those who adopt the indirect method. If this cannot be established then the indirect method should not be used.

[44] Dynamic Range is a function of the receive antenna being used and the distance from the radar. In service measurements will always be subject to the ability to find a suitable site for locating the receiver antenna.

The direct method has been shown to give acceptable results when used both on a dedicated test range and on fielded antennas. The method does however have limitations:

- The measurements can only be made in planes close to the horizontal.
- Where there are many sources of interference at the measurement site, considerable time is needed to eliminate them from the measurement. It may be that interference precludes the carrying out of type approval measurements in-situ. Type approval may have to be carried out either on dedicated test sites or, for larger antennas, at a manufacturer's trials site.

3.4.14 Methods to improve the direct and indirect method

3.4.14.1 Near-Field Direct Method

The direct method could be improved by carrying out the measurement of unwanted emissions using a near-field test facility. These have the ability to measure the radiated SE emissions directly in the near-field and by using a near to far-field transform to calculate the far-field EIRP. It is likely that the near-field receiver will require a pre-selector to protect the receiver and that health and safety considerations may preclude the measurement of high-power radars. Some near-field facilities can measure radars operating at full-power although some require the transmitter to be "turned down", in which case the variation of unwanted emissions with transmitter power would need to be characterised. This would solve the two outstanding problems with the direct methods, those of weather and interference, as such facilities are generally housed in screened measurement chambers.

3.4.14.2 Indirect Method

The antenna used in the indirect method could be fully characterised using a precision near-field antenna test facility capable of measuring over the full hemisphere. Such facilities are available in the UK and would provide a highly accurate characterisation of the antenna gain over three dimensions and over the full frequency range. This could be used, subject to the concerns over transmitter to antenna interactions and the effect of the feeder waveguide, together with the closed loop power measurements to determine the UE levels. A precision far-field range or anechoic chamber could be used to provide the antenna characterisation however in these cases it is far more difficult to achieve the 3D coverage in the measurement.

3.4.15 Interpretation of Results/Confusion in Specified Limits

In order to devise a method to make useful measurements and particularly to judge the results against a pass or fail criterion of a meaningful specification, it is necessary that published limits have units that are clear and consistent. Currently the ITU-R documents that provide the limits that will form the basis of testing using ITU-R Recommendation M.1177-2 are inconsistent.

The confusion arises from the fact that for some services the limits are specified at the transmitter output but for radar they are specified as off-air measurements in line with ITU-R Recommendation M.1177-2.

In particular there is confusion in the specifications between Power, Spectral Power Density and EIRP.

The peak envelope power is defined in the Radio Regulations as follows:

"1.157 peak envelope power *(of a radio transmitter)*: *The average power supplied to the antenna transmission line by a transmitter during one radio frequency cycle at the crest of the modulation envelope taken under normal operating conditions."*

In radar terms it is equivalent to the peak power of the radar waveform in the time domain. PEP is expressed in units of power, dBW, dBm, W, kW etc and is referenced in ITU-R Recommendation SM.329-9 "Spurious emissions". In order to accurately measure the PEP it is necessary to use a bandwidth wide enough to capture all the energy in the pulse. In practice this is the impulse bandwidth of the pulse. This bandwidth is defined as $B_{pep} \approx 1/\tau$.

$dB_{pp}W$ is the peak power measured across the spectral envelope measured in a specified bandwidth. This is defined in ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain".

EIRP is the total radiated power (can be expressed in peak or mean) multiplied by the relative gain of the transmit antenna to an isotropic radiator (normally the peak unless specified otherwise[45]). EIRP is expressed in units of power and represents the power that would be required to generate the equivalent power density if the antenna was an isotropic radiator i.e. of 0 dB gain. EIRP takes the units of power sometimes written as dBWi, dBmi to indicate they are referenced to an isotropic source. EIRP includes a term for the transmit antenna gain.

Power units are not appropriate in off-air measurements as they contain terms related to the receive antenna gain and the range. See section 3.4.17 of this report for a discussion on the measurement of EIRP.

3.4.15.1 OOB Limits

The way the OOB limits are specified in ITU-R Recommendation M.1177-2 requires the use of peak dB_{pp}. The specification limits are given in ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain" and do not explicitly specify the resolution bandwidth to be used. Because the document specifies the shape of the spectrum it must be implied from this that the resolution bandwidth should be narrow enough to accurately measure the shape of the spectrum i.e. between approximately $0.03/\tau$ to $0.1/\tau$ (5% of main-lobe width). Once this is achieved, because the limits are specified as relative dB_{pp} the relative result will not change if the resolution bandwidth is reduced (because the spectrum shape is not changing). However it is necessary to ensure that the resolution bandwidth does not go too low, below the 1.7 x PRR[46] restriction or more likely, that the pulse desensitisation limits the dynamic range of the measurement. Because the specification

[45] Sometimes side-lobe power is expressed as EIRP

[46] This is where the pulse spectrum method is no longer valid and the Fourier transform method is applicable.

envelope is expressed in relative units, the resolution bandwidth does not become an issue. Strictly speaking, as the limits are being measured off-air they should be expressed as dB_{pp} EIRP, however for relative measurements, the other factors such as antenna gain cancel out - see section 3.4.16. Because the OOB region is essentially close to the carrier any changes in receiver antenna gain can be neglected.

3.4.15.2 SE Limits

The SE limits are specified in ITU-R Recommendation SM.329-9 "Spurious emissions". For radar systems two sets of limits apply; class A and class B. Unlike OOB limits, SE limits do not contain a spectral mask that has to be applied; they are specified as a simple level. ITU-R Recommendation SM.329-9 initially specifies a 1 MHz reference bandwidth but then confuses the situation by referring to ITU-R Recommendation M.1177-2 in the notes to tables 2 and 3[47].

ITU-R Recommendation SM 329-9 defines that SE limits are relative to PEP. In order to get an accurate measurement of PEP, measurements must be made in, or corrected for the $1/\tau$ bandwidth if the resolution bandwidth is not wide enough.

The SE limits are however required to be measured in the reference bandwidth as defined in ITU-R Recommendation SM 329-9 and referred back to PEP which may or not be defined and/or measured in the same bandwidth.

The Class A limits are specified as relative measurements of PEP (should be PEP EIRP) for a similar argument to that for OOB limits provided the same resolution bandwidth is used, the measurement of SE is consistent within itself.

The following is an extract from ITU-R Recommendation SM.329-9:

"Radiodetermination (7) 43 - 10 log PEP, or 60 dB, whichever is less stringent

The following notes apply:

(1) In some cases of digital modulation and narrow-band high power transmitters for all categories of services, there may be difficulties in meeting limits close to ±250% of the necessary bandwidth.

(2) Use the e.i.r.p. method shown in Annex 2, § 3.3, when it is not practical to access the transition between the transmitter and the antenna transmission line.

(7) For radiodetermination systems (radar as defined by RR No. 1.100), spurious domain emission attenuation (dB) shall be determined for radiated emission levels, and not at the antenna transmission line. The measurement method for determining the radiated spurious domain emission levels from radar systems should be guided by Recommendation ITU-R M.1177."

The 60 dB limit is clear, the SE signal measured in the reference bandwidth must be at a level of 60 dB below the PEP signal measured in $1/\tau$ bandwidth if different from B_{ref}.

There is however some confusion in the *43 - 10 log PEP* limit. For other services the PEP is as defined in the Radio Regulations as follows:

"1.157 peak envelope power (of a radio transmitter): The average power supplied to the antenna transmission line by a transmitter during one radio frequency cycle at the crest of the modulation envelope taken under normal operating conditions."

That is, it is the power supplied to the antenna transmission line. For radio determination, when the measurements are made off air, (referred to in note (2) above, as the EIRP method), the question is then, is the PEP referred to in "43 - 10 log PEP" the transmitter power, or the EIRP? It is not clear which should be used.

[47] There are moves afoot within ITU working party 8B to resolve these inconsistencies. The proposal is that for radar the reference bandwidth should be 1 MHz or $1/\tau$ whichever is the smaller.

Table 10 of ITU-R Recommendation SM.329-9 "Absolute levels of spurious domain emissions – Category A" leads to a further confusion. The levels are specified in PEP Watts and dBm, (PEP for the transmitted level, dBm for the SE), but the units for both should be in EIRP watts. If not, the level specified for PEP depends on the Tx and Rx antenna gains and the measurement range.

"Radiodetermination(7)	*–13 dBm*	*if PEP ≤ 50 W*
	10 log PEP – 30	*if PEP > 50 W*

For radiodetermination systems (radar as defined by RR No. 1.100), spurious domain emission attenuation (dB) shall be determined for radiated emission levels, and not at the antenna transmission line. The measurement method for determining the radiated spurious domain emission levels from radar systems should be guided by ITU-R Recommendation M.1177.

A gain refers to power not EIRP, "Maximum permitted spurious domain emission power in the relevant reference bandwidth (see further recommends 4.1) (dBm) with P, PEP or X (W)"

There is now however an inconsistency at the boundary between OOB and SE and also for any OOB emissions that fall in the SE domain. In order to make the two limits consistent, the same resolution bandwidth would have to be used. This would imply using a measurement bandwidth (equal to the SE reference bandwidth) that may well be too wide to demonstrate the performance in the OOB domain, an alternative is to measure the SE region using a bandwidth narrower than the reference bandwidth and correcting the data to allow for this.

For Class B limits are defined as :

"Radar systems in the radiodetermination service:

Fixed radiodetermination stations (5), (6), (7), (8) (wind profiler, multi-frequency and active array radars are excluded) –30 dBm or 100 dB attenuation below the PEP, whichever is less stringent

(5) For radiodetermination systems (radar as defined by RR No. 1.100), spurious domain emission attenuation (dB) shall be determined for radiated emission levels, and not at the antenna transmission line. The measurement method for determining the radiated spurious domain emission levels from radar systems should be guided by ITU-R Recommendation M.1177.

(6) European and some other countries have determined that insofar as they are concerned, Category B spurious limits for radar systems should apply to transmitters used in those countries and installed after 1 January 2006.

On a site-by-site basis, administrations may permit the use of maritime mobile radar equipment in fixed installations (e.g. vessel traffic services radar), using the appropriate limits for mobile radars.

Further study is to be undertaken by the relevant regional body, any interference will be handled on a case-by-case basis."

There are further complications in the class B limits. These are specified as -30 dBm or 100 dB below PEP, whichever is less stringent. As for the above Class A, there is not an issue for the relative measurement, however -30dBm is specified as PEP. This has the units of power, it needs to be specified explicitly as an EIRP to be meaningful, and a resolution bandwidth must be assigned. There will also be a problem of the SE/OOB boundary, however the shape of the OOB mask and the class B SE OOB boundary have yet to be defined within the ITU.

There are however potential drawbacks in specifying the absolute level in PEP EIRP. With the same value as currently given due allowance needs to be taken for the antenna, otherwise it will apply to transmitters of much lower powers than those stated in Table 10 of ITU Recommendation SM.329-9.

3.4.15.3 Limit Masks Issues

Given that the OOB mask is defined in dB_{pp} and the SE limits in PEP, if an unwanted emission mask is to be applied, then it will have a discontinuity at the OOB/SE boundary. A way to resolve the inconsistency is to make the resolution bandwidths equal. This means that the bandwidth has to be wide enough to measure the peak power, which will result in a distortion of the spectral shape close to the fundamental.

A further problem in applying the mask occurs when it is not possible to use a receiver with a resolution bandwidth wide enough to measure the peak power without desensitisation. This occurs for pulses less than 200/300 ns and the most common receivers have maximum bandwidths between 3 & 5 MHz. The question then arises as to how to set the reference level for the emission mask? If the mask is set to the peak of the main spectral lobe then it implies that all the SE signals have the same desensitisation factor.

In the measurement campaign the OOB masks were referenced to the peak of the measured pattern. The SE region however was not corrected for PEP or resolution bandwidth to reference bandwidth.

The levels are rationalised when the resolution bandwidth equals the reference bandwidth.

The following is the proposed method for applying the limit masks in the future:

- Where B_{res} is less than B_{pep} then to allow for the true measurement of in band PEP, add the following dB corrections to all measured data in the SE domain:

  For CW and Phase Coded Pulses $-20 \log(B_{pep}/B_{res})$
  For Swept-Frequency (FM or Chirp) pulsed radars $-10 \log(Bc/(B_{res}^2 x\tau)$

- To allow for any difference between the resolution bandwidth and the specified reference bandwidth for SE emissions, add the following correction factor to all the measured data in the SE domain.

  For all types of pulses $10\log(B_{ref}/B_{res})$[48]

- In the OOB domain, no correction is applied and the OOB mask is positioned on the peak of the fundamental.

- The OOB/SE boundary is taken as $\pm 5 \text{ x } B_{-40dB}$ about the frequency of the fundamental signal.

3.4.15.4 Comparison with Other Limits

There are two other frequently used spectrum-engineering standards:

- MIL STD 469
- NTIA RSEC[49]

Both of these standards are based on the -40 dB bandwidth calculated from pulse parameters. Both specify the limits in terms of the spectral power density. The equations for the -40 dB differ. In MIL STD 469 they do not have the correction factors A in the equations for chirped waveforms. This leads to a wider value of Bw_{-40dB} in the RSEC and the ITU limits.

The ITU limits give a minimum value for SE, then, once this is exceeded, gives a fixed value of suppression relative to the radar's peak power. This means the higher the power, the higher the SE level that is permitted.

[48] This value is taken from ITU-R Recommendation SM.1541, it strictly only applies to noise like SE, the value can vary from 0 for CW SE to $20X\log(B_{ref}/B_{res})$ for pulsed SE.

[49] NTIA Document Radio Spectrum Engineering Criteria

MIL STD 469 and the RSEC give a maximum level that must not be exceeded independent of transmitter power. The higher the power, the more suppression is required.

MIL STD 469 gives the lesser of P_t -60 or -30 dBW/kHz. In 469 this is specified at the transmitter output.

RSEC gives the lesser of P_t -60 or P_t -(P_t +30) dBW/kHz, which equates to the same level as 469.

The ITU Cat A gives PEP-(43+PEP) dBW or PEP- 60 whichever is less stringent.

ITU Cat B gives a level of -60 dBW or PEP-100 dB.

This means that with the ITU limits, the level of SE can rise with the transmitter power where as in the other two limits, the SE is capped to a maximum level.

Both the RSEC and 469 standards also have special categories for radars in the band 2700 to 2900 MHz with tighter limits.

3.4.16 Practical Measurement Issues

3.4.16.1 Interpretation of ITU-R Recommendation M.1177-2

When making SE and OOB measurements, it is necessary to understand several practical issues if the results are to be meaningful and consistent. The ITU recommendations are only specified limits in terms of measured relative power or EIRP levels. They do not specify how these limits should be applied in practice. Take for example SE limits all they require are the SE's to be a certain number of dB relative to the fundamental when measured in the appropriate bandwidths.

ITU-R Recommendation M.1177-2 does not specify whether measurements are to be made on the elevation bore-sight of the radar antenna or whether measurements are required at different heights or elevation angles off of the bore sight to determine off-axis unwanted emissions, nor is the measurement distance defined. It does not say if the limits apply over all space, (i.e. relative to fundamental peak gain wherever it is), or at all points in space, (i.e. relative to the local fundamental frequency power levels) or any other interpretation such as a mean level.

The nature of the harmonic performance of antennas is such that harmonic beams are generated at different angles in both the azimuth and elevation planes relative to the position of the fundamental frequency beam. For electronically scanning systems, the position of the harmonic beams vary with both scan angle and frequencies.

Consider the antenna performance at SE region frequencies. Generally SE measurements have been made in the azimuth plane with the antenna rotating. This removes any beam modulation in azimuth that occurs in antennas with travelling wave feeds or frequency sensitive phase shifting components. However in the SE region, even antennas that do not have travelling wave feeds can squint in both azimuth and elevation and produce multiple "grating lobe" beams.

Consider the simplest of antennas, the horizontal half wave dipole spaced $\lambda/4$ above a ground plane. At the design frequency the current distribution is a half sinusoid with a peak normal to the arms. This produces a beam normal to the arms of the dipole. The reflection from the ground plane is such that this reinforces the broadside pattern. At the frequency of the 2^{nd} harmonic the current distribution is still such as to form a beam on broadside but the reflection from the group plane is in anti-phase. This results in a beam with a null normal to the arms of the dipole and peaks either side of normal. The radiation pattern is said to have bifurcated. At the third harmonic, the peak returns to the normal but extra nulls form in the plane of the dipole arms.

The same effect can occur in reflector antennas if the higher order asymmetric modes are formed in the feed horn. These can be excited by discontinuities of asymmetric feed excitation. In waveguide fed horns, these modes can be generated by the feed run and the exact mix depends on the design and spacing of the feed components.

It is thus possible that in the SE region, particularly at harmonic frequencies, the peak of the antenna gain can deviate from the azimuth plane. Thus measuring in the azimuth plane may not measure the peak of any SE beam.

The problem is further exacerbated in array antennas where changes in the phase shift in the beam-forming network combine with element pattern changes to scan the beam at SE region frequencies. If the antenna contains phase-shifting components to steer the beam, then the position of the beam formed at these frequencies is a function of the position of the beam at the fundamental frequency.

As well as the squinting of the main beam, if the antenna is an array, then at SE frequencies "grating" beams can also occur. These are further representations of the main beam caused because the element spacing exceeds $\lambda/2$ at frequencies in the SE region.

Thus in order to be sure that the maximum SE is measured, it is necessary to "look" over the full hemisphere enclosing the radar. Using the direct method this approach would be impractical both in physical terms (i.e. the positioning of the measuring antenna), and in time. This is made less practical by the need to repeat the measurement at all beam positions.

It is thus necessary to decide a pragmatic approach that has to be taken.

3.4.16.2 The Pragmatic Approach

Initially measure the system in the azimuth plane. Harmonic beams are rarely unique or well formed, so it is highly likely that any SE will be detected in the azimuth plane. If any emissions are detected at frequencies that are likely to cause interference with receivers situated in the elevation plane (i.e. airborne), then further investigation is required.

For rotating antennas the interpretation would seem to be that the comparison should be made of the maximum levels seen in the measurement plane independent of azimuth position. This would seem a good engineering solution as it makes the measurement in a plane close to the plane that the maximum interference potential exists. However, this does not address any SE in the elevation plane.

This approach needs to be generalised for antennas that do not rotate but electronically scan in azimuth. Because the harmonic radiation is also a function of the scan angle, measurements may need to be made at several fixed azimuth positions, one on-boresight and one each at either end of the scan.

Making direct measurements in the far-field is virtually impossible above the principle azimuth planes, since generally radars are positioned such that this area of the radiation pattern is not accessible. For radars in an elevated position, it is generally possible to gain access below the principle plane if this is assessed as the worst possible plane for potential interference.

The best approach to addressing SE in the elevation plane would seem to be based on assessing the likely interference potential from measurements in the azimuth plane. Interference caused in the elevation direction is likely only to effect airborne and space based systems. If the measurements in the azimuth plane indicates no significant radiation in these bands, then it may be safe to assume that there will be no significant radiation into the elevation direction. If however significant SE are found in the candidate bands, then further investigation may be required. The extent of this further investigation requires further study. The investigation could take the form of scanning the antenna to high elevation angles and measuring in the azimuth plane to ascertain if spurious emissions are being produced. This investigation however would need to be tailored to the specific radar under test with detailed knowledge of the design and the likely performance in the spurious emission domain .

As well as considering where relative to the radar head the measurements should be made, it needs to be considered in what operational modes the radar should be set to when being measured.

