SECTION 3

PRIMARY RADAR SIGNAL PROCESSING

INTRODUCTION

This section discusses the signal processing properties of radar receivers in the 2.7 to 2.9 GHz band. A detailed discussion of the receiver signal processing properties to noise, desired signal, and asychronous interfering signals is given. Because of the types of services (aeronautical, radionavigation, meteorological, and radiolocation) provided by radars in the 2.7 to 2.9 GHz band, and number of nomenclatures, it was necessary to limit the signal processing investigation to the ASR-7 and ASR-8 radars which are FAA radars used for aeronautical radionavigation.

The ASR-7 and ASR-8 are later model radars which use digital signal processing after signal detection. Both radars have the capability of selecting several modes of operation for display of the received video information.

Normal Channel:

Normal Video
Enhanced Normal Video
Normal Log-FTC Video
Enhanced Normal Log-FTC Video
Normal LOG-FTC with Weather Background Video
Enhanced Normal LOG-FTC with Weather Background Video

MTI Channel:

MTI Video
Enhanced MTI Video
MTI Log-FTC Video
Enhanced MTI Log-FTC Video
MTI Log-FTC with Weather Background Video
Enhanced MTI Log-FTC with Weather Background Video

The weather background channel of the ASR-7 and ASR-8 is very similar to the circuitry of the meteorological radars (WSR-57 and WSR-74S) in the 2.7 to 2.9 GHz band. Therefore, an investigation of the ASR-7 and ASR-8 radar signal processing characteristics is also applicable to the meteorological radars in the band. Also both the normal and MTI channels of the ASR-7 and ASR-8 are very similar to the radiolocation height finding radar in the 2.7 to 2.9 GHz band. Therefore, an analysis of the ASR-7 and ASR-8 radars is generally applicable to all radars in the 2.7 to 2.9 GHz band. Also since the trend in new radar systems is toward digital signal processing, the analysis of the ASR-7 and ASR-8 radars will be more applicable to other new radar systems coming in the band.

GENERAL SYSTEM DESCRIPTION

Radar system characteristics of major aeronautical radionavigation, meteorological, and radiolocation radars in the 2.7 to 2.9 GHz band is given in Appendix G. As stated previously, this section will only investigate the signal processing properties of the ASR-7 and ASR-8. However, the analysis is applicable to other aeronautical radionavigation, meteorological, and radiolocation radars in the 2.7 to 2.9 GHz band as well as radars in other bands.

In general, all radar receivers in the 2.7 to 2.9 GHz band can be divided into three sections: antenna and RF waveguide, receiver unit, and processor unit. Figure 3-1 shows a typical radar system block diagram of a radar which only operates one channel at a time (non-diversity mode). Figure 3-2 shows a typical radar system block diagram of a radar which has frequency diversity capability (simultaneous dual channel operation). Radars operating in the frequency diversity mode use one of the channels as a master channel for timing information to the slave channel. The two reflected signals from a target are separated in the diplexer and applied to the two receivers. Each signal is processed in its receiver and the two signals are realigned in time and additively combined in the video processor unit of the master channel before being displayed. The following is a general description of antenna and RF waveguide, receiver unit, and processor units of radars in the 2.7 to 2.9 GHz band.

Antenna and RF Waveguide

Several different types of antennas are used by radars in the 2.7 to 2.9 GHz band. All the aeronautical radionavigation radars use a shaped beam reflector which produces a cosecant-squared elevation pattern. The antenna gain of the aeronautical radionavigation radars range between 31 and 34 dBi. The meteorological radars have parabolic dish antennas with a gain of 32 to 38 dBi. The type of radiolocation radar antennas is varied with antenna gains between 32 and 39 dBi. Some of the later model radars have antennas with several horns.

The RF waveguide system generally consists of rotary-joint, several couplers, waveguide switches, circulators, and Transmit-Receiver (TR) limiters. Radars with frequency diversity capability also have RF diplexers. In general, the RF waveguide characteristics of all radars in the 2.7 to 2.9 GHz band are similar, and therefore, the signal processing properties can be generalized.

Receiver Unit

The radar receiver unit includes all the analog circuitry between the receiver RF input and the detector output of the normal, MTI, and log normal radar channels. The receiver unit generally includes a parametric amplifier,

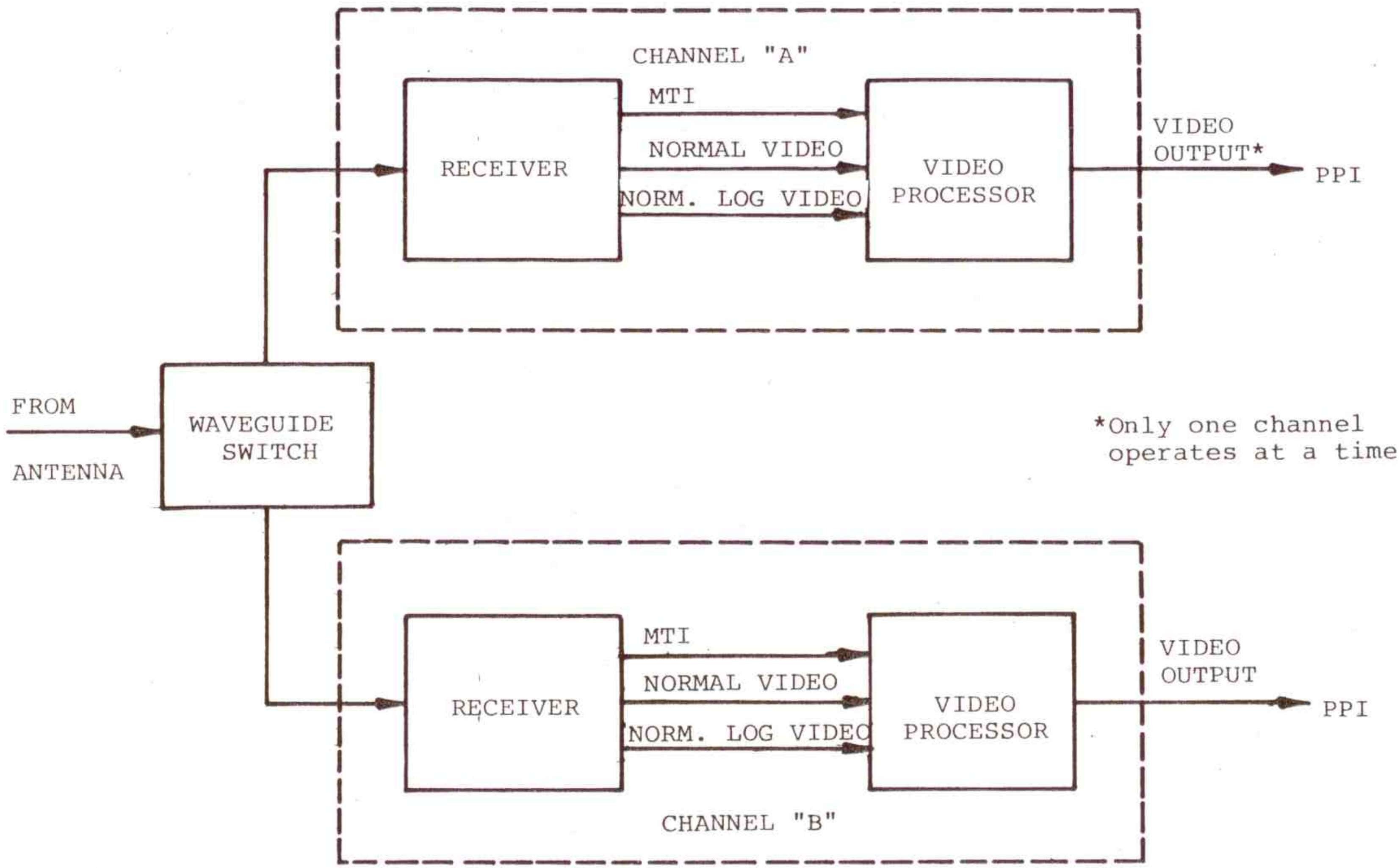

Figure 3-1. Block Diagram of Non-Diversity Radar Receivers

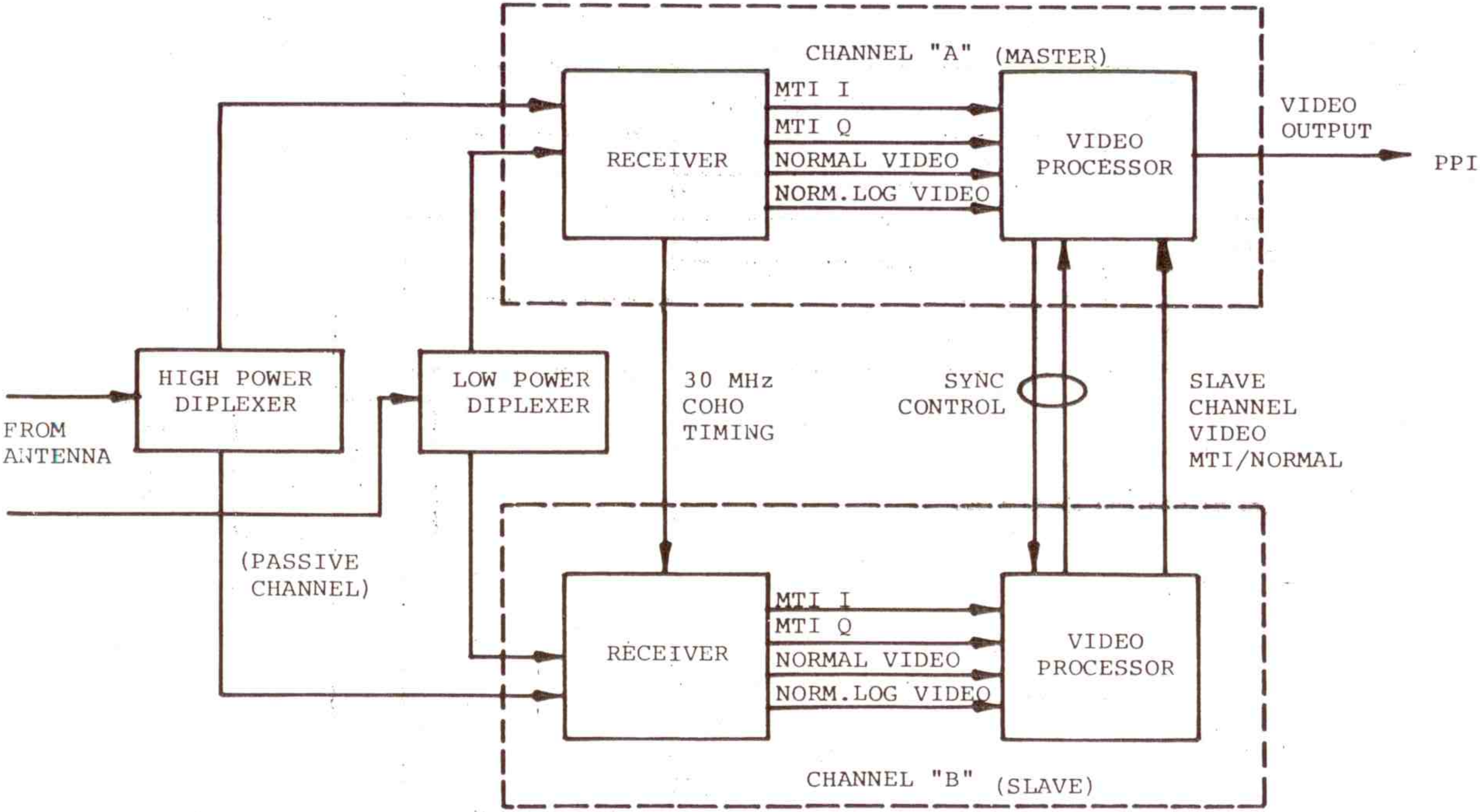

Figure 3-2. Block Diagram of Frequency Diversity Radar Receivers

mixer, IF amplifier, and detectors. The newer radars have solid-state receiver units with the older radars being tube-type. The signal processing properties of the solid-state and tube-type radar receiver units are essentially the same. Since the ASR-7 and ASR-8 have normal, MTI, and log normal channels, the signal processing properties of the ASR-7 and ASR-8 receiver units are generally applicable to all radars in the band.