If possible the radar needs to be measured with a fixed pulse pattern. If OOB emissions are being measured then this can be considered against the appropriate OOB mask. If the radar cannot be operated in a single mode then it needs to be operated in its "normal" mode with comparison being made against the widest appropriate transmission mask based on the modulation being used. When interpreting the results however, the level of pulse desensitisation must be considered.

For SE measurements, it is most appropriate to operate the radar in its normal mode of operation.

Once the measurements have been made and the levels have been determined, it is necessary to decide whether the measurements pass or fail the specified criteria.

The subject of measurement tolerances needs to be addressed. Generally two options are available; make the decision based on indicated values or require the limits to be exceeded by a margin equal to the estimated measurement errors (so called indented limits). When using indicated values the method of measurement needs to be defined so as to limit the measurement errors involved. Given the difficulty in making these measurements, the likely level of error and the possible insensitivity to errors, it would seem that the appropriate approach to be adopted would be to use indicated values based on a well described method of direct measurements.

3.4.16.3 Interpreting ITU Limits Pass & Fail Criterion

As has been previously discussed, the measurement bandwidth required in the SE domain does not only depend on the fundamental signal alone but on how the specific SE emissions are related in the time domain to the fundamental signal.

It could be argued that there is no one appropriate bandwidth for measuring the whole SE region. ITU-R Recommendation M.1177-2 in Appendix 1 to Annex 1 step 7 discusses the need to use differing resolution bandwidths to identify any of these issues. In the case of quantifying the level of the Π_{-1} mode this is particularly important. As there is no appropriate resolution bandwidth, so it is not appropriate to apply a continuous mask as described in the ITU recommendations over the full SE region. Parts of the mask may have to be offset by the appropriate desensitisation levels. These offset levels would have to be determined by the use of different resolution bandwidths.

This issue is highlighted in the case where the receiver does not have a sufficient bandwidth to measure the fundamental signal without desensitisation. This is the case for very narrow pulses, where if the emissions in the SE region are time related to the fundamental then it is appropriate to set the reference equal to the fundamental peak, or if they are not related then it may be appropriate to offset the mask by the desensitisation factor.

3.4.17 Measurement of EIRP

The aim of the direct measurement is to measure the EIRP of spurious emissions and to relate them to a peak envelope power level.

Consider the power received by the measuring antenna under far-field conditions. The power received is the power density at the receiver multiplied by the collecting area of the receive antenna.

The equation which describes the coupling between two antennas in the far-field and free space, well matched in bandwidth and polarisation, is the FRIIS transmission equation.

$$P_r = \frac{G_t \times P_T}{4 \times \pi \times R^2} \times A_{eff}$$ Equation 3.4.17-1

where:

P_r =Power Received (watts)

G_t =Transmit Antenna Gain

P_T =Power Transmitted (watts)

R = Range (m)

A_{eff} = Effective aperture area of receiving antenna (m^2)

This can be turned into the FRIIS equation by using the relationship,

$$A_{eff} = G_r \times \frac{\lambda^2}{4 \times \pi}$$ Equation 3.4.17-2

and substituting into the above equation,

$$P_r \quad = \quad \frac{G_t \times P_T \times G_r \times \lambda^2}{(4 \times \pi \times R)^2} \quad = \quad (G_t \times P_T) \times \frac{1}{4 \times \pi \times R^2} \times \frac{G_r \times \lambda^2}{4 \times \pi}$$

Equation 3.4.17-3

The equation can be rearranged, using the following terms:

EIRP = $G_t \times P_T$ a factor relating to the transmitter power and antenna gain.

Range Factor = $Rf = \frac{1}{4 \times \pi \times R^2}$, a factor solely related to the range at which the measurement is made.

Antenna factor = $Af = \frac{G_r \times \lambda^2}{4 \times \pi}$, a factor that converts incident power density into received power which is a function of receiver antenna gain and frequency only.

In dB form:

$$P_r(dBW) = EIRP(dBW) + Rf(dB/m^2) + Af(dBm^2)$$

Equation 3.4.17-4

It can be seen that if the gain of the receiving antenna increases as a function of frequency squared, then the antenna factor is independent of frequency.

In practice this would mean that the antenna effective area would have to be constant with frequency, and the only antenna which exhibits this behaviour is an ideal aperture.

The EIRP can thus be calculated:

$$EIRP(dBW) = P_r(dBW) - Rf(dB/m^2) - Af(dBm^2)$$ Equation 3.4.17-5

Thus to measure the level of the spurious emission $EIRP_s$ relative to the fundamental frequency $EIRP_f$ Δ_{eirp} at a given range (R), then assuming an ideal aperture receiving antenna[50].

$$\Delta_{eirp} = EIRP_f - EIRP_s = P_{rf} - Rf - Af - (P_{rs} - Rf - Af) = P_{rf} - P_{rs}$$

Equation 3.4.17-6

This shows that in this relative measurement it is not necessary to know the gain of the receiving antenna or the range.

If the absolute EIRP is required to be measured then this can be obtained from knowledge of the measurement range and the receive antenna factors.

[50] If an ideal aperture is not available, then a suitable correction factor needs to be applied. This is specific to a given antenna and can be derived from the gain of the antenna at the spurious emission frequency

3.4.18 Conclusions and Recommendations

The investigation has shown that the direct measurement currently gives the best option for measuring unwanted emissions from radar systems. The most suitable approach is the use of a dedicated test range, however in-service measurements are possible. It is doubtful, however, due to interference that it would be appropriate for a type approval process to be carried out in-situ. This however does to some extent depend on what control is available of the radar being measured and other associated radars during the exercise. Type approval is likely to be better carried out at a manufacturer's facility where their radars are integrated and tested, using the QinetiQ portable facility used in this study and where more control of the EM environment is likely to be possible.

When revising ITU-R Recommendation M.1177-2 "Techniques for measuring unwanted emissions from radar systems", the following areas of change are recommended:

- The document needs to specifically clarify the requirements for OOB and SE measurements and recognise that they are different.
- A pragmatic approach to the choice of the resolution bandwidth B_{res} and step size needs to be adopted to reduce the overall measurement time and allow for investigation of spurious signals. This approach should reflect the following points:

  - ❑ It needs to resolve the issue of resolution bandwidths being recommended. It is suggested $B_{res}= 1/\tau$ be recommended for SE measurements and for an initial assessment of the OOB region. For chirped pulses a resolution bandwidth of B_{res}=sqrt(Bc/τ) is recommended for SE domain measurements.
  - ❑ For un-chirped pulses should the OOB domain fail to meet the mask, or more accurate measurements be required for any other reason, then a finer measurement should be made using a narrower resolution bandwidth of $B_{res} = 0.2/\tau$.
  - ❑ For Chirped pulses for measuring the shape of the OOB region:

    If 0.1Bc is greater than 0.5*sqrt(Bc/τ), then a resolution bandwidth between the two values should be used.

    If 0.1Bc is less than 0.5*sqrt(Bc/τ), then a resolution bandwidth of 0.1Bc should be used.

    If however it is required for other practical reasons, then carrying out measurements using a bandwidth of less than that recommended is acceptable, subject to the requirements of dynamic range.

    This leaves the possibility for some combinations of pulse lengths and chirps of using the same bandwidth as for the SE domain this would simplify the measurement and the presentation of results.
  - ❑ Differing resolution bandwidths should be used to identify the true levels of signals in the SE region and to correct for any desensitisation issues. Bandwidth settings above and below the initial bandwidth setting should be used to ascertain the desensitisation law. If the initial setting is the widest bandwidth available on the test equipment, then the two settings below the initial setting should be used.
  - ❑ The required step size for SE measurements needs to be defined as half the resolution bandwidth being used (0.5 B_{res}) to avoid missing the peak of signals. However, when measuring with narrow filters, such as those required to accurately resolve the OOB domain, then a step size of equal to B_{res} is acceptable. If measurement time is a problem or a less accurate measurement is acceptable, (say for a spectrum survey) then the fundamental region should be measured using a step size of 0.5 B_{res} and

other regions with B_{res} . When measuring with narrow filters such as those required to accurately resolve the OOB domain then a step size equal to B_{res} is acceptable.

- When measuring in the OOB region with narrow resolution bandwidth to determine the shape of the spectrum such as $B_{res} = 0.2/\tau$ for a non-chirped pulse or the appropriate bandwidth for a chirped radar, the step size could be increased to B_{res}.

- The requirements to measure 'indicated' values as read off the equipment as opposed to 'indented' values that are corrected to account for the measurement tolerance needs to be confirmed.
- The conflict in the units specified for OOB & SE needs to be addressed, and in particular the need to specify power levels as EIRP.
- The use of the indirect method should not be recommended and should be dropped from ITU-R Recommendation M.1177-2. However it is recognised that some administrations would like it to remain. In this case, text must be added to state that the method "should only be used if the user can satisfy themselves that the characterisation of the antenna can be carried out to the stated accuracy of $\pm$ 6 dB". The transform programme given in the document should be withdrawn.
- Guidance as to the interpretation of the limits in terms of where in space to make measurements needs to be provided, in line with the pragmatic approach set out in this section.
- Time blanking receivers to filter out individual pulse types needs to be considered.
- Although it may not be possible to ascertain the peak of the Π-1 mode due to analyser limitations, the rate of change of the signal with bandwidth should be investigated so an assessment of its likely level (above or below) any limit mask can be made. It is likely that with present systems a full characterisation will not be possible. Future wider band systems may provide a way forward in this area, however they may not provide sufficient dynamic range for the full investigation of the SE domain.
- Guidance shall be included on how to correct the measured data when measurements are made with a resolution bandwidths differing from the reference bandwidths either for PEP or SE.
- In the current draft of the document there is an Annex 2 related to a version of the direct method for measuring low frequency radar, in particular HF and VHF radars. The resolution bandwidths specified are an order of magnitude lower than those recommended in Annex 1 of the document. They should be made equal to those specified in Annex 1.

Section 4

Conclusions and Recommendations

Contents:

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4.1 Introduction

These conclusions have been drawn from the complete report and apply to the study as a whole and are broader in their extent than those in the summary of each individual section. This section also contains some recommendations, shown in ***bold italics.***

This report has addressed several topics:

- The use and characteristics of commercial radar within the UK which includes:
  - The uses and distribution of radars deployed within the UK.
  - The wanted transmission characteristics and operational parameters of commercial radars in use within the UK.
  - The measured characteristics of a sample of commercial radars in use within the UK.
- The mitigation options which could be considered in the design and implementation of radar systems to reduce unwanted emissions and/or occupied bandwidth.
- The radar receiver characteristics and protection criteria required for the protection of radar services.
- An assessment of the measurement technique described in the latest draft revision of ITU-R Recommendation M.1177-2 "Techniques for measurement of unwanted emissions of Radar Systems".

4.2 The Use and Characteristics of Commercial radar in the UK

4.2.1 The Use of Commercial Radar in the UK

This topic is covered in section 3.1 of this report. In the frequency range 1 to 16GHz, civil radar is extensively used in the UK for aeronautical, maritime and weather surveillance on both fixed and mobile platforms. Other more specialised uses such as radar altimeters, vehicle speed measurement and ground probing radar have also been identified. The UK also has a comprehensive network of Secondary Surveillance Radar (SSR) systems used for Air Traffic Control (ATC). Radar is also extensively used by the military. Some military applications have been identified where information is in the public domain. Other types of radar, such as UHF & VHF and those operating at millimetre wavelengths, have been excluded as they do not fall within the specific bands identified for this study. Of those excluded, vehicle collision avoidance radar and intelligent cruise control could be areas of significant growth of civil radar use in the future.

Section 3.1.1 of this report details the numbers, types and roles of the various radars that are currently in civil use within the UK.

The uses identified have remained reasonably constant since the beginnings of the civil use of radar in the 1950's; in fact some of the actual radar types identified in this study date from designs of that vintage. Radars, particularly the larger, more costly types, tend to have a very long service life, a fact that must be remembered when any changes to requirements are being considered.

The performance, display and interface requirements of each radar type may have been improved over the years but the basic tasks being performed have not changed. Over the years, the major changes in civil radar technology have been in the areas of small signal electronics, digital signal processing and displays. In the area of high power transmitter design, it has only been during the past 10 years that the availability of solid state devices has led to the beginnings of significant changes in civil radar transmitter design.

In some areas, particularly in the lower cost end of the Marine and Vessel Traffic System (VTS) services, the equipment provided by different manufacturers is very similar and it is hard to distinguish any significant technical differences. Price constraints have driven the suppliers of these types to provide only the very basic of transmitter/receiver designs needed to meet the international standards applied to these types.

It is the case that, with a few exceptions, the military are also users of the majority of radar types used for civil purposes. The military also has radars that have no civilian application and whose roles would only be fully used in wartime. It is worth noting that in the past many of the more complex of the civil radars were often derived from military procurement programmes while in recent years the situation has become somewhat reversed with the military buying radars based on civil 'Commercial Off The Shelf' (COTS) products. In section 3.1.1 details are given of the technical parameters of some radar types. These serve to illustrate what is available in the market place and should not be taken as representing any specific type of radar operating in the UK unless specifically stated in the text.

Section 3.1.1 also documents the main roles of civil radar within the UK. The associated radar types are identified and typical data presented. Using information available in the public domain, this section also identifies various military and experimental uses of radar within the UK. The uses of radar band by band are examined and presented in both tabulated and geographical distribution formats.

The report gives an estimate of the total number of radars operating within the UK. The largest numbers within a single band are the X-Band marine, airborne weather and altimeters. Within these classes, the largest numbers are associated with small radars used by pleasure and fishing vessels. In terms of use of the spectrum, these types of radar do not control their emissions particularly well, with their magnetron transmitters being prone to producing wide band energy, particularly as the magnetrons age. However, these radars do seem to operate together in an acceptable fashion using only a small number of the frequencies within the band. The limited number of frequencies is a consequence of the availability of magnetrons and the manufacturers' need to limit the number of variants of the magnetrons for economic reasons. A point to note is that a large number of these radars are in the hands of users with no recourse to regular servicing or performance monitoring. Magnetrons in particular, as they approach the end of their life, can produce a greater amount of unwanted emissions and these emissions are unlikely be noticed by the user.

In summary the major uses of radars fall into four areas:

- Ground based Aeronautical Navigation
- Marine Navigation
- Weather Detection
- Radio Altimeters.

Aeronautical Navigation Radars operate through all stages of flight, from long range en-route radars, through medium range Terminal Manoeuvring Area, short range Airfield Control, very short range Precision Approach Radar (PAR) to Airport Surface Detection Equipment (ASDE). These radars operate in L, S, X & Ku-Bands and, with the exception of the X-Band ASDE, each installation typically operates on more than one frequency. The transmitter technologies used vary from 40-year-old magnetron designs through driven systems (based on TWTs and Klystrons), to state-of-the-art 'solid state' technology. The technology used in the transmitter can make a considerable difference to the output spectra of radars carrying out essentially the same role. Apart from the recent designs that are based on stringent Federal Aviation Administration (FAA) requirements, historically very few attempts were made to actively control the bandwidth occupied by the radar. In the older designs, due to the limitation of the transmitting valve being used, the design concentrated exclusively on generating an RF pulse, which delivered the required energy onto the target in the time required to achieve the radar detection requirements. Some of the Magnetron based systems have been, and are currently being, upgraded to Coaxial Magnetron designs. These upgrades improve the stability and ageing characteristics of the transmission although still generating significant amounts of wide-band emissions.

SSR is also used for aeronautical navigation. These aids to navigation operate in the crowded Aeronautical Radio Navigation Service Band around 1 GHz and their output pulse shapes and radiated spectra are closely controlled by international conventions. These systems use filters to shape the output spectrum, however they operate at very low mean power where transmitter efficiency and power handling are not an issue.

Marine Navigation radars are used in two distinct roles;

- VTS are shore-based systems used to monitor the movement of shipping vessels into ports and harbours or in areas of dense shipping traffic;
- Ship based systems are used by vessels to aid navigation and to prevent collision.

These radars are almost entirely single frequency radars operating in X or S-Band and employ magnetron transmitter designs. The larger ships covered by the SOLAS Convention are required to carry at least two radars and many large ships carry three or more with a mixture of S and X-Band. Small vessels such as fishing boats and pleasure craft generally carry one X-Band Radar.

Weather Detection radars come in two distinct types:

- Ground based operating in C-Band;
- Airborne operating in X-Band.

Ground based weather radars are used as part of the UK forecasting network to track and measure rainfall. The ground based radars used in the network all operate on the same single frequency in C-Band and use coaxial magnetron transmitters.

Airborne systems are used to detect and warn pilots of weather hazards. They operate on single frequencies in X-Band and use either magnetron or solid state technology, the newer systems using low power solid state transmitters. Aircraft also carry radio altimeters that operate in C-Band.

Many of these radars are generally referred to as SOL radars, in particular those related to air traffic and marine navigation. The failure of a radar used to aid navigation could result in a major catastrophe. The recent incident over Switzerland[1] graphically illustrates what happens when air traffic control fails. The failure of on-board aircraft systems (such as altimeters, weather radars or TCAS (an SSR based system)) can also result in catastrophes. A recent unreported incident at a UK airport where the TCAS systems of aircraft taking off were being triggered unnecessarily was believed to result from interference and caused much concern. Maritime navigation, if it fails, can result in ship collisions or ships running aground resulting in loss of life or pollution. Even small radars fitted to pleasure craft can aid in the prevention of accidents at sea. Ground weather radars provide forecasts that are used by the water companies and environment agency to predict the possible areas of flooding allowing the warning and evacuation of the area to be affected. Future proposed weather radars for detecting microburst and wind sheer will provide high update rate weather data to airports to support landing and takeoff in poor weather. New Microwave landing systems will soon be fitted at several UK airports (including London Heathrow) to enable Cat 3 (Blind instrument controlled) landings to take place. These systems automatically shut down if they are interfered with such that their integrity is compromised. The consequence of a system shutting down during a blind landing could be catastrophic.

Examples are given of frequency reuse in the UK, this is defined as radars operating on the same frequency at differing geographical locations. An analysis is made of the factors that affect the acceptable distances between radars. These factors depend on the type of radar, in particular the power of the radars, the height of the scanner and the frequency. The reuse distance is also heavily dependent on local terrain screening. The report also gives suggestions on how the reuse distance could be reduced.

[1] 12 July 2002 - Mid air collision of a Bashkirian Airlines Tu-145 and a DHL cargo jet.

4.2.2 The Characteristics of Commercial Radars in the UK

Section 3.1.2 of this report gives tabulated information on the typical transmission characteristics of generic radar types fulfilling the different roles within the different frequency bands. Whilst the figures are based on currently in-service radar types they are not intended to represent any given radar. The details of specific types are given in Annex 1 of this report. These general parameters given in Section 3.1.2 give information on what an average system would be expected to achieve when operating in a specific role. Examples of measured spectra obtained from sources outside this study are provided where available as background information, as are the calculated emission masks appropriate to the radars defined in the tables.

This section also graphically illustrates how the technology used to implement the radar can affect the occupied bandwidth. It illustrates this by comparing the emission masks of various types of S-Band ATC radars. This shows that a solid state design has a reduction in the order of 10 times in the occupied -40 dB bandwidth compared with a Magnetron design. It should be remembered, however, that this is achieved at a considerable increase in cost. The increase in cost, which could be up to 100%, could be such that it may preclude the procurement of a radar and the subsequent provision of a radar service. In this case the value of not providing a safety service has to be balanced against the extra use of bandwidth by the more cost-effective system.