Processor Unit

The radar processor unit includes all the circuitry between the detector outputs and the display unit. The processor unit generally includes the MTI cancellers, integrator (enhancer), Log Fast-Time-Constant (Log-FTC), and weather background circuitry. The newer radars have digital processor units where the detector output is A/D (analog-to-digital) converted, the signal processing done, and then D/A (digital-to-analog) converted for display. The older radars have analog processor units. The transfer properties of the analog and digital processor units can be treated identically with the exception of the quantization noise due to A/D conversion and roundoff and truncation inherent in digital processing. Therefore, the signal processing properties of the ASR-7 and ASR-8 (digital processor units) is generally applicable to all radars in the 2.7 to 2.9 GHz band.

ANTENNA AND RF WAVEGUIDE SYSTEM

The following is a discussion of the signal processing properties of the antenna and RF waveguide system of typical radars in the 2.7 to 2.9 GHz band. The discussion includes the hardware from the antenna feed horn output to the receiver unit input. The analysis does not include antenna gain, antenna patterns, or polorization discrimination. The antenna types and antenna gains of radars in the 2.7 to 2.9 GHz band are given in Appendix G. Antenna pattern measurement of several radars in the band are contained in a report by Hinkle, Pratt, and Matheson (1976).

Several of the new radars in the band (ASR-8, AN/GPN-20, and AN/TPN-24) have multiple feedhorn antennas and diplexers in the waveguide to permit frequency diversity operation. These new radars have the more complex RF waveguide systems, and have all the waveguide components as the single-horn non-frequency diversity radars. Therefore, the ASR-8 RF waveguide system, which has a normal and passive channel, and frequency diversity capability, was selected as being representative of radars in the 2.7 to 2.9 GHz band.

Figure 3-3 shows a block diagram of the ASR-8 RF waveguide system. The passive channel is used to receive reflected target energy during the first part of the receive period and consists of a rotary-joint, low-power diplexer, TR tube, and waveguide couplers. The normal channel is used to transmit pulses and receive reflected target energy during the remainder of the receive period and consists of a rotary-joint, high-power diplexer, high-power waveguide switch, circulator, and waveguide couplers. Interfering signal power loss in the RF system may occur from insertion loss and, attenuation from the diplexer filter due to frequency separation between the

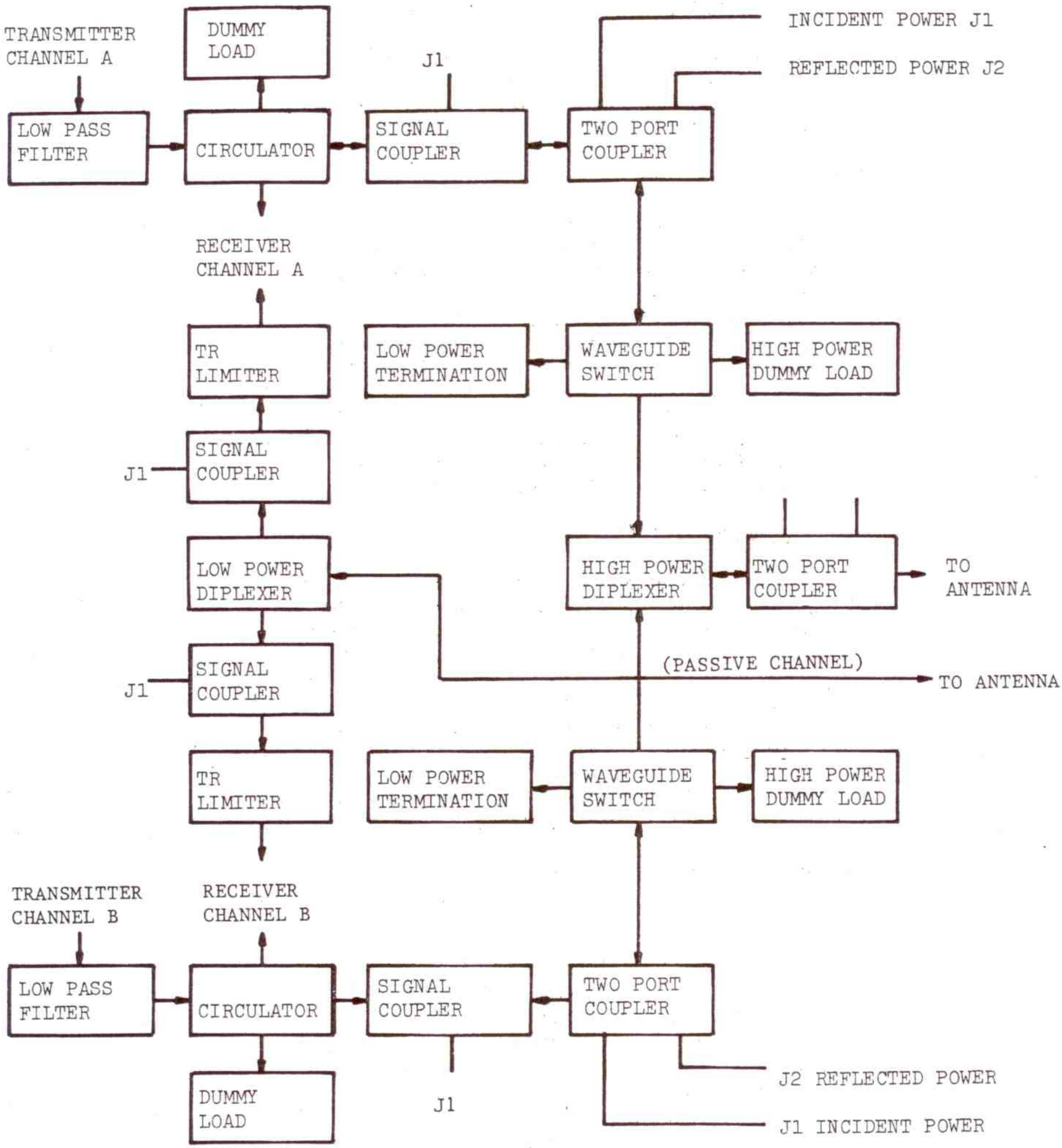

Figure 3-3. ASR-8 RF System Simplified Block Diagram

interfering signal and victim receiver channel tuned frequency. The insertion loss is approximately 2 dB for both the passive and normal channel. Since the low- and high-power diplexer filter bandwidth is much wider than the interference spectrum bandwidth of radars in the 2.7 to 2.9 GHz band, the interfering signal peak power loss for a symetrical emission is given by:

For: $\Delta f \leq 1/\pi\tau_i + B_d/2$

$$P_{I_{OUT}} = P_{I_{IN}} \tag{3-1}$$

For: $\Delta f > \frac{1}{\pi\tau_i} + B_d/2$

$$P_{I_{OUT}} = \frac{P_{I_{IN}} \; (B_d\tau_i)^2 \; F_{\Delta F}}{4} \tag{3-2}$$

where:

$P_{I_{IN}}$ = Interfering signal peak power level at diplexer input, in watts

$P_{I_{OUT}}$ = Interfering signal peak power level at diplexer output, in watts

Δf = Frequency separation between interferer carrier and victim receiver tuned frequency, in MHz

B_d = Diplexer 3 dB bandwidth, in MHz

τ_i = Interferer transmitter pulse width, in μsec

$F_{\Delta F}$ = Interfering signal emission spectrum level at ΔF relative to level at carrier, in dB

Figure 3-4 shows the selectivity of the ARS-8 diplexer. The frequency selectivity characteristics of diplexer of radars in the 2.7 to 2.9 GHz band varies depending on the radar nomenclature. However, the peak power loss of an interfering signal due to frequency separation is essentially determined by the victim receiver IF selectivity characteristics since the IF bandwidth is much smaller than the RF waveguide diplexer bandwidth.

RECEIVER UNIT

The following is a discussion of the signal processing properties of the receiver unit of the ASR-7 and ASR-8 radars. All the radars in the 2.7 to 2.9 GHz band have a receiver unit very similar to either the normal, log normal, or Moving Target Indicator (MTI) channel of the ASR-7 or ASR-8. Also the signal processing properties of the older tube-type receiver unit radars

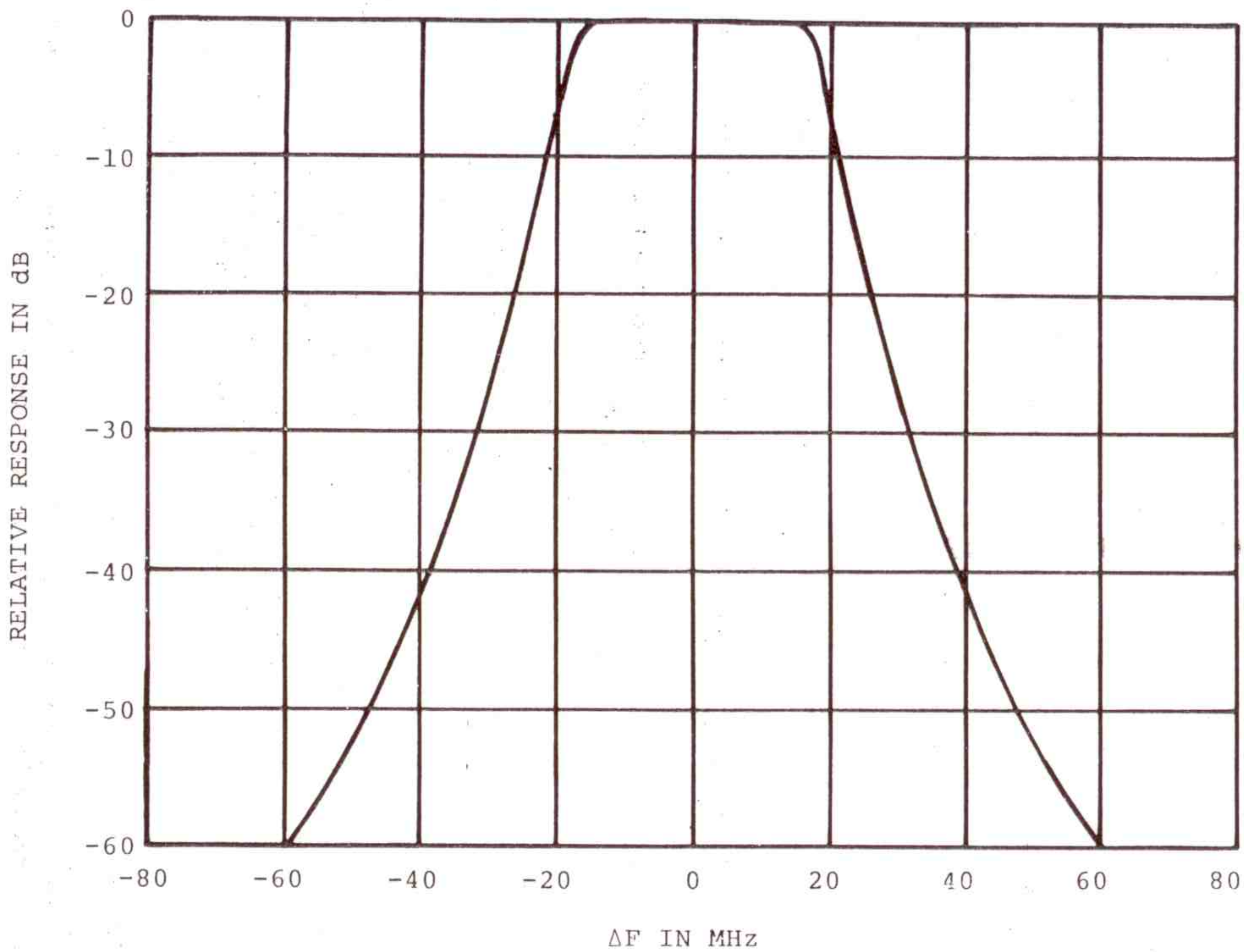

Figure 3-4. ASR-8 Diplexer Filter Characteristics

and the newer solid-state receiver unit radars can be treated identically. In those cases where the ASR-7 or ASR-8 circuitry is significantly different from the other radars in the band, a discussion of the signal processing properties of other types of circuitry will be given.

Figure 3-5 shows a block diagram of the receiver unit of the ASR-8 radar. The radar receiver unit accepts either normal channel or passive channel S-band radar signals from the antenna and waveguide subsystems and provides either normal video, log-normal video, or MTI video to the processor unit.