Section 3.1.3 of this report contains the background to, and the results of the radar measurement programme carried out by QinetiQ under this study. The measurement programme involved the measurement of the emissions from a number of installed and operational radars as well as one radar type tested at the QinetiQ test range at Funtington. The results of the programme provided useful information regarding the actual emissions of different radar types and the practical problems/advantages of measuring a radar in its operational environment.

The method adopted during the measurement campaign of performing a number of survey measurements with different receiver bandwidths in order to optimise the settings for both the Spurious Emissions (SE) and Out of Band (OOB) runs, proved to be an efficient use of measurement time. The full measurements could then be performed at the widest suitable bandwidth and hence with the largest step size with no degradation in the quality of the data measured.

The quality of the measurements was found to be improved when using a measurement step size equal to half of the resolution bandwidth and was considered an acceptable trade off against measurement time in most cases.

The quality of the Electro Magnetic (EM) environment at the measurement site was found to be an important factor if a quick, accurate and complete assessment of a radar installation is to be made. The EM environment encountered at the installed sites was extremely cluttered, and in some areas of the frequency band, totally unusable. When measuring a radar it is normal to use a high gain narrow beam receive antenna to provide very good discrimination against unwanted, signals. However at the airfield sites the unwanted signals were of such numbers that this was impossible. Unwanted signals were thus identified by correlation with the radar rotation period using the receiver tuned to a fixed frequency and were removed from the database. This method has one limitation in that any radar signal co-channel with a larger interference source would be removed. The relatively quiet site used for the meteorological radar and the fixed range at Funtington did not suffer from interfering signals.

The perfect measurement geometry is always extremely difficult to achieve without the use of a dedicated measurement range with positioning systems for the radar under test. When measuring an installed radar, the proposed measurement sites require surveying before the deployment of the test equipment. In the UK in particular, the choice of receive sites is often very limited, except at remote radar installations. In fact, for the measurement of the ATC and ASDE radars within this measurement campaign, the choice of available and suitable sites was limited to the choice of two, both with approximately the same geometry. In the case of the meteorological radar, the site was limited by the available line-of-sight range. The majority of the measurements were made with the receive antenna looking up at the radar under test due to a lack of range and a lack of height of the receive antenna.

In practical terms, it is better to configure the measurement geometry to best characterise the emissions that will most likely cause an interference problem. This will, in the case of installed radars, need to be performed on a case by case basis. As an example, the marine navigation radars are only measured in the azimuth or horizontal plane because in the marine environment, this is the plane that interference is most likely to occur, ship to ship or ship to shore.

These measurements showed that there was a wide range of different transmitted spectra that are dependant on the type and roles of the radar. These ranged from the wide uncontrolled spectra produced by the magnetron radars to the relatively well-controlled spectra developed by the pulse compression radars. Presented with the measured results are a set of emission masks based on the latest recommendations for ITU Catagory A & B SE limits. When the pulse width is too narrow to allow accurate determination of the fundamental peak power, then the convention has been adopted to reference the mask to the peak of the fundamental signal, thus effectively offsetting the masks by the receiver desensitisation figure appropriate to the PEP level. No further offset has been applied in the SE domain to account for any variance between the resolution bandwidth and the SE reference bandwidth.[2]

The results indicate that the pulse compression radars come close to, or meet the latest appropriate ITU Category A and Category B spurious emission limits. These limits will be applicable to radars installed after 1st January 2003 and for all transmitters after 1st January 2012. Of the types measured, solid state pulse compression radars gave the best performance. For these pulse compression systems, the non-compliances are minor and could be overcome by in-service modifications.

The in-service magnetron radars however generally do not meet the new requirements and may require more substantial modifications. Single frequency, fixed site magnetron radars, such as ground weather radars, will have the most difficulty in meeting the latest requirements as they will be required to meet the more stringent ITU Category B emission limits that apply to this type of radar. Category B imposes a limit of -100 dB_{pep} as opposed to the Category A limit of -60 dB_{pep}.

Some work has recently been informally reported within the ITU which suggests improvements in some classes of magnetrons against the new Class A limits. However it is very likely that the main approach to be adopted for the improvement of these fixed single frequency radars will be the provision of high "Q" band-pass filters centred on the operating frequency and low pass filters to provide the suppression of harmonic signals.

The problems with all radar types in meeting the ITU emission limits are further exacerbated by proposals to further restrict the OOB radiation by the introduction of a new design aim in ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain". This has increased the roll off in the OOB region from 20 dB/dec to 40 dB/dec. The plan is to start work on the adoption of the new aim after 2006. It is very likely that many categories of radars will have to be exempted from this design aim if it is adopted as a recommendation. However the final timescales for the adoption of such new recommendations is unclear and could be up to 20 years.

[2] Since this report was drafted, recent thinking suggests that this may not be the appropriate convention to adopt and that correction of the SE data is required. No correction is required in the OOB region and the OOB roll-off mask should be referenced to the measured peak of the fundamental whatever the resolution bandwidth used.

The implication of the imposition of the design aim is currently being studied by companies in the UK. The initial indications are that solid state systems may well be able to achieve the new design aim. Possible new magnetron developments may allow the Category A requirements to be met without using filters, however without substantial filtering they will find it very difficult if not impossible to meet the design aim.

4.3 Mitigation Options which could be considered in the design and implementation of radar systems to reduce unwanted emissions and/or occupied bandwidth

This topic is discussed in section 3.2 of this report. Primary radar detects targets by looking for the reflected signals from the surface(s) of the targets, i.e. its receiver is optimised for the detection of the transmitted pulses. The prime outputs are the range and bearing of the targets; and height in the case of 3-D radars. The degree of resolution of these parameters is defined by the signal bandwidth and the antenna beamwidth. The bandwidth is related to the pulse length in the case of CW pulses or, in the case of coded pulses, the compressed pulse length. Some radars can also determine the size and velocity of targets by the amplitude of the echo and the doppler frequency shift. A succession of echoes from the target can then be used to determine the target's track.

The pulse length, the rise and fall times and modulation, if any, determine the spectrum of the radar transmission. In the case of tube transmitters (i.e. Magnetrons, Klystrons, TWTs, etc.) the transmitter designer is limited in the range of options for extending the rise and fall times because of the likely generation of unwanted modes and instability during these transitions from OFF to ON and back to OFF; these instabilities, such as AM to PM conversion, would reduce the ability of the radar to improve the target to clutter and noise ratios.

Although a near rectangular pulse is generated on transmit, the signal is normally band limited on reception so the far out emissions are not generally processed on reception and therefore could be removed on transmit[3]. Filters could be used to remove some of these spurious emissions. The amount of filtering that can be applied however depends on the acceptable pulse shape distortion. It has been shown that filters of pass bands with widths between the -20 dB (necessary bandwidth) and the -40dB bandwidths of the signal can be used to improve the OOB response. Filters much narrower than this can distort the pulse but may have applications in some cases.

Filters are generally only effective in this role on single frequency radars or radars where each frequency is associated with a separate transmitter. Their use on multi-frequency or agile radars is much less effective, particularly in the case of active array systems where the ability to provide high Q filters is much more restricted. For frequency agile systems, filtering is generally only applicable to band limiting types.

Radars with a waveguide run between the transmitter and the antenna will suppress any unwanted signals below the cut-off frequency of the waveguide. A low pass or band pass filter after the transmitter offers the most cost-effective method of removing the harmonic and spurii from the transmitted signals.

Many in service radars use two or more frequencies to improve the target detection and de-correlation. It is important that this is not considered in the same light as frequency diversity in communications systems. Such communications systems can operate with full performance on one frequency only, and the second frequency is provided to improve the availability of the link. In radars, the two frequencies are required to maintain the detection performance in the presence of target fluctuations.

In the limit, the bandwidth occupied by the radar depends to a first order on the resolution required and the technology used to implement the transmitter. It has not proven possible to

[3] Excessive filtering however can lead to unacceptable ripple, ringing and excessive time sidelobes being produced.

identify reliable techniques that operate in the presence of noise that can resolve two targets using a bandwidth less than one range cell. This approximates to $1/\tau$ where τ is the pulse length or in the case of pulse compression radars the compressed pulse length. Thus range resolution in terms of metres is bought in units of bandwidth in Hz. Improvements in the design of transmitters however can achieve output spectra close to the theoretical $1/\tau$ limit[4]. The achievement of this goal however may be at the expense of much higher cost or loss of other features such as frequency agility.

The spectrum used is only one of the trade-offs that has to be considered by the designer. However in the current climate of scarce spectrum resource and changes to international regulations, coupled with band sharing etc, much greater account needs to be taken of minimising spectrum occupancy of radars. The report presents a set of design rules to achieve the minimum bandwidth occupied subject to the resolution requirements.

The following conclusions on waveforms has been drawn:

- High time bandwidth chirped pulses provide very rectangular spectra that constrain the spectral extent of the signal when compared with pulsed CW radars. The chirped pulses may be filtered to remove far out sidelobes with less distortion than CW pulses.
- Gaussian pulses have been considered. These have very narrow spectra but are of limited use as radar pulses as they are difficult to generate at high power and are very inefficient at delivering energy on the target in a short time commensurate with the range resolution requirements.
- Low Probability of Interception (LPI) waveforms having low peak energies are considered but are limited to relatively short ranges by close-in clutter eclipsing distant targets.
- When designing a radar of a given required resolution, the largest time bandwidth product pulse that can be accommodated, given the other constraints imposed by the radar, should be used. Given that the bandwidth is set by the resolution, then to increase the time bandwidth product, the longest pulse length should be used.

Improvements in antenna design can provide spatial filtering and reduce the generation of interfering signals.

Each of the mitigation options identified has a cost involved and this will vary significantly with the radar system. Also, modifying an existing system is more expensive than incorporating the design change prior to the build of a new system. In many cases, changes would have to be made when a system is replaced.

If a low priced, simple radar were to have a complex mitigation method applied to it, the cost per system would be significantly increased and it might be priced out of its market. Conversely if a similar change was made to a high priced, complex radar, the percentage cost increase could be minimal. The report shows the complexity and cost implications of the proposed mitigation methods.

When considering the spectral efficiency of a radar in terms of the information content/unit bandwidth used, the output data rate of the radar cannot be used as a measure of the efficiency, as it does not wholly depend on the bandwidth being occupied but is also a function of the amount of signal processing being carried out to extract information.

Given that the receiver is well-matched in bandwidth and there is a need to achieve an adequate signal to noise ratio then the spectral efficiency is wholly related to the total[5] bandwidth used to achieve the required range resolution or range cell size.

[4] The $1/\tau$ limit being driven by the range cell of the radar.

[5] The word total refers to all the signal transmitted by the radar in both the necessary bandwidth, OOB and SE domains.

For a well-matched system the spectral efficiency depends wholly on the transmitted spectrum which in turn is a function of the transmitter. This determines how close the radar approaches the theoretical limit of N bits/sec/Hz where N is the number of data bits used to describe the contents of each range cell. That is how well the transmitter constrains the transmitted signal to the bandwidth associated with the specified range resolution.

Thus the spectral efficiency is related to how much bandwidth is used to achieve the required range cell size, as in radar range cell size is traded directly for bandwidth. When considering the bandwidth used, due account needs to be taken not only of the necessary bandwidth of the spectrum that is produced but the unused energy spread into the OOB and SE domains.

One further recommendation must be that the requirements to minimise the bandwidth occupied by the signal must be included as part of the design specification along with the other technical requirements associated with the performance and role of the radar. The procedure defined in this report will help achieve this subject to cost constraints. The final bandwidth which results is specific to a given radar design and is a function of the role of the radar.

4.4 The Radar Receiver Characteristics And Protection Criteria Required For The Protection Of Radar Services

This topic is addressed in Section 3.3 of this report and considers what design options are available in the receiver and how receivers respond to interfering signals. It is understandable that radar systems must endure a certain amount of external interference. However, the recent upsurge in mobile and personal communications has exacerbated the current interference situation. With many interference sources appearing in close proximity to the pre-defined radar bands, and causing cross-modulation throughout, this introduces increased levels of broad-band noise-like signals.

The increase in broad-band noise-like signals can cause undesirable effects, such as, a reduction in maximum detection range and an increase in the number of false alarms generated depending on the doppler and temporal structure of the signals. Coupled with this are the complexities associated with pulsed interference sources and the signals produced. Whilst in theory techniques are available for the removal of pulse interference, these techniques by definition reduce the basic sensitivity of the radar. In practice both types of interference signal are difficult to remove without compromising the basic performance of the radar.

Radar systems do employ certain techniques within their receivers and signal processing, which have the effect of reducing the probability that an interference signal will cause corruption. These techniques fall into two types, those that have the effect of reducing interference as a by-product of their radar function and those which are specifically designed to reduce interference. These techniques are not 100% effective and if they are biased towards an increase in interference rejection attributes, the performance of the radar may suffer. It is a general rule that the more that interference rejection techniques are employed the greater the loss of information collected by the radar. In many cases these techniques are expensive and in some cases are not appropriate for introduction into older systems.

Defruiting, Pulse Blanking, Dicke Fix Receiver, Side Lobe Blanking and Side-lobe-Cancellation are some techniques used to reduce interference. Sector blanking can also be effective at reducing interference however several services are reluctant to use this as, in addition to removing interference they make the radar totally "blind" over that sector.

Multi-frequency operation, frequency selective down conversion, single, double or triple super-het receivers, Moving Target Indication (MTI) and Tracking are techniques that can mitigate the effect of interference, however, they are primarily aimed at improving radar performance and not reducing the effect of interference.

The radar community is always making significant technological advances, especially with the development of the Adaptive Phased Array Radar and its improved immunity to any possible interference signals and sources. Such systems, however, require multi-receiver channels and their cost can only be justified on radars performing the most demanding roles. These improvements do come at a price, and with current economical restraint, the Adaptive Phased Array is an expensive option to consider for civil use[6].

Interference effects need to be fully analysed and correctly specified, as each interference scenario may cause a reaction that is system dependent. This phenomenon will mask the interference effect when applied to one system and amplify its effect when applied to another. The multitude of radar systems available makes the process of definition and specification a difficult one.

The one overriding factor that cannot be ignored is the effect that interference may have on Safety Of Life (SOL) services. If any future spectral allocations involve the possibility for a potential interference source to be generated, then its full effect must be investigated on the applicable systems and specific measures introduced to mitigate the effect.

In order to protect radars from interference from other services, the ITU defines a protection requirement. This is generally set at an Interference to Noise Ratio (I/N) of -6 dB.

Work has shown how noise-like interference will degrade radar coverage due to the effect of the Constant False Alarm Rate (CFAR) processing system raising the detection thresholds to keep the false alarm rate constant. However, it is unlikely that all interference types will match the noise-like model. It has also been shown that there is a likelihood of increased false alarms when the interference deviates from noise-like like due to the CFAR circuits being most effective against Gaussian noise. Also, it is shown that pulsed Continuous Wave (CW) interference can degrade the radar more than noise interference due to the action of pulse compression on CW signals. False alarms can result in operator fatigue and can degrade the tracking performance of the radar.

The effect of interference 6 dB below system noise results in a 1dB reduction in S/N, (this equates to a 1 dB loss in radar performance). This has been shown to produce degradation to the radar detection on 1 m^2 targets[7]. The radar would still achieve detection out to the full-instrumented range due to the detection margin on the beam peak built into the design,[8] but both low-level cover and high-level cover would start to be eroded. Civil aircraft usually have relatively large radar cross-sections and many will have areas much larger than the 1m^2 specified; the problem comes in detecting small uncontrolled targets such as some military or general aviation aircraft (which may not have or do not chose to use SSR).

At the required levels of Probability of Detection (P_d), a 1 dB reduction due to interference would result in a reduction in azimuth accuracy. Weak targets at lower P_d and under conditions of interference at the maximum protection level, - 6 dB I/N, could considerably exceed the limits on azimuth accuracy performance. Selective interference on one frequency of a two-frequency diversity radar can have more drastic effects that results from the corruption of a complete block of pulses of one of the frequencies being used.

Measurements on several radar systems have now been carried out world-wide and the effect on the average P_d has been determined. These reports have been published within the ITU and CEPT.

Using this average P_d as a measure of the detection performance reduction, the results suggest that if interfering signals are of a noise-like nature, and are at, or around, the current ITU protection levels of I/N = -6 dB, then this gives a measurable and significant reduction in radar performance. The evidence presented in this report suggests that for SOL services a -12 dB I/N should be adopted.

[6] Design considerations for adaptive active phased array "multifunction" radars IEE, ECEJ Dec 2001

[7] 1 or 2 m^2 targets are generally use to specify the performance of ARNS radars.

[8] Instrumented ranges are generally set below the maximum detection range for safety margin

There are possible other effects such as false alarms and false tracks; these effects are related to the temporal or spectral properties of the interference and result from the interference departing from Gaussian noise. Radar CFAR circuits operates best on Gaussian noise. Methods to reduce false alarms can only reduce the effective sensitivity of the system.

In pulse compression systems, for signals that do not appear noise-like the I/N needs to be considered at the output of the pulse compressor, (which the same as the input to the detector). Thus the effective compression ratio of the interfering signal needs to be ascertained.

Consideration has been given to the effects of RadioNavigation-Satellite Service (RNSS) signals on L-Band radar systems. Measurements have shown that such signals have very similar effects as the noise-like signals studied on the S-Band systems.

The paper in Annex 3 of this report replicates a recent UK paper on the subject of possible RNSS (GPS) interference with L Band ARNS radars. The two systems operate on a non-interference basis. A recent survey has shown that despite the RNSS signal strength being well above the radar system noise, no interference was reported. This is being used as evidence to introduce further services at higher power levels.[9]

One approach to mitigating the effect of interference is to design the radar assuming that the interference is present, effectively increasing the Signal to Noise Ratio (S/N) requirement for a given P_d. In older radars it may be possible to reduce the system noise level by replacing or adding a lower noise front end, thus increasing the S/N by reducing the noise or reducing other losses.[10] In more modern systems, the scope for reducing losses may be limited and the only mitigation option would be to increase the transmitter power. This seems perverse if the overall aim is to make better use of the spectrum as an increase in transmitter power will result in more interference to other users.

The following recommendations are made with respect to Protection Requirements that:

- ***The protection level of SOL systems be set to I/N of -12 dB and that specific sharing studies be carried out to confirm the adequacy.***
- ***The protection level for other radars is studied further to ascertain if -6 dB I/N is adequate.***
- ***The I/N level is specified at the input to the detector, not the receiver. This ratio should be defined in terms of total interference power and total noise***

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[9] The possible reasons that no effects have been observed are mainly due to the fact that radars currently have the ability to avoid operating close to RNSS frequencies and no radar has been currently identified as operating co-channel with an RNSS signal. It has also been confirmed that several of the GLONASS satellites are not operational. Recent work carried out in France has attempted to address the issues of why the interference is not seen by modelling the effects of targets moving against the background of a moving constellation of satellites. The model calculated the P_d for each detection of the target and used a tracking model to calculate the probability of maintaining a track. This showed that under the conditions in which the L-Band radars are used in France, the probability of maintaining the track is high and hence the interference may go unnoticed. In the UK, NATS have questioned the applicability of these results to the UK situation which is different to France. It is believed that some work is proposed to model the UK situation more closely prior to the development of a UK position for WRC 2003.

The current situation regarding the non-detection of interference may change, of course, if extra GLONASS frequencies come into use and if the Galileo satellite is given frequencies above 1260 MHz or the proposed increase in Global Positioning System (GPS) power density takes place.

[10] Assuming the protection criteria is observed for the lower level of system noise.

power to ensure that any issues of spectral power densities and relative bandwidths are resolved.