Receiver Front End

Normal channel RF energy entering the receiver is first applied to the TR-limiter through the waveguide system. The TR-limiter is a passive device. Two diode limiters are used within the TR-limiter for reduction of spike leakage. Output from the TR-limiter is applied through a waveguide-to-coax adapter to the Sensitivity Time Control (STC) attenuator. The attenuator uses bias voltage-controlled RF attenuation of PIN diodes to provide a continuously variable 40 dB range of attenuation at frequencies of 2.7 to 2.9 GHz. STC control voltages are provided to the attenuator from the processor unit. Using control voltages in steps 0 and +10 volts the attenuation provides linear attenuation throughout the input frequency band. Insertion loss is less than 0.6 dB at zero control voltage. Bias voltages of +15 and -15 Vdc are supplied to the attenuator from the respective power supplies located in the module rack. RF energy from the STC attenuator is sent to the antenna pattern switch. The antenna pattern switch is a solid-state device using PIN diodes to switch RF from the normal beam to the passive beam. Switch control logic signals from the processor unit are converted to normal and passive drive signals in the switch driver assembly. The switch drive signals are used by the antenna pattern switch to perform the switching. Either normal or passive beam RF energy is coupled out to the parametric amplifier.

TR Limiter

The TR limiter protects the receiver from high level RF energy during the transmitter pulse. Lower level energy which might not have sufficient amplitude to ionize the TR tube directly is reflected by the limiter portion of the assembly. The effect of the TR limiter on an interfering signal would be to attenuate the interfering signal if it coincided with the transmitted "on" period. During the receive period the TR limiter has approximately a 0.3 dB insertion loss.

Sensitivity Time Control (STC) Attenuators

High levels of reflected energy from ground clutter will saturate the receiver if not reduced in level before entering the parametric amplifier and the following receiver elements. The STC attenuators reduce this clutter as required at any particular site. The attenuators are controlled by signals from the processor unit. Two separate but identical function generators in

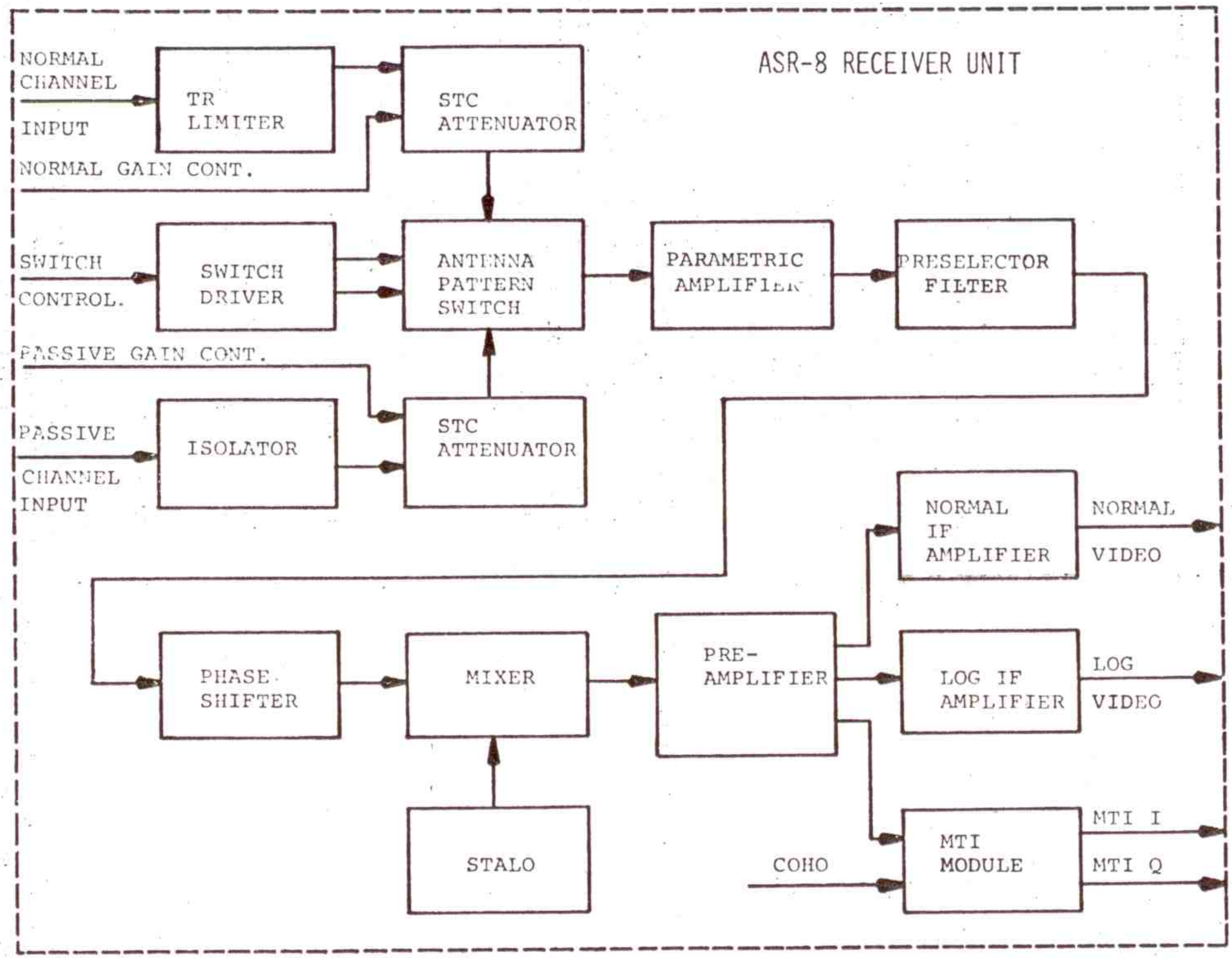

Figure 3-5. ASR-8 Receiver Unit Block Diagram

the processor are provided, one for the normal antenna beam and one for the passive antenna beam. Board-mounted switches permit selection of the initial attenuation (up to 40 dB), delay of initiation of the STC curve after the transmitter pulse up to 100 microseconds, and selection of the STC curve exponent from 1/R to $1/R^5$. Receiver sensitivity control, using the RF attenuator, is digitally added to the STC function. Five values of preset receiver sensitivity can be selected by the radar control panel; the individual levels are preset using board-mounted switches. A digital-to-analog converter changes the composite digital STC and sensitivity control signal to an analog voltage to control the RF attenuator. Figure 3-6 shows the STC characteristics of the ASR-8.