- ***If the -12 dB I/N protection level is exceeded, then further studies are required to ascertain if any mitigation option such a terrain screening or operational procedures can be applied.***
- ***The protection of Aeronautical Radio Navigation Service (ARNS) radars in the L-Band (Including that from RNSS[11]) is increased to -12 dB from the current -6 dB recommended in ITU-R Recommendation M.1463. It is also recommended that a specific PFD limit is imposed with respect to the protection of ARNS radars from interference from RNSS systems in the band 1215 to 1300 MHz. This would require consideration being given to footnote 5.329[12] of the Radio Regulations.***

The following recommendations are made in respect of general receiver design:

- ***The system should use the maximum values of IF and RF selectivity subject to the operational requirements of the design.***
- ***The appropriate mitigation options as defined in this report should be included subject to the required operation and cost of the radar.***

4.5 Summary of Mitigation Options Used In current Radar Systems

Table 4.5-1 gives a summary of mitigation options implemented in the generic radar types in use within the UK. **(note: some of these options are not implemented for interference reduction but for radar performance reasons)**

[11] Currently RNSS operates on a no interference basis.

[12] "5.329 Use of the radionavigation-satellite service in the band 1 215-1 300 MHz shall be subject to the condition that no harmful interference is caused to, and no protection is claimed from, the radionavigation service authorized under No.5.331. See also Resolution 606 (WRC-2000). (WRC-2000)"

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Table 4.5-1 Applicability of Mitigation Techniques

Radar Band	L-Band		S-Band			S-Band Marine		C-Band	X-Band		X-Band ATC			X-Band Marine				Ku-Band
Role ?	ATC		ATC			VTS	SOLAS	Weather	Weather		ACR	PAR	ASDE	SOLAS	VTS	Pleasure	Fishing	ASDE
TX Technology ? (mag = magnetron)	TWT	Mag	Solid State	TWT	Mag	Mag	Mag	Coaxial Mag	Solid State	Mag	Mag	Solid State	Mag	Mag	Mag	Mag	Mag	Mag
Mitigation Technique?																		
Receivers																		
Frequency Selective Down Converter	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sensitivity Time Control (STC)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Out of Band Interference Traps	✓	MO	MO	MO	MO	MO	MO	MO	NF	NF	NF	NF	MO	MO[13]	MO[13]	NF	NF	MO
Multi-frequency Operation	✓	OA	✓	✓	OA	NA	NA	NA	NA	NA	✓	NA	OA[14]	OA[14]	OA[14]	NA	NA	✓
Frequency Agility	NA	NA	NA	OA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Multiple PRR[15]	✓	✓	✓	✓	✓	✓[14]	✓[14]	OA	NF	NF	✓	✓	NF	✓[14]	✓[14]	NF	NF	✓
Constant False Alarm [16]Rate (CFAR)	✓	✓	✓	✓	✓	✓	✓	✓[17]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Matched Filter Receiver	✓	NF	✓	✓	NF	NF	NF	NF	✓	NF	NF	✓	NF	NF	NF	NF	NF	NF
Dicke Fix	NF	✓	NF	NF	NF	NF	NF	NF	NF	NF	✓	NF	NF	NF	NF	NF	NF	NF
Pulse Compression	✓	NA	✓	✓	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA
Pulse - Pattern Correlation	NF	NF	NF	OA	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
Pulse Integration	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pulse Blanking	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF	NF
De-Fruiting	NF	NF	NF	NF	NF	✓[14]	✓[14]	NF	NF	NF	NF	NF	NF	✓[14]	✓[14]	NF	NF	NF
Automatic Tracking	✓	OA	✓	✓	OA	✓	✓	✓	✓	✓	NF	NA	✓	✓	✓	NF	NF	✓

Key to table ✓ - This techniques is generally used
NA - This technique is not applicable to this type of system
OA - This technique is generally available as a standard option
MO - The technique could be provided as a modification
NF - This technique is generally not fitted and the required changes would be considered too extensive to fit as a modification

[13] Not applicable on systems where the Transmitter is located above the point of rotation.

[14] More expensive systems

[15] Not associated with a change of range

[16] Generally all systems have methods of reducing false alarms based on traditional CFAR methods or other systems.

[17] Long Term Integration acts to remove False Alarms

Radar Band	L-Band		S-Band			S-Band Marine		C-Band	X-Band		X-Band ATC			X-Band Marine				Ku-Band
Role ?	ATC		ATC			VTS	SOLAS	Weather	Weather		ACR	PAR	ASDE	SOLAS	VTS	Pleasure	Fishing	ASDE
TX Technology ? (mag = magnetron)	TWT	Mag	Solid State	TWT	Mag	Mag	Mag	Mag	Solid State	Mag	Mag	Solid State	Mag	Mag	Mag	Mag	Mag	Mag
Mitigation Technique ?																		
Transmitters																		
Main Beam Sector Blanking	NU	NU	NU	NU	NU	✓	✓	✓	✓	✓	NU	NA	✓	✓	✓	NF	NF	✓
Fit coaxial magnetrons	NA	MO	NA	NA	OA	MO	MO	OA	NA	✓	NA	NA	NA	NA	NA	NA	NA	NA
Fit filter between Transmitter & Antenna to suppress OOB	✓	MO	MO	MO	MO	MO	MO	MO	NA	NA	NA	NA	MO	MO[13]	MO[13]	NA	NA	✓
Fit Harmonic Filters	MO	MO	MO	MO	MO	MO	MO	MO	NA	NA	NA	NA	MO	MO[13]	MO[13]	NA	NA	MO
Fit filters to oscillators & mixers	MO	NA	✓	MO	NA	NA	NA	NA	✓	NA	NA	✓	NA	NA	NA	NA	NA	NA
Minimise swept frequency and maximise rise and fall time	✓	NA	✓	✓	NA	NA	NA	NA	NA	NA	NA	NA	✓	NA	✓	NA	NA	✓
Use longer pulse length, modify swept frequency and pulse compression	✓	NA	✓	✓	NA	NA	NA	NA	NA	NA	NA	✓	NA	NA	NA	NA	NA	NA
Use longest possible pulse length	NA	NA	✓	NA	NA	NA	NA	NA	✓	NA	NA	✓	NA	NA	NA	NA	NA	NA
LPI Waveforms	NA	NA	NA	NA	NA	NA	NF	NA	NA	NA	NA	NA	NA	OA	NA	NA	NA	NA
Antennas																		
Use solid reflector in place of mesh	MO	MO	✓	MO	MO	NA	NA	NA	NA	NA	✓	NA	✓	NA	✓	NA	NA	✓
Use latest design and manufacturing methods for low side & back lobes	MO	MO	✓	✓	MO	NA	NA	NA	NA	NA	NA	NA	MO	NA	NA	NA	NA	NA
Use single curve reflectors in place of double curved	MO	MO	MO	MO	MO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Radomes																		
Use sandwich radome in place of space frame designs	✓	OA	OA	✓	OA	NA	NA	OA	✓	✓	OA	✓	NA	NA	NA	NA	NA	✓
Frequency Selective[18] Surfaces	NA	NA	NA	NA	MO	MO	MO	NA	OA	MO	NA	MO	MO[19]	MO	MO	MO	MO	NA

Key to table:
- ✓ - This techniques is generally used
- NA - This technique is not applicable to this type of system
- NU - This technique is generally fitted but not used
- OA - This technique is generally available as a standard option
- MO - The technique could be provided as a modification
- NF - This technique is generally not fitted and the required changes would be considered too extensive to fit as a modification

[18] This techniques is only applicable for suppression of harmonic radiation. The cost on large radomes generally precludes its use.

[19] Slotted array antennas only

4.6 An Assessment of the Measurement Techniques described in ITU-R Recommendation M.1177-2 "Techniques for measurement of unwanted emissions of Radar Systems."

The investigation has shown that the direct measurement method currently gives the best option for measuring unwanted emissions from radar systems. The best results achieved with this method are obtained with the use of a dedicated test range, however in-service measurements are possible. It is doubtful, however, due to interference, that it would be appropriate for a formal "type approval" process to be carried out in situ. This does, to some extent, depend on what control is available of the radar being measured and other associated interference sources during the exercise. Type approval is likely to be better carried out on a manufacturer's integration facility, using the portable facility used for most of the measurements under this study, where more control of the EM environment and the radar is likely to be possible.

When revising ITU-R Recommendation M.1177-2 "Techniques for measuring unwanted emissions from radar systems", the following areas of change are recommended:

- ***The document needs to specifically clarify the requirements for OOB and SE measurements and recognise that they are different.***
- ***A pragmatic approach to the choice of the resolution bandwidth B_{res} and step size needs to be adopted to reduce the overall measurement time and allow for investigation of spurious signals. This approach should reflect the following points:***
  - ***It needs to resolve the issue of resolution bandwidths being recommended. It is suggested B_{res}= 1/t be recommended for SE measurements and for an initial assessment of the OOB region. For chirped pulses a resolution bandwidth of B_{res}=sqrt(Bc/t) is recommended for SE domain measurements.***
  - ***For un-chirped pulses should the OOB domain fail to meet the mask, or more accurate measurements be required for any other reason, then a finer measurement should be made using a narrower resolution bandwidth of B_{res} = 0.2/t.***
  - ***For chirped pulses for measuring the shape of the OOB region:***

    If 0.1Bc is greater than 0.5*sqrt(Bc/t) then a resolution bandwidth between the two values should be used.

    If 0.1Bc is less than 0.5*sqrt(Bc/t) then a resolution bandwidth of 0.1Bc should be used.

    If however it is required for other practical reasons, then carrying out measurements using a bandwidth of less than that recommended is acceptable, subject to the requirements of dynamic range.
  - ***This leaves the possibility in some combinations of pulse lengths and chirps of using the same bandwidth as for the SE domain, this would simplify the measurement and the presentation of results.***
  - ***Differing resolution bandwidths should be used to identify the true levels of signals in the SE region and to correct for any desensitisation issues. Bandwidth settings above and below the initial bandwidth setting should be used to ascertain the desensitisation law. If the initial setting is the widest bandwidth available on the test equipment, then the two settings below the initial setting should be used.***
  - ***The required step size for SE measurements needs to be defined as half the resolution bandwidth being used (0.5 B_{res}) to avoid missing the***

peak of signals. If measurement time is a problem or a less accurate measurement is acceptable, (say for a spectrum survey) then the fundamental region should be measured using a step size of 0.5 B_{res} and other regions using B_{res}. When measuring with narrow filters, such as those required to accurately resolve the OOB domain, then a step size equal to B_{res} is acceptable.

When measuring in the OOB region with narrow resolution bandwidth to determine the shape of the spectrum such as $B_{res} = 0.2/t$ for a non-chirped pulse or the appropriate bandwidth for a chirped radar, the step size could be increased to B_{res}.

- ***The requirements to measure 'indicated' values (as read off the equipment) as opposed to 'indented' values (that are corrected to account for the measurement tolerance) needs to be confirmed.***
- ***The conflict in the units specified for OOB & SE needs to be addressed, and in particular the need to specify power levels as EIRP.***
- ***Guidance as to the interpretation of the limits in terms of where in space to make measurements needs to be provided in line with the pragmatic approach set out in this section.***
- ***Time blanking receivers to filter out individual pulse types need to be considered.***
- ***Although it may not be possible to ascertain the peak of the P_{-1} mode due to analyser limitations, the rate of change of the signal with bandwidth should be investigated so an assessment of its likely level (above or below) any limit mask can be made. It is likely that with present systems a full characterisation will not be possible. Future wider band systems may provide a way forward in this area, however they may not provide sufficient dynamic range for the full investigation of the SE domain.***
- ***The use of the indirect method should not be recommended and should be dropped from ITU-R Recommendation M.1177-2. However it is recognised that some administrations would like it to remain. In this case, text must be added to state that the method "should only be used if the user can satisfy themselves that the characterisation of the antenna can be carried out to the stated accuracy of ± 6 dB". The transform programme given in the document should be withdrawn.***
- ***Guidance should be included on how to correct the measured data when measurements are made with a resolution bandwidth differing from the reference bandwidths defined either for PEP or SE.***
- ***In the current draft of the document there is an Annex 2 related to a version of the direct method for measuring low frequency radar, in particular HF and VHF radars. The resolution bandwidths specified are an order of magnitude lower than those recommended in Annex 1 of the document. They should be made equal to those specified in Annex 1.***

Given that it is not possible in a single measurement bandwidth to accurately measure all the parts of the spectrum, a pragmatic approach to the choice of the measurement bandwidth needs to be adopted in order to reduce the overall measurement time.

The following proposal is made as to the method to be defined in the revision of ITU-R Recommendation M.1177.

Step 1 ***Initial measurements should be made with the widest available bandwidth in order to ascertain the position of the peak values of the radar signal***

under consideration and for the identification of any potential interference sources.

Step 2 ***If the pulse parameters of this signal are known or can be measured, then the measurement of the UE region should be carried out with resolution bandwidth as recommended.***

If the pulse parameters are not known, then the practice of determining the resolution bandwidth by reducing the measurement bandwidth until the measured power is seen to drop should be used.

If it is not possible due to limitations of the measuring device to achieve a wide enough resolution bandwidth to accurately measure the PEP as described above, then the widest available resolution bandwidth should be used.

Step 3 ***Measure the fundamental and the UE using a step size equal to half the resolution bandwidth.***

Step 4 ***Following the measurement, the results need to be compared to the appropriate ITU UE mask. When applying the SE limits, for all cases the limit levels should be referenced to the fundamental PEP. If the resolution bandwidth used was sufficient to measure the true PEP, then the limit level shall be drawn reference to the peak of the fundamental signal. If not the level shall be offset by the desensitisation figure.***

The OOB region limit mask shall be referenced to the peak of the fundamental signal irrespective of the resolution bandwidth used.

Step 5 ***If the measurements in the SE domain were not made in a resolution bandwidth (B_{res}) equal to the reference bandwidth (B_{ref}) defined for SE, then the data in this region should be corrected for the difference in the bandwidth[20].***

Step 6 ***OOB Region[21]***

Should the OOB region fail to meet the ITU mask, or for any other reason it is required to make a higher fidelity measurement of this region, then a measurement should be made using a resolution bandwidth of either:

a) For non-chirped signals 0.2/τ , or 0.2/τc for phase coded pulses.

b) For chirped pulses:

- ***If 0.1Bc is greater than 0.5*sqrt(Bc/τ), then a resolution bandwidth between the two values should be used.***
- ***If 0.1Bc is less than 0.5*sqrt(Bc/τ), then a resolution bandwidth of 0.1Bc should be used.***

Note: This step is important because the OOB masks are derived from theoretical spectra. Using too wide a filter would disadvantage those manufacturing radars that produce a nearly rectangular spectrum the bandwidth of which will approaches the minimum required to achieve the required resolution.

[20] Using a range of different measurement bandwidths can aid in determining the appropriate correction factor. This is carried out by measuring the signal in bandwidths above or below the resolution bandwidths, or two bandwidths below the resolution bandwidth and calculating the rate of change of measured power with bandwidth.

[21] For chirped pulses in many cases the proposed SE resolution bandwidth will be more than adequate to resolve the OOB region.

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Section 5

Proposals for further work

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5 Proposals for further work

During the study several areas have been identified as being worthy of further investigation:

These proposals fall into two categories:

- Those associated with improvement to the measurement method:
- Pulse blanking measurement receivers.
- Wide band measurement receivers.
- Scanning antenna characterisation.
- Near-field characterisation.
- Those associated with the mitigation options for radar systems:
- The provision of fast tuning transmitter filters.
- Effects of non-noise-like interference.
- FM Radars for Maritime Radio Navigation.
- Further Analysis of Protection Requirements.
- Design Aim in ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain."

5.1 Proposals associated with improved measurement methods

5.1.1 Pulse Blanking Measurement Receivers

Radar systems operate with complex pulse patterns, with mixtures of pulses of differing length and chirps. It is not always possible to operate the radar in a single pulse mode while undertaking the measurements, either because it is not physically possible or the radar may have to be taken out of service to operate with a single pulse shape. The study has shown that it can be difficult to interpret composite patterns because of the issues of pulse desensitisation, the use of peak detectors and the variation in the maximum spectral power density (P_t).

One solution to the problem is to use a pulse-blanking receiver. Such receivers can be time gated so as to filter out the required pulse type.

Further work is required to investigate the feasibility of the use of such receivers.

5.1.2 Wide Band Measurement Receivers

Currently the measurement systems use receivers of bandwidths between 3 and 5 MHz, though some spectrum analysers can operate with bandwidths up to 10 MHz. Modern radars operate with pulses of 40 ns, which require measurement bandwidths of 25 MHz or more.

Further work is required to investigate the possibility of using a receiver with a bandwidth of up to 50 MHz.

5.1.3 Scanning Antenna Characterisation

The measurement of a mechanically rotating antenna is relatively straightforward, however antennas with scanning beams in azimuth and elevation present issues in just where in space to make the measurement. It must be remembered that UE emissions are a function not only of the pulse shape and frequency of the systems, but, in a scanning system, of the beam scan angle. This is particularly true of beams at harmonic frequencies that depend on the detailed phase response of the antenna and electronics. At harmonic frequencies, grating lobe beams are also formed which occur in directions well away from the main beam. There is also evidence that UE generated in the sidelobes may differ from those in the main beam.

Further work is required to develop a pragmatic solution to measuring such systems.

5.1.4 Near-field Characterisation

The indirect method requires the antenna to be measured in the near-field. The near-field measurement method described in ITU-R Recommendation M.1177 is however flawed due to the inherent errors in the method described and the near to far field transform proposed. A better method using a more comprehensive near-field range could be developed. In parallel the direct method could be adapted to use near-field measurements. This would give a more complete assessment of multi-beam scanning systems that can currently only be achieved with the direct method using far-field measurements.

5.2 Proposals associated with Mitigation Options

5.2.1 The Provision of Fast Tuning Transmitter Filters

Work in section 3.2 of this report has shown that filters can provide efficient suppression of unwanted emissions. They are particularly efficient for use in single channel radars or combinations of single channel radars where the filtering elements can be provided as part of the combining or diplexing/multiplexing functions. It has also been shown that filters can be used effectively to suppress radiation in bands outside the radar bands, in particular low pass filters are efficient at reducing harmonically related radiation. This type of filter can also be used where radars are operating in defined sub-bands.

Multi-frequency radars however present a problem since such radars generally operate in a frequency hopping mode in pulse to pulse or burst to burst timescales. Such a radar would require a filter that can be retuned in timescales in the orders of low numbers of milliseconds. Electronic tuning is the only option but as yet there are no devices known that can tune this fast with a sufficiently high Q. The requirement for high Q circuits enables the insertion loss to be kept within manageable proportions. This is particularly important in the transmitter side where insertion loss can lead to waste heat and power handling problems. High Q front end filters could also provide a benefit on receive, in that they would increase the ability of the radar to use the frequency band by reducing the adjacent channel separation required between radars and making them less susceptible to interference from other sources.

Further work is required to identify any possible candidate technologies suitable for use in active array radars.

5.2.2 Effects of Non-Noise-like Interference from Communication Systems

Communications signals are not truly Gaussian in nature and the assumptions generally used up until now by the radar community that the effect of this interference will wholly be on sensitivity, not on false alarms, may not be completely correct.

Further work is required to model in detail the operation of the radar signal processing and CFAR to assess the likelihood of false alarm generation.

5.2.3 Further Analysis of Protection Requirements

The recommendation of this report is that the protection requirements for SOL radars are increased to an I/N of -12 dB and that for other radars work is continued to underwrite (or not) the current level of -6dB.