The STC function in some radars in the 2.7 to 2.9 GHz band is achieved by varying the IF amplifier gain as a function of time. However, the affect of STC circuitry on a desired or interfering signal is the same. That is, the STC attenuators will attenuate the signal level as a function of the radar receiver period in which the pulse arrives, generally eliminating low level interference in the center of the PPI scope.

Antenna Pattern Switch

The antenna pattern switch accepts signal drive current from the switch driver and connects the receiver to either the normal or passive channels. The switch uses fast-acting PIN diodes which allow channel switching to occur within 100 ns. The antenna pattern switch will reduce the interfering signal power level when the interference is coupled in through the passive horn which has a higher tilt antle than the normal horn. The reduction in interfering signal power can be determined from the mainbeam antenna elevation patterns of the passive and normal horns. The affect of the antenna pattern switch in the interference is that from mainbeam antenna coupling of the victim receiver, the level of interference will be reduced in the center of the PPI display. When the interference is coupled in through the backlobe of the victim radar, the switching between passive and normal horn will not have a significant effect on the median interfering signal level.

Passive Channel

Passive channel RF energy enters the receiver unit from an externally-connected TR-limiter. The energy passes through a two-port isolator to the STC attenuator. Operation of the passive STC attenuator is identical to the normal STC attenuator.

Parametric Amplifier

The antenna pattern switch feeds the signals from the passive and normal channel to the parametric amplifier. The parametric amplifier provides low-noise amplification of RF energy prior to down conversion. The amplifier covers the entire radar frequency range of 2.7 to 2.9 GHz, and has a minimum gain of 15 dB. Noise figure of the parametric amplifier is 1.25 dB maximum.

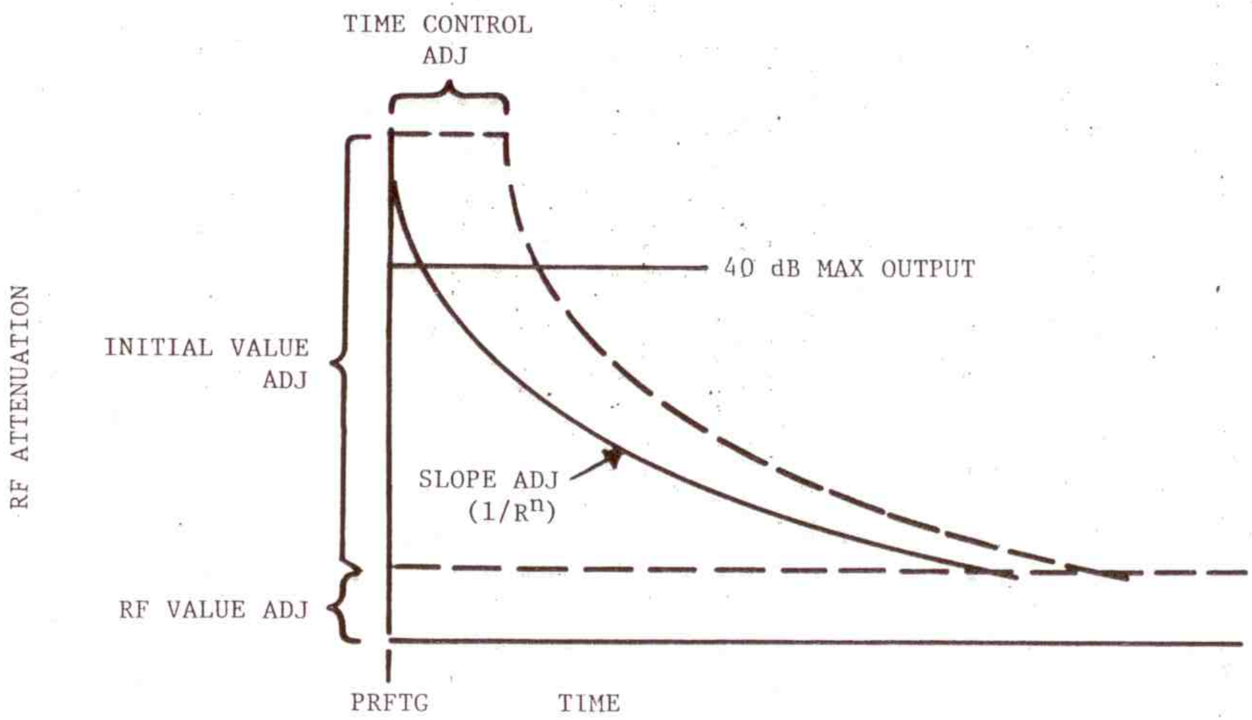

Figure 3-6. STC Waveform Generation

Saturation, the signal level at which the gain decreases 1.0 dB, occurs at an input power level of -30 dBm.

Since this investigation only covers interference from radars in the 2.7 to 2.9 GHz band, the parametric amplifier will not provide any Frequency-Dependent-Rejection to radars in the 2.7 to 2.9 GHz band. For analytical reasons, the parametric amplifier is assumed to be a linear amplifier with 0 dB gain. This assumption of linearity and 0 dB gain allows signal and noise to be treated separately.

Preselector Filter

The preselector filter prevents external signals not in the receiver passband from interfering with receiver operation. The preselector filter is composed of four direct-coupled cavities and has a 10 MHz passband at any selected frequency between 2.7 and 2.9 GHz. The filter has 60 dB rejection at frequencies 50 MHz from the center of its passband. Four micrometer tuners are used to set the filter to any desired frequency from 2.7 to 2.9 GHz. The insertion loss of the filter is approximately 0.6 dB. The effect of the preselector filter on an interfering signal will be to attenuate those signals which fall outside the receiver passband. Since the interfering signal peak power loss as a function of frequency separation (ΔF) is mainly determined by the IF filter selectivity, the analysis of interfering signal peak power loss as a function of interfering signal frequency separation will be discussed in the IF filter section.

Phase Shifter

The phase shifter is used to vary the electrical length of the line between the preselector filter and mixer. Some power from the incoming signal is converted to the image frequency in the mixing process. This power propagates out the mixer input port toward the preselector. It is reflected from the preselector back to the mixer. The phase shifter adjusts the phase of the reflected image so that the IF signal voltage resulting from it is in phase with the IF voltage from the signal frequency. Mixer conversion loss is improved in this manner. The insertion loss of the phase shifter is approximately 0.3 dB. The phase shifter will change the phase of the interfering signal.

Mixer

RF to IF signal conversion of received signals is accomplished by mixing the stable local oscillator (STALO) output signal with the amplified RF return signal. Mixing takes place in the crossbar mixer while the preselector filter and phase shifter are also employed to improve conversion efficiency. The echo signal at frequency ω_o or an interfering signal at frequency $\omega_o+\Delta\omega$ mixes in the mixer with the STALO signal ($\omega_o+\beta_o$) where β_o is equal to 30 MHz. The main signal component produced is the difference between the two inputs, which is the IF frequency β_o. In addition to the IF frequency, harmonics of the STALO frequency and harmonics of the sum of the

STALO and input signal frequencies are produced.

The STALO provides a reference RF signal between 2.67 and 2.93 GHz for the receiver signal mixer to down or up convert received signals to the 30 MHz IF. A three-cavity tunable bandpass filter selects the desired STALO frequency and attenuates the adjacent frequencies by 30 dB or greater applying the output to a RF network. The RF network is a two-stage S-band transistor amplifier which provides +11 dBm gain to the output. The noise 30 MHz away from the carrier is suppressed to near thermal noise. This precludes the STALO signal in the receiver mixer from having appreciable noise or spurious products at the intermediate frequency.

It is shown in Appendix A that the signal-to-noise ratio (SNR) and interference-to-noise ratio (INR) at the mixer output is the same as at the mixer input. Thus the signal transfer properties of the mixer can be expressed as:

$$SNR_{mo} = SNR_{mi} \tag{3-3}$$

Preamplifier

The preamplifier model provides low noise amplification of the IF signal. Outputs from the preamplifier are coupled to the normal, log normal, and MTI radar channels. The bandwidth of the preamplifier is approximately 10 MHz, same as the preselector. Therefore the interfering signal time waveform at the preamplifier output will be similar to that at the preselector output (if saturation does not occur) with the exception of the frequency conversion produced by the mixer. As previously mentioned the effect of the preamplifer 10 MHz bandwidth on an interfering signal will be to attenuate those signals which fall outside the receiver passband. Since the interfering signal peak power loss as a function of frequency separation (ΔF) is mainly determined by the IF filter selectivity, the analysis of interfering signal peak power loss as a function of interfering signal frequency separation will be discussed in the IF filter section.

Normal Channel

The normal channel IF subassembly accepts the 30 MHz IF signal from the preamplifier module and provides IF amplification, video detection, and video amplification. The normal channel video amplifier output is a low-noise high-gain video signal supplied to the processor unit.

IF Amplifiers

The normal channel IF amplifiers consist of four wide-band symetrical limiter amplifiers followed by five IF passband filter stages. The overall bandwidth of the IF stages is 1.2 MHz. Appendix B contains a detailed analysis of the ASR-8 IF selectivity and signal transfer properties.

The relative IF filter selectivity response $A_{dB}(F)$ is derived in Appendix B, Equation B-19, and can be expressed as:

$$A_{dB} = -20 \log (1 + X^2)^{5/2} \tag{3-4}$$

where:

$$X = \frac{2\Delta F'}{B_s}$$

and:

$\Delta F'$ = Frequency relative to the receiver IF tuned frequency B_o, in Hz

B_s = IF amplifier stage 3 dB bandwidth, in Hz

Since the normal channel IF amplifier stages have a narrower bandwidth and sharper selectivity characteristics than the preceding receiver unit stages, a desired signal or interfering time response at the IF amplifier output is essentially governed by the normal channel IF selectivity characteristics.

For an interfering signal, the peak power and time waveform response at the IF filter output is determined by the receiver IF selectivity characteristics, interfering signal emission spectrum, and frequency separation between the interfering signal carrier and the victim receiver tuned frequency. In general, the receiver front end prior to the receiver normal channel input can be modeled as a linear receiver with 0 dB gain allowing the IF input interference-to-noise ratio, $(INR)_{IF_i}$, to be expressed as (Equation B-37a):

$$INR_{IF_i} = I_{i_{dbm}} - N_{i_{dBm}} \tag{3-5}$$

where:

$I_{i_{dBm}}$ = Interfering signal peak power level at the receiver input, in dBm

$N_{i_{dBm}}$ = Receiver noise level, in dBm

The amplitude distribution of the noise at the IF input and output is

Gaussian. The IF output interference-to-noise ratio, INR_{IF_o} can be expressed as (Equation B-38):

$$INR_{IF_o} = INR_{IF_i} - FDR \qquad (3\text{-}6)$$

where:

FDR = Receiver Frequency Dependent Rejection, in dB

The Frequency-Dependent-Rejection (FDR) of the interfering signal is determined by Equation B-21 and is discussed in detail in Appendix B.

The interfering signal IF output time waveform can be expressed as an amplitude and phase modulated pulse given by:

$$V_{IF_o}(t) = Bp(t') \cos [\beta_o t + \phi_o + \phi(t')] \qquad (3\text{-}7)$$

where:

B = Interfering signal voltage amplitude

p(t') = Interfering signal amplitude modulation after IF filtering, value between 0 and 1

β_o = Receiver tuned IF frequency, in radians per second

ϕ_o = Interfering signal carrier phase angle

t' = $t - t_o$ where t_o is the delay time of the IF filter

$\phi(t')$ = Interfering signal phase modulation after IF filtering

The interfering signal IF output time response is a function of the interfering signal pulse width (τ), frequency separation between the interfering signal carrier and the victim receiver tuned frequency (ΔF), and the receiver IF bandwidth (B_{IF}). A detailed discussion of an interfering signal IF output time response as a function of these parameters is given in Appendix B. Figure 3-7 summarizes typical IF output time waveforms for different τB_{IF} products and ΔF's.