5.2.4 FM Radars for Maritime Radio Navigation

This report highlighted that FM/CW or other LPI waveforms may possibly be used to reduce the interference between these types of radars which are generally magnetron based. These types of waveforms however cannot currently trigger SARTs and RACONs. It may however be possible to include within the radar waveform short, low power, pulses aimed at specifically triggering these devices. It is proposed that a feasibility study be undertaken to ascertain the efficacy of such an approach, both in terms of its radar performance and in terms of its likely level of interference. This could then be compared to the result achieved by a more traditional Magnetron radar approach.

5.2.5 Design Aim in ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain."

ITU-R Recommendation SM.1541 "Unwanted emissions in the out-of-band domain." contains a design aim of an OOB roll-off of -40dB/dec. Administrations have until 2006 to confirm the design aim. Work is required to support the ITU Radar Correspondence Group in an investigation to confirm if and what kind of radars can meet the more stringent requirements. In particular generic classes that cannot meet the design aim need to be identified.

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Annex 1

UK Civil Radar Systems

Introduction

Under the radar study contract, a survey was made of the radar models installed in the UK; the information from this survey was reduced to generic radar types based upon the radar role and operational frequency band. The parameters for these generic radar types/roles are given in section 3.1.2.

Annex 1 lists the parameters of the radar models/types identified as installed in the UK. The parameters listed have been derived from a variety of sources, each source having its own level of confidence. The main sources were:

- Manufacturers published data;
- Experience of similar Radar systems;
- Assessment by experienced Radar Engineers.

Due to the varying levels of confidence that the data actually reflects the installed systems, Annex 1 only identifies the systems by their role and a unique number.

Within Annex 1 the following abbreviations are used:

N/A - (Not applicable) - means that the particular parameter is not applicable to this type of radar.

NDA (No data available) - means that no data is available for this particular parameter, although the parameter is thought to be applicable.

Platform type (airborne, shipborne, ground)	Where the radar system is used; on land, at sea or in the air
Roles	The purpose for which the radar is installed
CHARACTERISTICS	
Radar Band	The radar frequency band (L, S, C, Ku, or X) in which this type of radar operates
Tuning range (GHz)	The frequency range over which this radar can be used
Operational Frequencies	The number of discrete frequencies that any one radar uses
Specific operating frequency	The actual operational frequency(ies) where it is not installation specific
Modulation	The form of modulation applied to the radar transmitter pulses using the ITU Radio Regulation emission codes where applicable; most radars use an unmodulated pulse
Tx Power into Antenna (kW)	The peak power of the transmitter output pulse
Pulse width (μs)	The width of the pulse amplitude measured between the -3 dB points. Many radars use two or more pulse lengths
Pulse rise/Fall time (μs)	The rise and fall times of the transmitter output pulse measured between the 10% and 90% levels
Pulse repetition rate (Hz)	The pulse repetition rate of the radar. Some radars use a mixture of PRRs and others the PRR changes with the selected display range
Duty cycle (%)	The percentage of time that the transmitter is transmitting (the mark/space ratio)
Chirp bandwidth (MHz)	The bandwidth of the FM modulation of the pulses used on some radar types
Phase-coded sub-pulse width	*no radars of this type in civil use in the UK*
Compression ratio	The ratio by which the receiver compresses the received pulses
RF emission bandwidth (-3 dB) (MHz)	The bandwidth of the transmitted pulses measured between the -3 dB points
RF emission bandwidth (-20 dB) (MHz)	The bandwidth of the transmitted pulses measured between the -20 dB points
RF emission bandwidth (-40 dB) (MHz)	The bandwidth of the transmitted pulses measured between the -40 dB points
Output device	The type of device used as the final output power amplifier in the transmitter
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	The shape of the elevation beam produced by the radar antenna
Antenna type (reflector, phased array, slotted array, etc.)	The type of antenna fitted to the radar
Antenna horizontal beamwidth (degrees)	The azimuth beamwidth of the antenna measured between the -3 dB points
Antenna polarisation	Whether the antenna radiates horizontal, vertical or circularly polarised RF
Antenna mainbeam gain (dBi)	The gain of the antenna compared to an isotropic radiator measured on the peak of the beam
Antenna vertical beamwidth (degrees)	The elevation beamwidth of the antenna measured between the -3 dB points
Antenna horizontal scan rate (degrees/sec)	The rate at which the antenna beam rotates in the azimuth plane
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Whether the antenna rotates continuously or performs a scan pattern
Antenna vertical scan rate (degrees/sec)	The rate at which the antenna beam scans in the elevation plane
Antenna vertical scan type	Whether the antenna scans continuously or performs a scan pattern in the elevation plane (i.e. continuous, random, 360 degrees, sector, etc.)
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	The level of the sidelobes with respect to the beam peak. Where only 1 figure is given, this can be taken to reflect both SLs.
Antenna height above ground or sea (m)	The height in metres that the electrical centre of the antenna is above ground (or sea) level
Receiver IF bandwidth (3 dB) (MHz)	The bandwidth of the radar receiver response measured at IF and between the -3 dB points
Receiver noise figure (dB)	The noise figure of the radar receiver
Minimum detectable signal (dBm)	The minimum signal that the radar receiver can detect in the presence of background noise and in a clutter free region
Receiver front-end 1 dB Gain Compression point. Power density at antenna (W/m^{2})	The power density into the radar antenna that causes the radar receiver to have a 1 dB gain compression
Receiver on-tune saturation level Power density at antenna (W/m^{2})	The power density into the radar antenna that causes the radar receiver to saturate
RF receiver 3 dB bandwidth (MHz)	The bandwidth of the radar front end receiver measured between the -3dB points
Proportion of time in use	The Proportion of time that the radar is normally in use

	ATC - 1	ATC - 2	ATC - 3
Platform type (airborne, shipborne, ground)	Ground	Ground	Ground
Roles	Civil ATC (TMA)	Civil ATC (TMA)	Civil ATC (TMA)
CHARACTERISTICS			
Radar Band	S	S	S
Tuning range (GHz)	2.7 to 3.1	2.7 to 2.9	2.7 to 2.9
Operational Frequencies	2 or 4 spaced at > 10 MHz	2 spaced at > 26 MHz	1 or 2
Specific operating frequency	-	-	-
Modulation	Non-linear FM, P0N	Non-linear FM, P0N	P0N
Tx Power into Antenna (kW)	60 Typical	12 Typical	750
Pulse width (μs)	0.4 to 40	4.0 to 73.5	0.85
Pulse rise/Fall time (μs)	0.015 typical	≈ 0.1	0.06
Pulse repetition rate (Hz)	550 to 1100	800 to 1225	1000(max)
Duty cycle (%)	2.5 Max	9.0	0.085
Chirp bandwidth (MHz)	2.5	1.7 to 2	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	Up to 100	Up to 100	N/A
RF emission bandwidth (-3 dB) (MHz)	2.5 (short pulse)	1.7 (short pulse) [1] 2 (long pulse)	1.2
RF emission bandwidth (-20 dB) (MHz)	16.8 (short pulse)	5.2 (short pulse) [1] 5.6 (long pulse)	5.2
RF emission bandwidth (-40 dB) (MHz)	55 (short pulse)	8.1 (short pulse) [1] 13 (long pulse)	22
Output device	TWT	Solid state	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Cosecant-squared	Cosecant-squared	Cosecant-squared
Antenna type (reflector, phased array, slotted array, etc.)	Reflector	Reflector	Reflector
Antenna horizontal beamwidth (degrees)	1.5	1.5	1.5
Antenna polarisation	Circular	Circular	Continuous variable Linear to Circular
Antenna mainbeam gain (dBi)	33.5 Typical	33.4 min	34
Antenna vertical beamwidth (degrees)	4.8	6.25	≈ 5
Antenna horizontal scan rate (degrees/sec)	72 to 90	72 to 90	72 to 90
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-26, -35	-30, -46	-28, -35
Antenna height above ground or sea (m)	4 to 30	4 to 30	12 to 30
Receiver IF bandwidth (3 dB) (MHz)	1.5 Long 3.5 Short	NDA	NDA
Receiver noise figure (dB)	2.0 max	1.5 max	3.5
Minimum detectable signal (dBm)	-123 Long pulse -104 Short pulse	-131.4	≈110
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	8.9×10^{-5} Short pulse	9×10^{-5}	2×10^{-5}
Receiver on-tune saturation level Power density at antenna W/m^2	3.1×10^{-10} Short pulse	1.2×10^{-9}	1×10^{-9}
RF receiver 3 dB bandwidth (MHz)	400	290	200
Proportion of time in use	1	1	1

[1] Estimated from pulse parameters

	ATC - 4	ATC - 5	ATC - 6
Platform type (airborne, shipborne, ground)	Ground	Ground	Ground
Roles	Civil ATC (TMA)	Civil ATC (TMA)	EnRoute
CHARACTERISTICS			
Radar Band	S	S	L
Tuning range (GHz)	2.7 to 2.9	2.7 to 3.1	1.26 to 1.30
Operational Frequencies	1 or 2	1 or 2	2 or 4
Specific operating frequency	-	-	-
Modulation	P0N	P0N	Non-linear FM
Tx Power into Antenna (kW)	900	625	160
Pulse width (μs)	0.5 to 3	1.0	66 & 3
Pulse rise/Fall time (μs)	NDA	0.06	0.03
Pulse repetition rate (Hz)	500 to 1500	700	420 & 830
Duty cycle (%)	≈ 0.15	0.07	2.8
Chirp bandwidth (MHz)	N/A	N/A	2.5
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	100:1 & 5:1
RF emission bandwidth (-3 dB) (MHz)	0.38 to 2	1	≈ 2.5 & 2.5
RF emission bandwidth (-20 dB) (MHz)	≈ 2.0 to 10.5	6.4	≈5.6 & 8
RF emission bandwidth (-40 dB) (MHz)	≈ 11.4 to 60	45	≈ 10.8 & 26.8
Output device	Coaxial Magnetron	Magnetron	TWT
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Cosecant Squared	Cosecant-squared	Composite
Antenna type (reflector, phased array, slotted array, etc.)	Reflector	Reflector	Reflector
Antenna horizontal beamwidth (degrees)	1.5	1.5	1.03
Antenna polarisation	Circular / Linear	Variable Linear to Circular	Circular
Antenna mainbeam gain (dBi)	34	32	35.3
Antenna vertical beamwidth (degrees)	≈ 5	5	3
Antenna horizontal scan rate (degrees/sec)	72 to 90	90	45 or 90
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-28, -35	Better than - 24	-22 , -34
Antenna height above ground or sea (m)	12 to 30	9 (standard tower)	35
Receiver IF bandwidth (3 dB) (MHz)	NDA	1.2	1.1 Short pulse 1.4 Long pulse
Receiver noise figure (dB)	3.5	4.5	4.5
Minimum detectable signal (dBm)	-107 Short pulse -115 Long pulse	NDA	-110
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	2.5×10^{-5}	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	1.4×10^{-9} Short pulse 2.1×10^{-10} Long pulse	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	200	100 (two Frequency systems)	200
Proportion of time in use	1	1	1

	ATC - 7	ATC - 8	ATC - 9
Platform type (airborne, shipborne, ground)	Ground	Ground	Ground
Roles	TMA	EnRoute	EnRoute
CHARACTERISTICS			
Radar Band	L	L	L
Tuning range (GHz)	1.26 to 1.30	1.25 to 1.30	1.20 to 1.30
Operational Frequencies	2 or 4	2 or 4	2 minimum of 35 MHz apart
Specific operating frequency	-	-	-
Modulation	Non-linear FM, P0N	Non-linear FM, P0N	P0N
Tx Power into Antenna (kW)	75	150	1800
Pulse width (μs)	33 & 1	0.8 & 50	3.6
Pulse rise/Fall time (μs)	≈ 0.03	0.02	0.06
Pulse repetition rate (Hz)	800 & 1600	680	380
Duty cycle (%)	2.6	3.4	0.14
Chirp bandwidth (MHz)	1	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	33:1	62.5:1	N/A
RF emission bandwidth (-3 dB) (MHz)	1.1 & 0.7	1.25 & 1.7	0.3
RF emission bandwidth (-20 dB) (MHz)	2.9 & 3	8.5 & 9.2	1.5
RF emission bandwidth (-40 dB) (MHz)	8.1 & 7.8	7 & 10	≈ 15
Output device	TWT	TWT	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Composite	Pencil/ cosec-squared	Cosecant-squared
Antenna type (reflector, phased array, slotted array, etc.)	Reflector	Reflector	Reflector
Antenna horizontal beamwidth (degrees)	1.03	1.03	1.1
Antenna polarisation	Circular	Circular	Variable Linear / Circular
Antenna mainbeam gain (dBi)	35.3	35.3	35
Antenna vertical beamwidth (degrees)	3	3	4.5
Antenna horizontal scan rate (degrees/sec)	45 or 90	60	42
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-22 , -34	-22, -34	-25 , -30
Antenna height above ground or sea (m)	35	35	15
Receiver IF bandwidth (3 dB) (MHz)	1.1 Short pulse 1.4 Long pulse	NDA	NDA
Receiver noise figure (dB)	4.5	1.25 nominal	3.5
Minimum detectable signal (dBm)	-110	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	200	NDA	NDA
Proportion of time in use	1	1	1

	ATC - 10	ATC - 11
Platform type (airborne, shipborne, ground)	Ground	Ground
Roles	Civil ATC (TMA)	Airfield Radar
CHARACTERISTICS		
Radar Band	S	X
Tuning range (GHz)	2.7 to 2.9	9 to 9.5
Operational Frequencies	4	2 Fixed
Specific operating frequency	-	9320, 9460
Modulation	Non-linear FM. P0N	P0N
Tx Power into Antenna (kW)	15, 30	55kW
Pulse width (μs)	1 & 100	0.2,0.5
Pulse rise/Fall time (μs)	0.169	≈ 0.15
Pulse repetition rate (Hz)	825 & 825	2000 & 1000
Duty cycle (%)	8.25	0.04 & 0.05
Chirp bandwidth (MHz)	1	N/A
Phase-coded sub-pulse width	N/A	N/A
Compression ratio	100:1(typical)	N/A
RF emission bandwidth (-3 dB) (MHz)	0.8 & 0.8	5, 2
RF emission bandwidth (-20 dB) (MHz)	2 & 1.4	≈ 22 & 16
RF emission bandwidth (-40 dB) (MHz)	4 & 2	50 - 150 [2]
Output device	Solid state	Magnetron x 2
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Cosecant-squared	Pencil (Lo beam), cosec squared (Hi beam)
Antenna type (reflector, phased array, slotted array, etc.)	reflector	reflector
Antenna horizontal beamwidth (degrees)	1.4	0.65
Antenna polarisation	linear and circular	circular
Antenna mainbeam gain (dBi)	35	Lo beam not less than 41.4, Hi beam not less than 37
Antenna vertical beamwidth (degrees)	4.5	2.5
Antenna horizontal scan rate (degrees/sec)	90	120 or 60
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A
Antenna vertical scan type	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-26, -40	Lo beam better than -23, Hi beam better than -20
Antenna height above ground or sea (m)	8.5	1.5
Receiver IF bandwidth (3 dB) (MHz)	≈ 0.8	7.5
Receiver noise figure (dB)	1.4	Not worse than 10
Minimum detectable signal (dBm)	≈ -110	-95
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	≈ 200	NDA
Proportion of time in use	1	0.33

[2] estimated from similar system

	Met - 1
Platform type (airborne, shipborne, ground)	Ground
Roles	Meterological
CHARACTERISTICS	
Radar Band	C
Tuning range (GHz)	5.450 to 5.825
Operational Frequencies	1
Specific operating frequency	5.625 GHz
Modulation	P0N
Tx Power into Antenna (kW)	250
Pulse width (µs)	0.5, 2.0
Pulse rise/Fall time (µs)	0.05
Pulse repetition rate (Hz)	300, 1200
Duty cycle (%)	0.06
Chirp bandwidth (MHz)	N/A
Phase-coded sub-pulse width	N/A
Compression ratio	N/A
RF emission bandwidth (-3 dB) (MHz)	2, 0.5
RF emission bandwidth (-20 dB) (MHz)	12, 3
RF emission bandwidth (-40 dB) (MHz)	60, 15
Output device	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil
Antenna type (reflector, phased array, slotted array, etc.)	reflector
Antenna horizontal beamwidth (degrees)	1
Antenna polarisation	vertical
Antenna mainbeam gain (dBi)	43
Antenna vertical beamwidth (degrees)	1
Antenna horizontal scan rate (degrees/sec)	Stationary, 0.6 to 36
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous or stationary
Antenna vertical scan rate (degrees/sec)	10
Antenna vertical scan type	sector, helix or stationary
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-25, -30
Antenna height above ground or sea (m)	5 to 20
Receiver IF bandwidth (3 dB) (MHz)	0.75 & 3.0
Receiver noise figure (dB)	4.5
Minimum detectable signal (dBm)	-108
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	1.25×10^{-3}
Receiver on-tune saturation level Power density at antenna W/m^2	NDA
RF receiver 3 dB bandwidth (MHz)	50
Proportion of time in use	1

	Marine - 1	Marine - 2	Marine - 3
Platform type (airborne, shipborne, ground)	Shipborne	Shipborne	Shipborne
Roles	Civil IMO/Fishing	Civil IMO/Fishing	Civil IMO/Fishing
CHARACTERISTICS			
Radar Band	S	X	X
Tuning range (GHz)	3.050 ± 10MHz	Fixed	Fixed
Operational Frequencies	1	1	1
Specific operating frequency		9.41	9.41
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	25	25/30	10
Pulse width (μs)	0.07/0.9	0.07/0.9	0.05/0.65
Pulse rise/Fall time (μs)	≈ 0.015	≈ 0.025	≈ 0.025
Pulse repetition rate (Hz)	3000, 375	1500	1500, 750
Duty cycle (%)	0.02, 0.03	0.02, 0.03	0.05, 0.0075
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	≈ 1.1 to 14.3	≈ 1.1 to 14.3	≈ 1.5 to 20
RF emission bandwidth (-20 dB) (MHz)	≈ 8 to 63	≈ 8 to 63	≈ 12 to 88
RF emission bandwidth (-40 dB) (MHz)	50 to 150	50 to 150	50 to 150
Output device	Magnetron	Magnetron	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	13 ft Slotted array	6 ft Slotted array	7.5 ft Slotted array
Antenna horizontal beamwidth (degrees)	1.8	1.2	1
Antenna polarisation	Pencil	Pencil	Pencil
Antenna mainbeam gain (dBi)	28	30.5	31
Antenna vertical beamwidth (degrees)	24	25	25
Antenna horizontal scan rate (degrees/sec)	144 or 240	138 or 168	138
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-26, -31	-26, -31	-0.75
Antenna height above ground or sea (m)	Depends on vessel	Depends on vessel	Depends on vessel
Receiver IF bandwidth (3 dB) (MHz)	20/4	20/4	20/4
Receiver noise figure (dB)	5	5.5	5.5
Minimum detectable signal (dBm)	NDA	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

	Marine - 4	Marine - 5	Marine - 6
Platform type (airborne, shipborne, ground)	Shipborne	Shipborne	Shipborne
Roles	Civil IMO/Fishing	Civil IMO/Fishing	Civil IMO/Fishing
CHARACTERISTICS			
Radar Band	S	X	X
Tuning range (GHz)	3.050 ± 10MHz	9.41 ± 10MHz	9.41 ± 10MHz
Operational Frequencies	1	1	1
Specific operating frequency			
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	25	25/30	10
Pulse width (µs)	0.07/0.9	0.07/0.9	0.05, 0.65
Pulse rise/Fall time (µs)	≈ 0.015	≈ 0.015	≈ 0.015
Pulse repetition rate (Hz)	3000/375	3000/375	1500, 750
Duty cycle (%)	0.02	0.02	0.05, 0.0075
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	≈ 1.1 to 14.3	≈ 1.1 to 14.3	≈ 1.5 to 20
RF emission bandwidth (-20 dB) (MHz)	≈ 8 to 63	≈ 8 to 63	≈ 12 to 88
RF emission bandwidth (-40 dB) (MHz)	50 to 150	50 to 150	50 to 150
Output device	Magnetron	Magnetron	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	13 ft Slotted array	6 ft Slotted array	7.5 ft Slotted array
Antenna horizontal beamwidth (degrees)	1.8	1.2	1
Antenna polarisation	Pencil	Pencil	Pencil
Antenna mainbeam gain (dBi)	28	30.5	31
Antenna vertical beamwidth (degrees)	24	25	25
Antenna horizontal scan rate (degrees/sec)	144	168	138
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-29	-29	-0.75
Antenna height above ground or sea (m)	Depends on vessel	Depends on vessel	Depends on vessel
Receiver IF bandwidth (3 dB) (MHz)	20/4	20/4	20/4
Receiver noise figure (dB)	5	5.5	5.5
Minimum detectable signal (dBm)	NDA	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

	Marine - 7	Marine - 8	Marine - 9
Platform type (airborne, shipborne, ground)	Shipborne	Shipborne	Shipborne
Roles	IMO	IMO	Civil IMO /Fishing
CHARACTERISTICS			
Radar Band	X	S	X
Tuning range (GHz)	9.401 ± 30 MHz	3.050 ± 10 MHz	9.401 ± 30Mz
Operational Frequencies	1	1	1
Specific operating frequency	-	-	-
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	25	30	10 or 25
Pulse width (µs)	0.08, 0.35, 0.80	0.07, 0.4, 0.85	0.05, 0.25, 0.8
Pulse rise/Fall time (µs)	≈ 0.015	≈ 0.015	NDA
Pulse repetition rate (Hz)	1600, 800, 400	2300, 800, 400	1800/785
Duty cycle (%)	0.01	0.01	0.01
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	≈ 1.25 to 12.5	1.2 to 14.3	≈ 1.25 to 20
RF emission bandwidth (-20 dB) (MHz)	≈ 5 to 10	6.3 to 9.6	≈ 5 to 88
RF emission bandwidth (-40 dB) (MHz)	50 to 150	51 to 150	52 to 150
Output device	Magnetron	Magnetron	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	8/10 ft Slotted array	13 ft Slotted array	4 ft, 6 ft, 8 ft slotted array
Antenna horizontal beamwidth (degrees)	1.0 or 0.75	NDA	2, 1.3, 1.0
Antenna polarisation	Horizontal	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	31 & 33	27	29/30/31
Antenna vertical beamwidth (degrees)	18	24	24
Antenna horizontal scan rate (degrees/sec)	216	216	168, 270
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-25	-25	-23, -30
Antenna height above ground or sea (m)	Depends on vessel	Depends on vessel	Depends on vessel
Receiver IF bandwidth (3 dB) (MHz)	20	20	23/30
Receiver noise figure (dB)	9	8	5
Minimum detectable signal (dBm)	NDA	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	20, 10, 2.5	20, 10, 2.5	NDA
Proportion of time in use	NDA	NDA	NDA

	Marine - 10	Marine - 11	Marine - 12
Platform type (airborne, shipborne, ground)	Shipborne	Shipborne	Shipborne
Roles	Civil IMO /Fishing	Navigation and surface surveillance	Navigation and surface surveillance
CHARACTERISTICS			
Radar Band	S	S	X
Tuning range (GHz)	3.050 ± 10 MHz	3 to 3.1	9.1 to 9.5
Operational Frequencies	1	1	1 or 2
Specific operating frequency	-	-	-
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	30	25	20
Pulse width (µs)	0.05, 0.25, 0.8	0.06 or 0.6	0.06 or 0.6
Pulse rise/Fall time (µs)	NDA	0.02	0.02
Pulse repetition rate (Hz)	1800 or 785	800 or 8000	800 or 8000
Duty cycle (%)	0.01	0.026	0.026
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	≈ 1.25 to 20	≈ 1 to 20	≈ 1 to 25
RF emission bandwidth (-20 dB) (MHz)	≈ 10 to 88	≈ 18 to 68	≈ 18 to 110
RF emission bandwidth (-40 dB) (MHz)	53 to 150	≈ 50 to 150	≈ 50 to 150
Output device	Magnetron	Magnetron	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	9 ft, 12 ft slotted array	7ft, 12 ft slotted array	15ft slotted array
Antenna horizontal beamwidth (degrees)	2.8, 2.0	<1.2, < 0.6	<2.0
Antenna polarisation	Horizontal	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	25, 26	> 30, > 32	>28.5
Antenna vertical beamwidth (degrees)	30	19	20
Antenna horizontal scan rate (degrees/sec)	168, 270	up to 288 , up to 360	up to 180
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-23, -30	NDA	NDA
Antenna height above ground or sea (m)	Depends on vessel	Depends on vessel	Depends on vessel
Receiver IF bandwidth (3 dB) (MHz)	23, 30	3, 20	3, 20
Receiver noise figure (dB)	5	< 4.7	< 4.7
Minimum detectable signal (dBm)	NDA	-100 to - 88	-100 to - 88
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	3, 3.1	9.1, 9.5
Proportion of time in use	NDA	NDA	NDA

	Marine - 13	Marine - 14	Marine - 15
Platform type (airborne, shipborne, ground)	Shipborne	Shipborne	Shipborne
Roles	Navigation and surface surveillance	Navigation and surface surveillance	Navigation and surface surveillance
CHARACTERISTICS			
Radar Band	X	X	X
Tuning range (GHz)	Fixed	Fixed	Fixed
Operational Frequencies	1	1	1
Specific operating frequency	9.410 ± 0.03	9.410 ± 0.03	9.410 ± 0.03
Modulation	P0N, Q3N	P0N, Q3N	P0N, Q3N
Tx Power into Antenna (kW)	2	4	4
Pulse width (μs)	0.08, 0.25, 0.7	0.08, 0.25, 0.7	0.065, 0.09, 0.15, 0.35, 0.45, 0.6, 1.0
Pulse rise/Fall time (μs)	≈ 0.015	≈ 0.015	≈ 0.015
Pulse repetition rate (Hz)	2250, 1500, 750	2250, 1500, 750	3000, 2000, 1600, 1200, 740
Duty cycle (%)	0.02 to 0.05	0.01	0.02 to 0.27
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	≈ 1.4 to 12.5	≈ 1.4 to 12.5	1 to 15.4
RF emission bandwidth (-20 dB) (MHz)	≈ 11.2 to 58	≈ 11.2 to 58	≈ 8 to 68
RF emission bandwidth (-40 dB) (MHz)	≈ 50 to 150	≈ 50 to 150	≈ 50 to 150
Output device	Magnetron	Magnetron	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	18 inch, Patch Array	24 inch, Patch Array	48 inch Slotted Waveguide Array
Antenna horizontal beamwidth (degrees)	5.2	3.9	1.85
Antenna polarisation	Horizontal	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	NDA	NDA	≈ 29
Antenna vertical beamwidth (degrees)	25	25	25
Antenna horizontal scan rate (degrees/sec)	144	144	144
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	< -22	< -22	< -22
Antenna height above ground or sea (m)	Depends on vessel	Depends on vessel	Depends on vessel
Receiver IF bandwidth (3 dB) (MHz)	12, 3, 1	12, 3, 1	12.0, 3.0, 0.7, 0.5
Receiver noise figure (dB)	< 5	< 5	< 5
Minimum detectable signal (dBm)	-101 (worst case)	-101 (worst case)	-101 (worst case)
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

	Marine - 16	Marine - 17	Marine - 18
Platform type (airborne, shipborne, ground)	Shipborne	Shipborne	Shipborne
Roles	Navigation and surface surveillance	Navigation and surface surveillance	Navigation and surface surveillance
CHARACTERISTICS			
Radar Band	X	X	X
Tuning range (GHz)	Fixed	Fixed	Fixed
Operational Frequencies	1	1	1
Specific operating frequency	9.410 ± 0.03	9.410 ± 0.03	9.410 ± 0.03
Modulation	P0N, Q3N	P0N, Q3N	P0N, Q3N
Tx Power into Antenna (kW)	4	10	10
Pulse width (µs)	0.065, 0.09, 0.15, 0.35, 0.45, 0.6, 1.0	0.065, 0.09, 0.15, 0.35, 0.45, 0.6, 1.2	0.065, 0.09, 0.15, 0.35, 0.45, 0.6, 1.2
Pulse rise/Fall time (µs)	≈ 0.015	≈ 0.015	≈ 0.015
Pulse repetition rate (Hz)	3000, 2000, 1600, 1200, 740	3000, 2000, 1600, 1200, 740	3000, 2000, 1600, 1200, 740
Duty cycle (%)	0.02 to 0.27	0.02 to 0.09	0.02 to 0.09
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	1 to 15.4	1 to 15.4	1 to 15.4
RF emission bandwidth (-20 dB) (MHz)	≈ 8 to 68	≈ 8 to 68	≈ 8 to 68
RF emission bandwidth (-40 dB) (MHz)	≈ 50 to 150	≈ 50 to 150	≈ 50 to 150
Output device	Magnetron	Magnetron	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan	Fan
Antenna type (reflector, phased array, slotted array, etc.)	72 inch Slotted Waveguide Array	48 inch Slotted Waveguide Array	72 inch Slotted Waveguide Array
Antenna horizontal beamwidth (degrees)	1.15	1.85	1.15
Antenna polarisation	Horizontal	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	≈ 31	≈ 29	≈ 31
Antenna vertical beamwidth (degrees)	25	25	25
Antenna horizontal scan rate (degrees/sec)	144	144	144
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	< -25	< -22	< -25
Antenna height above ground or sea (m)	Depends on vessel	Depends on vessel	Depends on vessel
Receiver IF bandwidth (3 dB) (MHz)	12.0, 3.0, 0.7, 0.5	12.0, 3.0, 0.7, 0.5	12.0, 3.0, 0.7, 0.5
Receiver noise figure (dB)	< 5	< 5	< 5
Minimum detectable signal (dBm)	-101 (worst case)	-101 (worst case)	-101 (worst case)
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

	Marine - 19	Marine - 20
Platform type (airborne, shipborne, ground)	Shipborne	Shipborne
Roles	LPI Radar	LPI Radar
CHARACTERISTICS		
Radar Band	X	X
Tuning range (GHz)	NDA	NDA
Operational Frequencies	2	2
Specific operating frequency	NDA	NDA
Modulation	FMCW	FMCW
Tx Power into Antenna (kW)	1.0 - 0.001W	1.0 - 0.001 W
Pulse width (μs)	CW	CW
Pulse rise/Fall time (μs)	N/A	N/A
Pulse repetition rate (Hz)	Sweep repetition rate 1000Hz	Sweep repetition rate 1000Hz
Duty cycle (%)	1	1
Chirp bandwidth (MHz)	54	54
Phase-coded sub-pulse width	N/A	N/A
Compression ratio	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	≈ 54	≈ 54
RF emission bandwidth (-20 dB) (MHz)	N/A	N/A
RF emission bandwidth (-40 dB) (MHz)	N/A	N/A
Output device	Solid-state	Solid-state
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	uses existing antenna	fan
Antenna type (reflector, phased array, slotted array, etc.)	uses existing antenna	dual slotted waveguide
Antenna horizontal beamwidth (degrees)	uses existing antenna	1.4
Antenna polarisation	uses existing antenna	Horizontal
Antenna mainbeam gain (dBi)	uses existing antenna	30
Antenna vertical beamwidth (degrees)	uses existing antenna	20
Antenna horizontal scan rate (degrees/sec)	uses existing antenna	144
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A
Antenna vertical scan type	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	uses existing antenna	-26 , -30
Antenna height above ground or sea (m)	Depends on vessel	Depends on vessel
Receiver IF bandwidth (3 dB) (MHz)	0.512	0.512
Receiver noise figure (dB)	5	3.5
Minimum detectable signal (dBm)	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA
Proportion of time in use	NDA	NDA

	VTS - 1	VTS - 2	VTS - 3
Platform type (airborne, shipborne, ground)	ground, coastal	ground, coastal	ground, coastal
Roles	VTS	VTS	VTS
CHARACTERISTICS			
Radar Band	X	S	X
Tuning range (GHz)	9.3 to 9.5	3.05	9.375 to 9.9
Operational Frequencies	1	1	1
Specific operating frequency	-	-	-
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	10, 25	30	25
Pulse width (µs)	0.05, 0.25, 0.8	3 x 0.05 to 1 [3]	3 x 0.05 to 1 [3]
Pulse rise/Fall time (µs)	0.02	≈ 0.02	0.015
Pulse repetition rate (Hz)	1800, 785	3 x 500 to 4000 [4]	3 x 500 to 4000 [4]
Duty cycle (%)	NDA	0.05	0.05
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	1.25 to 20	1 to 20	2 to 20
RF emission bandwidth (-20 dB) (MHz)	≈10 to 88	≈ 8 to 88	≈ 16 to 88
RF emission bandwidth (-40 dB) (MHz)	≈ 50 to 100	≈ 50 to 100	≈ 50 to 100
Output device	Magnetron	Magnetron	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan	Inverse cosecant squared/ Fan
Antenna type (reflector, phased array, slotted array, etc.)	Slotted array 4 ft, 6 ft, 8ft	Slotted array, 14 ft	Reflector/ Slotted array 8 ft to 22 ft
Antenna horizontal beamwidth (degrees)	2, 1.3, 1	1.6	NDA / 0.9 to 0.3
Antenna polarisation	Horizontal	Horizontal	Circular / Horizontal
Antenna mainbeam gain (dBi)	29, 30,31	28	>39 / 31 to 36
Antenna vertical beamwidth (degrees)	24	20	NDA / 20
Antenna horizontal scan rate (degrees/sec)	168,270	120, 138	120, 138
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	continuous, 360 degrees	continuous, 360 degrees	continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	N/A	N/A	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-23,-30	-25, -30	NDA / -28, - 33
Antenna height above ground or sea (m)	NDA	30	≈ 30
Receiver IF bandwidth (3 dB) (MHz)	23/30	20	20
Receiver noise figure (dB)	5	3	3
Minimum detectable signal (dBm)	-93 (worst case)	-95 (worst case)	-95 (worst case)
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	3 to 3.1	NDA
Proportion of time in use	1	1	1

[3] Each installation uses 3 pulse widths within the range 0.05 to 1µs

[4] Each installation uses 3 PRR within the range 500 to 4000 Hz

	VTS - 4
Platform type (airborne, shipborne, ground)	ground, coastal
Roles	VTS
CHARACTERISTICS	
Radar Band	X
Tuning range (GHz)	9.1 to 9.5
Operational Frequencies	1 or 2
Specific operating frequency	
Modulation	P0N
Tx Power into Antenna (kW)	20
Pulse width (µs)	0.06 or 0.6
Pulse rise/Fall time (µs)	0.02
Pulse repetition rate (Hz)	NDA
Duty cycle (%)	NDA
Chirp bandwidth (MHz)	N/A
Phase-coded sub-pulse width	N/A
Compression ratio	N/A
RF emission bandwidth (-3 dB) (MHz)	≈ 1 to 25
RF emission bandwidth (-20 dB) (MHz)	≈ 12.6 to 63
RF emission bandwidth (-40 dB) (MHz)	≈ 50 to 150
Output device	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan
Antenna type (reflector, phased array, slotted array, etc.)	8 ft Slotted array
Antenna horizontal beamwidth (degrees)	≈ 0.4
Antenna polarisation	Circular
Antenna mainbeam gain (dBi)	≈ 36
Antenna vertical beamwidth (degrees)	≈ 24
Antenna horizontal scan rate (degrees/sec)	120, 138
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A
Antenna vertical scan type	N/A
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	≈ 26 - 33
Antenna height above ground or sea (m)	NDA
Receiver IF bandwidth (3 dB) (MHz)	3 to 50
Receiver noise figure (dB)	<4.7
Minimum detectable signal (dBm)	-100 to - 88
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA
RF receiver 3 dB bandwidth (MHz)	9.1 to 9.5
Proportion of time in use	1

	Airborne-1	Airborne-2	Airborne-3
Platform type (airborne, shipborne, ground)	Airborne	Airborne	Airborne
Roles	Weather	Weather	Weather
CHARACTERISTICS			
Radar Band	X	X	X
Tuning range (GHz)	9.3 to 9.5	9.3 to 9.5	9.3 to 9.5
Operational Frequencies	1	1	1
Specific operating frequency	9.33 GHz	9.33 GHz	9.33 GHz
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	0.145	0.035	0.035
Pulse width (µs)	1 to 20	1.8,2.4,4.8,9.6, 19.2,28.8	1.8,2.4,4.8,9.6, 19.2,28.8
Pulse rise/Fall time (µs)	≈ 0.02	≈ 0.02	≈ 0.02
Pulse repetition rate (Hz)	180 to 9000	NDA	NDA
Duty cycle (%)	NDA	NDA	NDA
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	0.05 to 1 [5]	0.035 to 0.55 [5]	0.035 to 0.55 [5]
RF emission bandwidth (-20 dB) (MHz)	0.32 to 6.4 [5]	0.30 to 6.4 [5]	0.30 to 6.4 [5]
RF emission bandwidth (-40 dB) (MHz)	3.2 to 53 [5]	3.2 to 54 [5]	3.2 to 54 [5]
Output device	Solid state	Solid state	Solid state
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil	Pencil	Pencil
Antenna type (reflector, phased array, slotted array, etc.)	Flat Plate	Flat Plate	Flat Plate
Antenna horizontal beamwidth (degrees)	3.5	8	8
Antenna polarisation	Pencil	Pencil	Pencil
Antenna mainbeam gain (dBi)	34.4	26	26
Antenna vertical beamwidth (degrees)	3.5	8	8
Antenna horizontal scan rate (degrees/sec)	NDA	27	27
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	60 degree Sector	120 degree Sector	120 or 60 degree Sector
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	tilt range ± 15 degrees	tilt range ± 15 degrees	tilt range ± 15 degrees
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-31 dB	NDA	NDA
Antenna height above ground or sea (m)	N/A [6]	N/A [6]	N/A [6]
Receiver IF bandwidth (3 dB) (MHz)	NDA	NDA	NDA
Receiver noise figure (dB)	4dB	NDA	NDA
Minimum detectable signal (dBm)	-125	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