<u>Envelope Detector</u>

The envelope detectors used in the normal channel of radars in the 2.7 to 2.9 GHz band generally consists of a full-wave detector followed by a low pass filter and a video amplifier. The IF signal level at the detector input

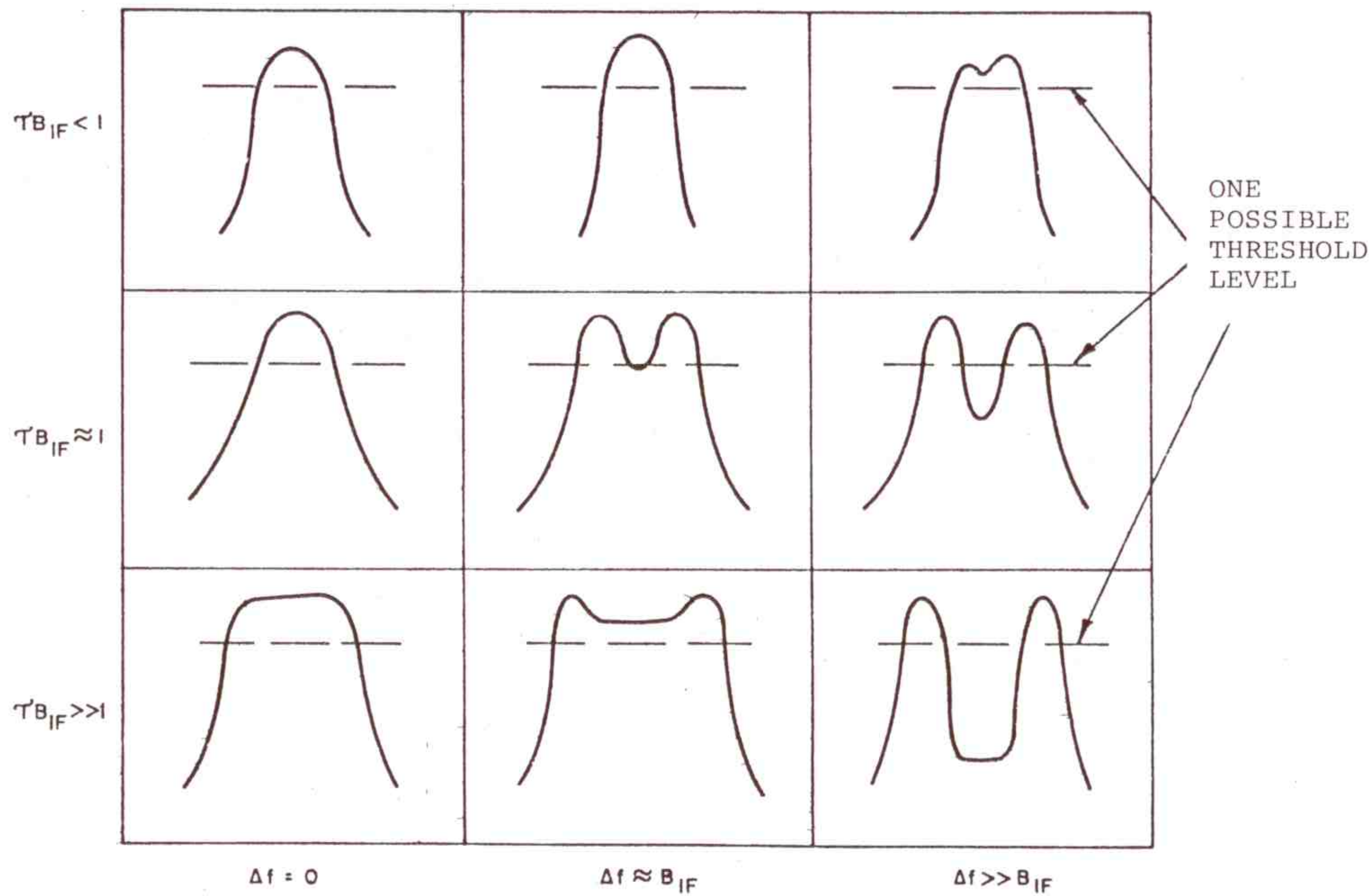

Figure 3-7. Typical IF Output Time Waveform Responses for On-Tune and Off-Tune Pulses

is generally large enough for operation in the linear portion of the diode detectors. However, for completeness both the signal-to-noise transfer properties of a linear and square law detectors are given.

Figure 3-8 shows the signal-to-noise (SNR) transfer characteristics of a linear detector (R. Gannaway, 1965). The signal-to-noise (SNR) transfer characteristics of the square-law detector are shown in Figure 3-9, and are given by (R. Gannaway, 1965 and Davenport and Root, 1958):

$$SNR_o = \frac{(SNR)_i^2}{1 + 2\,(SNR)_i} \qquad (3\text{-}8)$$

For small input signal-to-noise ratios (SNR; <10 dB), the linear and square-law detectors have similar transfer properties. For large input signal-to-noise ratios (SNR; >10), the linear detector performance is better than the square-law detector. However, the collapsing loss for a linear detector is much greater than the collapsing loss for a square-law detector. Thus the difference between the linear and square-law detector performance in the required detector input signal-to-noise ratio is less than a dB (Trunk, 1972). The collapsing loss is the additional signal required to maintain the same probability of detection (P_d) and probability of false alarm (P_{fa}) when noise along with the desired signal-plus-noise are integrated. Figures 3-8 and 3-9 can also be used for the interference-to-noise (INR) transfer properties of a linear and square-law envelope detector, respectively.

The noise amplitude distribution at the linear detector output is Rayleigh distributed. The signal-plus-noise probability density function (PDF) at the envelope detector output for a non-fluctuating target (Marcum Case 0) has a Rice distribution (1954) given by:

$$p(v,A) = \frac{v}{\sigma^2} e^{\frac{-(v^2+A^2)}{2\sigma^2}} I_o\left(\frac{vA}{\sigma^2}\right) \qquad (3\text{-}9)$$

where:

$I_o(\ )$ = Modified Bessel function of the first kind of order zero

A = Peak signal amplitude, in volts

σ = rms noise level, in volts

The normal channel envelope detector output signal-plus-noise was simulated to investigate trade-offs in suppressing asychronous interfering signals. The simulation of the radar normal channel is discussed in Appendix E. Figure 3-10 shows the Rice PDF given by Equation 3-9 as a function of the signal-to-noise ratio.