[5] Estimated from pulse shape

[6] Many Aircraft use their weather radar on landing

	Airborne-4	Airborne-5	Airborne-6
Platform type (airborne, shipborne, ground)	Airborne	Airborne	Airborne
Roles	Weather	Weather	Weather
CHARACTERISTICS			
Radar Band	X	X	X
Tuning range (GHz)	9.3 to 9.5	9.3 to 9.5	9.3 to 9.5
Operational Frequencies	1	1	1
Specific operating frequency	9.33 GHz		
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	0.035	0.035	0.15
Pulse width (μs)	1.8,2.4,4.8,9.6, 19.2,28.8	1.8,2.4,4.8,9.6, 19.2,28.8	1 to 20
Pulse rise/Fall time (μs)	≈ 0.02	≈ 0.02	≈ 0.02
Pulse repetition rate (Hz)	NDA	NDA	180 to 9000
Duty cycle (%)	NDA	NDA	0.36 to 0.9
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	0.035 to 0.55 [5]	0.035 to 0.56	1 to 0.05
RF emission bandwidth (-20 dB) (MHz)	0.30 to 6.4 [5]	0.22 to 3.56 [5]	0.3 to 64 [5]
RF emission bandwidth (-40 dB) (MHz)	3.2 to 54 [5]	2.2 to 35.6 [5]	3.2 to 54 [5]
Output device	Solid state	Solid state	Solid State
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil	Pencil	Pencil
Antenna type (reflector, phased array, slotted array, etc.)	Flat Plate	Flat Plate, 18 inch	Flat Plate, 28
Antenna horizontal beamwidth (degrees)	7	6	3.5
Antenna polarisation	Pencil	Pencil	Pencil
Antenna mainbeam gain (dBi)	27	28	35
Antenna vertical beamwidth (degrees)	7	6	2.5
Antenna horizontal scan rate (degrees/sec)	27	27	NDA
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	120 or 60 degree Sector	120 or 60 degree Sector	NDA
Antenna vertical scan rate (degrees/sec)	N/A	N/A	N/A
Antenna vertical scan type	tilt range ± 15 degrees	tilt range ± 15 degrees	tilt range ± 15 degrees
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	NDA	NDA	-30 dB
Antenna height above ground or sea (m)	N/A [6]	N/A [6]	N/A [6]
Receiver IF bandwidth (3 dB) (MHz)	NDA	NDA	NDA
Receiver noise figure (dB)	NDA	NDA	NDA
Minimum detectable signal (dBm)	NDA	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

	Airborne-7	Airborne-8	Airborne-9
Platform type (airborne, shipborne, ground)	Airborne	Airborne	Airborne
Roles	Weather	Weather	Weather
CHARACTERISTICS			
Radar Band	X	X	X
Tuning range (GHz)	Fixed	Fixed	Fixed
Operational Frequencies	1	1	1
Specific operating frequency	9.345 GHz	9.345 GHz	9.345 GHz
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	10 nom, 12 max.	12 max.	3.5
Pulse width (μs)	1 or 2	1 or 2	1 or 2
Pulse rise/Fall time (μs)	0.015	0.015	0.015
Pulse repetition rate (Hz)	NDA	NDA	NDA
Duty cycle (%)	NDA	NDA	NDA
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	1 to 0.5	1 to 0.5	1 to 0.5
RF emission bandwidth (-20 dB) (MHz)	≈ 2.2 to 8	≈ 2 to 4	≈ 2.2 to 8
RF emission bandwidth (-40 dB) (MHz)	≈ 50 to 150	≈ 50 to 150	≈ 50 to 150
Output device	Magnetron	Magnetron	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil	Pencil	Pencil
Antenna type (reflector, phased array, slotted array, etc.)	Flat Plate Slotted array 12 inch dia.	Flat Plate Slotted array 12 or 18 inch dia.	Flat Plate slotted array 10 or 12 inch dia.
Antenna horizontal beamwidth (degrees)	NDA	NDA	NDA
Antenna polarisation	Horizontal	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	NDA	NDA	NDA
Antenna vertical beamwidth (degrees)	NDA	NDA	NDA
Antenna horizontal scan rate (degrees/sec)	NDA	NDA	NDA
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	120 or 60 degree Sector	120 or 60 degree Sector	120 or 60 degree Sector
Antenna vertical scan rate (degrees/sec)	N/A	NDA	NDA
Antenna vertical scan type	tilt range ± 15 degrees	tilt range ± 15 degrees	tilt range ± 15 degrees
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	-20, -25	-20, -25	-20, -25
Antenna height above ground or sea (m)	N/A [6]	N/A [6]	N/A [6]
Receiver IF bandwidth (3 dB) (MHz)	NDA	NDA	NDA
Receiver noise figure (dB)	NDA	NDA	NDA
Minimum detectable signal (dBm)	NDA	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

	Airborne-10	Airborne-11	Airborne-12
Platform type (airborne, shipborne, ground)	Airborne	Airborne	Airborne
Roles	Surface mapping, Weather & Beacon	Weather & turbulence	Weather & turbulence
CHARACTERISTICS			
Radar Band	X	X	X
Tuning range (GHz)	Fixed	Fixed	Fixed
Operational Frequencies	1	1	1
Specific operating frequency	9.345 GHz	9.345 GHz	9.345
Modulation	P0N	P0N	NDA
Tx Power into Antenna (kW)	12 max.	12 max.	125 Watts
Pulse width (μs)	1 or 2	1 or 2	1.5, 6, 18
Pulse rise/Fall time (μs)	0.015	0.015	≈ 0.02
Pulse repetition rate (Hz)	NDA	NDA	6000, 1600, 380
Duty cycle (%)	NDA	NDA	1 max
Chirp bandwidth (MHz)	N/A	N/A	NDA
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	1 to 0.5	1, 0.5	0.8, 0.17, 0.06
RF emission bandwidth (-20 dB) (MHz)	≈ 2.2 to 8	≈ 2.2 to 8	5.1, 1.1, 0.4 [5]
RF emission bandwidth (-40 dB) (MHz)	≈ 50 to 150	≈ 50 to 150	51.2, 10.7, 3.6 [5]
Output device	Magnetron	Magnetron	Solid State
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Pencil	Pencil	Pencil
Antenna type (reflector, phased array, slotted array, etc.)	Flat Plate Slotted array 5 sizes, 10 to 24 inches	Flat Plate Slotted array 3 sizes 12, 18 & 24 inches	Flat Plate Slotted array 2 sizes 30 & 24 inches
Antenna horizontal beamwidth (degrees)	NDA	NDA	2.9 & 3.6
Antenna polarisation	Horizontal	Horizontal	Horizontal
Antenna mainbeam gain (dBi)	NDA	NDA	35, 33
Antenna vertical beamwidth (degrees)	NDA	NDA	2.9, 3.6
Antenna horizontal scan rate (degrees/sec)	NDA	NDA	45, 38
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	NDA	NDA	Sector
Antenna vertical scan rate (degrees/sec)	NDA	NDA	38 or 45
Antenna vertical scan type	tilt range ± 15 degrees	tilt range ± 15 degrees	tilt range ± 15 degrees
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	NDA	NDA	NDA
Antenna height above ground or sea (m)	N/A [6]	N/A [6]	N/A [6]
Receiver IF bandwidth (3 dB) (MHz)	NDA	NDA	NDA
Receiver noise figure (dB)	NDA	NDA	NDA
Minimum detectable signal (dBm)	NDA	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

	Military - 1	Military - 2	Military - 3
Platform type (airborne, shipborne, ground)	Ground based (mobile)	Ground based (mobile)	Ground based (mobile)
Roles	Air Defence	Air Defence	Air Defence
CHARACTERISTICS			
Radar Band	L	S	S
Tuning range (GHz)	1.215 to 1.4	NDA	2.7 to 3.1
Operational Frequencies	NDA	NDA	NDA
Specific operating frequency			
Modulation	NDA	NDA	NDA
Tx Power into Antenna (kW)	46	> 24	150
Pulse width (μs)	NDA	NDA	NDA
Pulse rise/Fall time (μs)	NDA	NDA	NDA
Pulse repetition rate (Hz)	NDA	NDA	NDA
Duty cycle (%)	18	NDA	NDA
Chirp bandwidth (MHz)	NDA	NDA	NDA
Phase-coded sub-pulse width	NDA	NDA	NDA
Compression ratio	NDA	NDA	NDA
RF emission bandwidth (-3 dB) (MHz)	NDA	NDA	NDA
RF emission bandwidth (-20 dB) (MHz)	NDA	NDA	NDA
RF emission bandwidth (-40 dB) (MHz)	NDA	NDA	NDA
Output device	NDA	NDA	NDA
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	NDA	NDA	NDA
Antenna type (reflector, phased array, slotted array, etc.)	array	slotted array	slotted array
Antenna horizontal beamwidth (degrees)	3.4	NDA	1.4
Antenna polarisation	NDA	NDA	NDA
Antenna mainbeam gain (dBi)	38.9	NDA	NDA
Antenna vertical beamwidth (degrees)	1.7 to 1.4	NDA	2.4
Antenna horizontal scan rate (degrees/sec)	72 & 36	36	36
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	continuous 360 degrees	continuous 360 degrees	continuous 360 degrees
Antenna vertical scan rate (degrees/sec)	NDA	NDA	NDA
Antenna vertical scan type	NDA	NDA	NDA
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	NDA	NDA	NDA
Antenna height above ground or sea (m)	NDA	NDA	NDA
Receiver IF bandwidth (3 dB) (MHz)	NDA	NDA	NDA
Receiver noise figure (dB)	NDA	NDA	NDA
Minimum detectable signal (dBm)	NDA	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA	NDA
Proportion of time in use	NDA	NDA	NDA

	Military - 4	Military - 5
Platform type (airborne, shipborne, ground)	Ground based	Ground based
Roles	PAR	PAR
CHARACTERISTICS		
Radar Band	X	X
Tuning range (GHz)	9 to 9.6	9 to 9.6
Operational Frequencies	NDA	NDA
Specific operating frequency	9 to 9.2GHz	9 to 9.2GHz
Modulation	NDA	NDA
Tx Power into Antenna (kW)	80	NDA
Pulse width (µs)	NDA	NDA
Pulse rise/Fall time (µs)	NDA	NDA
Pulse repetition rate (Hz)	NDA	NDA
Duty cycle (%)	NDA	NDA
Chirp bandwidth (MHz)	NDA	NDA
Phase-coded sub-pulse width	NDA	NDA
Compression ratio	NDA	NDA
RF emission bandwidth (-3 dB) (MHz)	NDA	NDA
RF emission bandwidth (-20 dB) (MHz)	NDA	NDA
RF emission bandwidth (-40 dB) (MHz)	NDA	NDA
Output device	Solid state	Magnetron
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	NDA	Fan & Pencil
Antenna type (reflector, phased array, slotted array, etc.)	active circular array	Line fed reflector
Antenna horizontal beamwidth (degrees)	NDA	NDA
Antenna polarisation	NDA	NDA
Antenna mainbeam gain (dBi)	NDA	NDA
Antenna vertical beamwidth (degrees)	NDA	NDA
Antenna horizontal scan rate (degrees/sec)	NDA	NDA
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	sector 0 to 7 degrees	NDA
Antenna vertical scan rate (degrees/sec)	NDA	NDA
Antenna vertical scan type	NDA	NDA
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	NDA	NDA
Antenna height above ground or sea (m)	NDA	NDA
Receiver IF bandwidth (3 dB) (MHz)	NDA	NDA
Receiver noise figure (dB)	NDA	NDA
Minimum detectable signal (dBm)	NDA	NDA
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	NDA
Proportion of time in use	NDA	NDA

	ASDE-1	ASDE-2	ASDE-3
Roles	Airport surface movement	Airport surface movement	Airport surface movement
Platform type (airborne, shipborne, ground)	Groundbased	Groundbased	Groundbased
CHARACTERISTICS			
Radar Band	X	X	Ku
Tuning range (GHz)	Fixed	9.1 to 9.5	15.4 to 16.4
Operational Frequencies	1	1 or 2	2
Specific operating frequency	9410 GHz		15.9 & 16.4 GHz
Modulation	P0N	P0N	P0N
Tx Power into Antenna (kW)	10	20	20
Pulse width (µs)	0.04	0.06 or 0.6	0.04
Pulse rise/Fall time (µs)	0.015	0.02	0.016
Pulse repetition rate (Hz)	4000	800-8000	8192
Duty cycle (%)	0.016	0.026	0.033
Chirp bandwidth (MHz)	N/A	N/A	N/A
Phase-coded sub-pulse width	N/A	N/A	N/A
Compression ratio	N/A	N/A	N/A
RF emission bandwidth (-3 dB) (MHz)	25	≈ 1 to 25	14.3
RF emission bandwidth (-20 dB) (MHz)	≈ 73	≈ 12.6 to 63	50
RF emission bandwidth (-40 dB) (MHz)	≈ 150	≈ 50 to 150	119
Output device	Magnetron	Magnetron	Magnetron x 2
Antenna pattern type (pencil, fan, cosecant-squared, etc.)	Fan	Fan	Inverse $cosec^{1.4}$
Antenna type (reflector, phased array, slotted array, etc.)	18ft, open array	15ft slotted array	Shaped Reflector
Antenna horizontal beamwidth (degrees)	0.4	<2.0	0.33
Antenna polarisation	Horizontal	Horizontal	Circular
Antenna mainbeam gain (dBi)	36	>28.5	41
Antenna vertical beamwidth (degrees)	≈ 20	20	3.5
Antenna horizontal scan rate (degrees/sec)	360	up to 180	360
Antenna horizontal scan type (continuous, random, 360 degrees, sector, etc.)	Continuous, 360 degrees	Continuous, 360 degrees	Continuous, 360 degrees
Antenna vertical scan rate (degrees/sec)	N/A	NDA	NA
Antenna vertical scan type	N/A	N/A	NA
Antenna sidelobe levels (1st SLs and remote SLs) (dB)	≈ -23, -30	NDA	≈ -26, -35
Antenna height above ground or sea (m)	NDA [7]	NDA [7]	NDA [7]
Receiver IF bandwidth (3 dB) (MHz)	NDA	3 to 20	30
Receiver noise figure (dB)	NDA	< 4.7	NDA
Minimum detectable signal (dBm)	NDA	-100 to - 89	-90
Receiver front-end 1 dB Gain Compression point. Power density at antenna W/m^2	NDA	NDA	NDA
Receiver on-tune saturation level Power density at antenna W/m^2	NDA	NDA	NDA
RF receiver 3 dB bandwidth (MHz)	NDA	9.1 to 9.5	NDA
Proportion of time in use	0.75	0.75	0.75

[7] Normally mounted on an airport building

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Annex 2

COMMENTS ON “PRELIMINARY DRAFT REVISION OF

RECOMMENDATION ITU-R M.1177-2”

Document 8B/159-E

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COMMENTS ON "PRELIMINARY DRAFT REVISION OF RECOMMENDATION ITU-R M.1177-2"

Techniques for measurement of unwanted emissions of radar systems

1 Introduction

This document comments on some outstanding technical issues that are associated with the current draft of the Document 8B/100, Attachment 2, June 2001.

These issues should be resolved before the adoption of such a document can take place.

Essentially the issues relate to the following areas:

a) the use of the appropriate measurement bandwidth for the type of measurements being made;

b) the required step size between measurements;

c) the achievable accuracy and appropriateness of the indirect method;

d) error budgets;

e) anomaly in the specified limits.

a) The use of the appropriate measurement bandwidth for the type of measurements being made

The document[1] is titled "Techniques for measurement of unwanted emissions of radar systems". Unwanted emissions include both Spurious Emissions (SE) and Out-of-Band (OOB) emissions. These are referenced in ITU documents RR Appendix S3 "Spurious Emissions" (See also Final Acts WRC-2000) and ITU-R SM.[OOB], "Out-of-Band emissions" (Doc. 1/BL/11) as the specified method of measurement for radar systems.

The documents "Annex 8 of Doc. 1/BL/11" & "Spurious emissions" (Doc. 1/BL/8), likewise cross-refer to the Recommendation ITU-R M.1177.

The measurement bandwidths required to make accurate measurements of these two parameters is very different. In Section 2 of the document, specifications for the measurement bandwidths are given which it is felt are inappropriate. In Appendix 1, a different method is given for setting the measurement bandwidth.

The measurement bandwidth needs to be set depending on the type of measurement being made.

Measurements of SE

These are effectively EIRP measurements at the spurious frequencies concerned, the aim being to measure the equivalent isotropically radiated power of each of the signals in the SE region. This requires a measurement bandwidth wide enough to capture all the significant power. If the measurement is defined in relative terms, then the signal level at the fundamental frequency is also important as this provides the reference. Section 2 specifies:- ***"≤(0.5/T) for fixed-frequency, non-pulse-coded radars, where T: pulse length. (E.g. if radar pulse length is 1 μs, then the measurement IF bandwidth should be ≤ 0.5/(1 μs) = 500 kHz.)".***

For a rectangular pulse 1/T is approximately the limit to capture all the energy; any narrower would introduce errors. For a trapezoidal pulse, 1/T is generally acceptable providing that the T>> Tr (Tr = Rise time). It would thus appear that setting the bandwidth to 0.5/T would give significant error in measuring the spurious EIRP.

When considering chirped or coded pulses, the bandwidth required in order to capture the energy, i.e. the measurement bandwidth required ≈ 1/Tcp (Where Tcp is the compressed pulse length).

The bandwidth specified in the document is:- ***"≤ (0.5/t) for fixed-frequency, phase-coded pulsed radars, where t : phase-chip length. (E.g. if radar transmits 26 μs pulses, each pulse consisting of 13 phase coded chips that are 2μs in length, then the measurement IF bandwidth should be***
≤ 0.5/(2 μs) ≤ 250 kHz.)" Assuming the system compresses down to one phase chirp length the bandwidth to measure the spurious EIRP should be 1/t not 0.5/t as specified.

For swept frequency radars the transmission bandwidth ≈ to the chirp bandwidth B, the document specifies ***"≤ 0.5 (B/T)½, for swept-frequency (FM, or chirp) radars, where B:***

[1] Throughout this paper the term "the document" refers to the latest draft issue of Rec. ITU-R M.1177 as specified in the title of this paper.

range of frequency sweep during each pulse and T: pulse length. (E.g. if radar sweeps (chirps) across frequency range of 1 250-1 280 MHz (= 30 MHz of spectrum) during each pulse, and if the pulse length is 10μs, then the measurement IF bandwidth should be: ≤0.5((30 MHz)/(10 μs))^{½} = 0.5 (3)^{½} = 0.87 MHz.)". This bandwidth if far too narrow to measure spurious EIRP.

For a multi-mode radar the process described in the document will arrive at a bandwidth approaching what is required, however a 5 dB tolerance would seem excessive.

Measurement of OOB emissions

The OOB emission limits are recommended in Annex 8 of Doc. 1/BL/11. These limits specify a spectral mask which OOB emissions must not exceed.

The aim of these measurements is to ascertain in fine detail the shape of the spectrum envelope. To do this the system must use a much narrower bandwidth than that required for SE. In order to resolve the spectrum including its spectral lobes, it is recommended that a bandwidth of 0.03/T is used for a rectangular pulse. Using this approach and approximating in order to simplify the recommendation, the following measurement bandwidths should be recommended.

Rectangular or Trapezoidal pulses where T >> Tr	= 0.03/T
Coded Pulses	= 0.03/t
FM Pulsed Radars T>> Tr	= 0.03*B

This will enable the system to resolve the shape of the main spectral lobes and the sidelobes accurately over the OOB region until the SE boundary is reached.

b) The required step size between measurements

Currently the document specifies a step size equal to the measurement bandwidth for the computer controlled method. This can lead to excessive measurement times. It is proposed that the step size be chosen as follows.

When measuring OOB emissions, the step size equals the measurement bandwidth over the region 10 X Bw_{-40} i.e. over the complete region between the upper and lower SE boundaries.

In the SE region the steps should be at a minimum of 1/T unless the system allows a dynamic range of 70 dB i.e. the SE limit (i.e. 60 dB category A limits of Doc. 1/BL/8) + 10 dB to be achieved with a wider filter. If it is possible, the step size should be set to the widest step commensurate with the measurement bandwidth. If spurious signals are at levels > -5 dB relative to the limit under consideration then these should be re-measured using the bandwidth defined above. The extent of the re-measurement should be limited to the frequencies adjacent to SE being measured.

c) The achievable accuracy and appropriateness of the indirect method

The indirect method as described would seem to have several in built error sources that have not been allowed for. As a detailed error breakdown is not available it is not possible to comment on what effect they would have on the final measurement uncertainty.

These include:

- Errors caused by the assumption that when added together the transmitter SE levels (measured into a correct load) and the measured gain can simply be added to give the SE value. Practice has shown that the result is a function of the system components and the feed layout.
- Test range multi-path errors.
- The use of the transform which does not correct for the receiver antenna gain and the effective aperture when the SE is not on boresight and any taper on the Antenna Under Test (AUT) can cause significant errors.
- The specified measurement distances particularly for larger low frequency antennas

It is suggested that further work is required in order to ascertain the final level of uncertainty, and whether the results that can be achieved, are of a suitable accuracy for the Recommendation.

d) Error budgets

In order to use the method to ascertain compliance with limits, or comparison between the methods an error budget needs to be provided. A typical error budget needs to be given for each of the methods. Once an error budget has been determined it will be possible to agree if the limits to be measured should be indicated or indented values.

e) Anomaly in the specified limits

The method described in the documents is to be used to ascertain compliance to the SE limits laid down in the new version of RR Annex S3. The current proposals are given in “Spurious emissions” (Doc. 1/BL/8). For radar systems two sets of limits apply; category A and category B.

The category A limits are specified as relative measurements of PEP (strictly speaking these should be EIRP). No resolution bandwidth is given. If the same measurement bandwidth is used and a correction is made for the receive antenna gain, then the SE limits are consistent within themselves.

There is now however an inconsistency at the boundary between OOB and SE and also for any OOB emissions that fall in the SE domain. In order to make the two limits consistent the same resolution bandwidth would have to be specified.

There are further complications in the class B limits. These are specified as -30 dBm or 100 dB below PEP, whichever is less stringent; again no resolution bandwidth is given. As indicated above, there is no difficulty for the relative measurement, however -30 dBm is specified as PEP. This has the units of power and needs to be specified as an EIRP to be meaningful, and a resolution bandwidth must be indicated.

There will also be a difficulty in defining the SE/OOB boundary however, as the shape of the OOB mask and the category B SE OOB boundary have yet to be defined.

There is a difficulty in Doc. 1/BL/8 Table 10; “Absolute levels of spurious domain emission”. The levels are specified in PEP watts and dBm, but again, no resolution bandwidth is specified and the power should be EIRP. If this is not the case, the level specified would depend on the TX & RX antenna gains and the range at which the measurement is made.

2 Conclusions

Further work and studies are being undertaken and it is proposed that until the aforementioned issues can be resolved, the document should not be finalised in its present form.

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Annex 3

SHARING BETWEEN THE RADIONAVIGATION SATELLITE SERVICE (SPACE-TO-EARTH) AND RADIOLOCATION/ RADIONAVIGATION (S5.331) SERVICES ALLOCATED ON A CO-PRIMARY BASIS IN THE 1 215-1 300 MHZ BAND

WRC-03 Agenda item 1.15, Resolution 606

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SHARING BETWEEN THE RADIONAVIGATION SATELLITE SERVICE (SPACE-TO-EARTH) AND RADIOLOCATION/ RADIONAVIGATION (S5.331) SERVICES ALLOCATED ON A CO-PRIMARY BASIS IN THE 1 215-1 300 MHz BAND

WRC-03 Agenda item 1.15, Resolution 606

1 Introduction

Currently the radiolocation service (RLS) is allocated on a co-primary basis with the radionavigation satellite service (RNSS) in the band 1 215-1 300 MHz. This band is also allocated to the radionavigation service in a number of countries under footnotes **S5.331** and the portion above 1 240 MHz is allocated to the aeronautical radionavigation service in two countries under **S5.334**. The use of the band by the RNSS is subject to **S5.329** and **Resolution 606 (WRC-2000).** The primary surveillance radar (PSR) systems in these bands are subject to the protection requirements defined in Recommendation ITU-R M.1463; "Characteristics and protection criteria for radars operating in the radiodetermination service in the frequency band 1 215-1 400 MHz" covering radars of the radiolocation and aeronautical radio navigation services.

ITU-R M.1463 specifies a protection requirement of I/N of -6 dB. Work reported in papers 8B/64 (8D/93) and 8D/18 indicate that a worst-case power flux density of [-133] $dBW/m^2/MHz$ can be present at the radar antenna from satellites of the RNSS. Using published radar characteristics (ITU-R M.1463), it is possible to calculate that in the worst case, using a pfd of -133 $dBW/m^2/MHz$, the resulting I/N ratio is $\approx$ 22 dB, some 28 dB greater than the current -6 dB I/N protection level.

Currently, the band 1 215-1 260 MHz is shared inter alia between the RNSS, RLS and RNS service, and papers report that no interference has been observed between them. Document 8B/148 (also 8D/185) carries out a simplified analysis on the likely effect of these levels of interference on the probability of detection (Pd) and probability of false alarms (Pfa). It concludes that whilst the performance of the radar would be seriously degraded in the direction of the satellites, that operationally, this is not significant. It is not known whether there are papers that carry out an operational analysis on the degradation of performance to assess the effect of such a reduction in performance on the safety of an air-traffic control (ATC) system using such radars.

Based on this lack of reported interference and the simplified analysis, it has been proposed to replace the protection criteria required for RNSS signals over the band 1 215-1 260 MHz to [-133] dBW/m^2/MHz and to extend this new protection requirement over the band 1 260-1 300 MHz.

To this end, modified CPM text was proposed in Attachment 16 of the chairman's report of the 11th meeting of WP8D.

This document comments on these proposals and raises concerns, in that the operational analysis may not be complete. Annex 1 of this document comments on the analysis method used in Document 8B/148.

2 Effect of interference

The effect of interference on the radar system depends on the level of the interference, how the interference is processed within the radar and what effect the output has, on the operation of the system.

Level of Interference

The level of interference from the RNSS seen by a radar depends on the number of satellites in the radar beam at any one time and their position within the antenna's radiation pattern. As the radar beam is narrow in azimuth and the satellites are well spaced, it is likely that only one satellite will appear at a specific azimuth. Satellites low on the horizon will appear close to the peak of the antenna's main beam. The antenna's elevation pattern and azimuth side-lobes will suppress others in view. Each satellite will produce a maximum pfd of -133 dBW/m^2/MHz. As the antenna scans, the level of interference will rise and fall depending on the elevation of the individual satellites.

The signal level received will also depend on the width of the radar receiver's IF filter. The wider the filter bandwidth, the more signal will be received, until the filter becomes wider than the bandwidth of the interference. Using the figures provided in the references, the interfering signal could be up to 22 dB above the noise using the maximum figures quoted for GLONASS (-133 dBW/m^2/MHz) and the most sensitive radar type (received pfd level producing I/N of –6 dB, pfd_{-6dB}) of $\approx$ -161 dBW/m^2/MHz.

How the interference affects the radar

The effect that the interference has on the radar depends on the type and structure of the interfering signal. Depending on the signal, the effect will be either to reduce the detection ability of the radar or produce false detections (false alarms) or a mixture of both. The analysis surveyed in Annex 1 would indicate that the interference of the type produced by satellites in the RNSS is likely to be noise-like and hence will predominantly result in loss of detections.

Effect of interference on the operation of the system

High levels of loss of detection results in the inability to detect targets or a loss of tracks on previously detected targets. False targets can have several effects; they can produce false plots or tracks and high levels of these can contribute to operator workload and fatigue. A very high number of false plots can overload the radar's data processing and data links.

Dependent on the bearing of the satellite, the loss of detection could persist for many scans resulting in a blind arc. Experiments with noise like interference at this level, on essentially a fixed bearing, have shown that there is a loss of the ability to detect targets in the sector containing the interference. See Annex 2. The levels shown in this Annex are comparable with the worst case figures based on the requested protection level of [-133] dBW/m^2/MHz at the antenna.

3 Operational Issues

Operationally, the acceptability of any proposed level of interference can only be decided on by those charged with operating the system, taking into account the requirements placed on the integrity of the radar data, and the availability of complimentary systems such as secondary surveillance radar (SSR) etc. It is not possible in this paper to make that judgement for the operating organisations. It is important however, to draw a distinction between these operating organisations and the end users of the radar system, for example air traffic controllers, as it is the latter that would be aware of the effects of interference on the operational radar display. However, requirements placed on radar manufacturers for design proving, system optimisation in the area of false alarms, Pd and missed plots etc, would not seem consistent with the degradation predicted in Document 8B/148.

Operationally, interference of this type would result in sectors of low Pd. As the satellites move, the bearing of this sector will move in azimuth.

Document 8B/148 shows sectors with the range reduced to 70% of normal range, or conversely, a loss of larger targets at maximum range and a loss of smaller targets at shorter ranges on the same bearing. It should be noted that these results are calculated using GPS interference levels of -142 dBW/m^2/MHz and -147 dBW/m^2/MHz which are well below the worst-case protection requirements (-133 dBW/m^2/MHz for GLONASS) which would result in ranges being reduced to ≈ 30%. The paper also uses in the example, a radar of pfd_{-6dB} ≈ -155 dBW/m^2/MHz. This is some 7 dB worse than the most sensitive radar quoted. Observation of Figure 2 of 8B/148 shows that even at the GPS level of –142 dBW/m^2/MHz quoted, the range would be approximately at the 50% figure for the more sensitive radars quoted.

Assessments of the nature of the interfering signal have led to the belief that it will cause the constant false alarm rate (CFAR) clutter map circuits to seriously reduce the sensitivity of the radar in the direction of the satellite, the absolute effect depending on the elevation angle. The worst effect will occur for low elevation satellites near the peak of the antenna's elevation pattern, typically 2° to 7°. The nature of the relatively slow motion of the satellite will mean that the reduction in Pd will be of an insidious nature that may not be noticed by operators or automatic tracking systems.

4 Why interference may not be reported

The submissions requesting the change in the current protection level make much of the issue that no interference from RNSS has been reported. This could be for several reasons; see 8D/137.

The signal is not causing interference

Currently RNSS systems operate in the band 1 215-1 260 MHz. It is possible that some administrations are limiting their radiolocation/radionavigation radars to the band 1 260-1 300 MHz, or at least avoiding the RNSS system frequencies, however, some of the responses to Administrative Circular CA/102 indicate that this is not the case for all administrations.

The interference exists but is not observed or reported

It may be that the interfering signal is lower than predicted (10 dB margin) or it may be that the effects are occurring as described, but that operators do not observe the interference. This may be due to many factors; the position of the satellites relative to air traffic areas for example, or the fact that the interference is in narrow sectors. It may be that the use of tracking algorithms on the outputs of the PSR to interpolate between successive targets is masking missing detections so that they are not obvious to the operator. The only way to check this is to specifically look for the interference. A possible method may be to record data from the PSR (Primary surveillance radar) and the SSR (Secondary surveillance radar) and correlate this with the satellite positions. The number of lost primary detections could then be measured directly as could the satellite's pfd.

However the fact that the interference is not obvious does not mean it does not exist and that it is not having an effect on the radar's Pd and its resulting SIL (Safety Integrity Level).

It may also be the case that the operators of radar systems are not providing a safety of life function and are able to mitigate against interference without requiring to report it to the administration concerned.

5 Comments on proposed new CPM Text

The proposed changes in Attachment 16 of the chairman's report of the 11 meeting of WP 8D are predicated by the fact that no interference has been reported. Work is under way to study if this assertion is correct (see 8D/98). The proposed text suggests the adoption of the new protection level of [-133] dBW/m^2/MHz over the whole 1 215-1 300 MHz band. If it transpires that protection is being provided by the assignment of suitable frequencies by administrations, this would be made much more difficult if more RNSS frequencies are spread over the whole band. There may be however, other reasons why it may be preferable to avoid the overlapping of RNSS system frequencies.

It is recommended that this new text and the proposed protection requirement of [-133] dBW/m^2/MHz should not be adopted until studies are complete and the operational issues have been studied further to confirm that the integrity of ATC radars in particular not being compromised. Any studies should include trials specifically designed to "look for" the effects of interference and to measure the associated pfd. Such trials could consist of recording PSR and SSR data in the areas of satellite interference and correlating the change in Pd and Pfa with the Pfd seen from the satellite. The SSR data would provide the reference data.

ANNEX 1

Specific comments on method of calculation and results given in 8B/148, 8D/185

The paper refers to a 'Safety Margin'. It is thought that this means that the maximum pfd can be XdB greater than the minimum pfd. This 'Safety Margin' changes from 10dB to 5dB, thus making the interference less severe. Since the purpose of the paper is to identify why the interference has not been observed, it may be argued that we should take the best case rather than the worst case in our assumptions, as the interference could be at the lower end of the predicted range, therefore 5 dB can be accepted as a conservative figure. However, if we wish to define a protection requirement, the 5 dB must be considered optimistic and the worst case [10] dB should be used.

The paper goes on to use this 5dB safety margin in the calculations and show that the performance of the radar is reduced in such a way that the range for a given Pd is reduced by 30% (to a value of 70%). This constitutes notable degradation but the paper has not considered what the value would be if the 10dB safety margin had been used. The result would be even worse. The illustration also uses figures quoted for GPS, however the results for GLONASS would be 11 dB higher. It also calculates the effect on the least sensitive radar. Taking this into account the reduction in range would be approaching 70% i.e. a detection range of 30%. The ranges are also all referenced to the pfd_{-6dB} that assumes an inherent degradation to start with, although they should be referenced to the no interference case.

Although a Pfa = 1e-5 is suggested in 8B/148, a Pfa = 1e-6 is generally considered for ATC systems. Figure 6 should be plotted on a log scale for Pfa to show the real extent of the change.

The paper comments that the increase in Pfa is small and not noticeable by the operator. However, the operator is quite likely to notice that many false alarms appear on the screen.

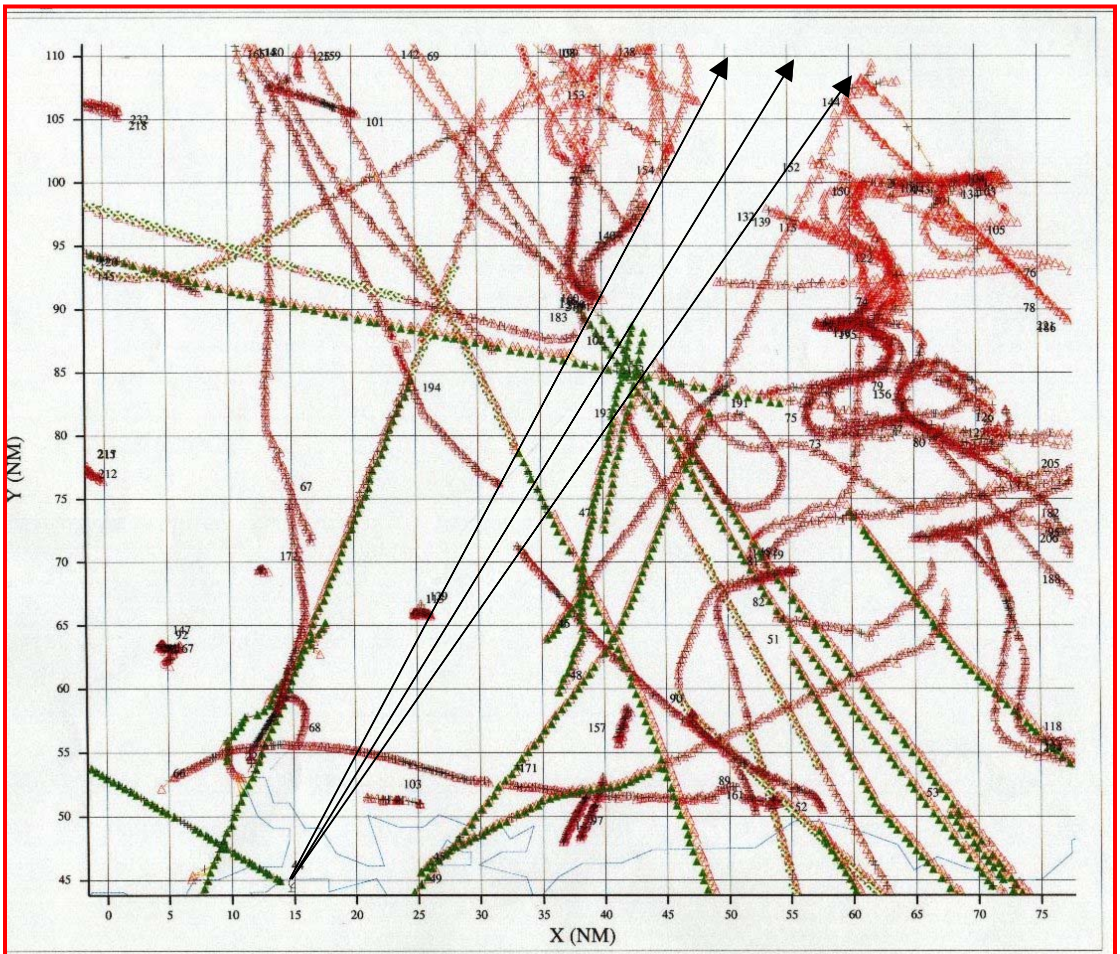
The paper notes that the operators do not seem to notice the reduction in Pd/range performance. This is not surprising since it is much more difficult to see a target that is not displayed than false ones that are. The source of this subjective information is unclear. It is not known in this case how the PSR and SSR data are fused, but it would be useful to compare the number of times a secondary reply is not matched with a primary target return. This would give some indication of what is occurring to the PSR's range performance.

Document 8B/148 is makes a judgement of what is acceptable. To a radar designer, reduction to 70% range would seem severe but it is not the radar designer's decision but the decision of the organisation operating the radar system and the ATC community may have some concerns with this approach. It is assumed that the performance requirements on the radars are defined from an operational requirement and if this is to detect a given target with a given Pd, then reducing that range to 70% or less would undoubtedly lead to the radar not meeting this requirement.

The interference originates from the satellites. As the paper illustrates, it may be coming from a number of directions. To the ground based radar these satellites appear to move slowly so that this interference will appear in the same Azimuth for some time. Thus, if a wanted target is at long range in the same azimuth as the satellite and is travelling towards the radar then the target may be invisible for a long time, which may be unacceptable.

ANNEX 2

Example of the effect of Noise Interference I/N 19 dB



umts_day_2_b (oc2f) , Step 10, Wedge 028 to 035, MDS + 35 dB, 1st Quadrant

Key: - Light triangles (red) - Primary Radar Detections

- Dark distinct triangles (green) - Secondary Radar Detections

This recording shows a ≈ 8° sector of simulated noise-like interference at a level of 19 dB above the radar system noise. The level of interference was set to within the 10 dB range of Max/Min pfd ratio (see 8B/64) of RNSS interference being proposed and less than the maximum of [-133] dBW/m^2/MHz. In the case of RNSS interference, this sector would correspond to the radar antenna's azimuth beamwidth plus a reduced level of interference in the beamwidths either side. The interference is thus likely to affect a sector of a few beamwidths in azimuth.

Note the specific lack of primary tracks within the sector showing that the radar has been desensitised in this region.

Notes:

1 The equipment used for the recording was a SASS-C.

2 The SSR was separate from the PSR and was range limited in the North and North East regions of the recording.

3 The PSR was a pulse compression type fitted with Plot Extraction, A (adaptive) MTI processing, CFAR and clutter map.

4 The extracted plots were passed through a Plot Filter Combiner, but the combining function was not used.

5 The SASS-C recorder carried out PSR to SSR combination and tracking.

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