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ELECTROMAGNETIC COMPATIBILITY TESTING OF A DEDICATED SHORT-RANGE COMMUNICATION SYSTEM

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PREFACE

This work was sponsored by the Federal Highway Administration (FHWA), McLean, Virginia, under the direction of J.A. Arnold, FHWA Contracting Officer Technical Representative.

Certain commercial companies, equipment, instruments, and materials are identified in this report to specify adequately the technical aspects of the reported results. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

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EXECUTIVE SUMMARY

Dedicated short-range communication (DSRC) systems have been proposed for operation at locations across the United States in the 5850- to 5925-MHZ band. This is part of a larger band, 5250-5925 MHZ ("5-GHz band"), that is currently allocated to radiolocation (radar) services. Deployment of DSRC systems is contingent upon assurances that their operations will be electromagnetically compatible with existing and future radar systems in the 5-GHz portion of the spectrum.

The Institute for Telecommunication Sciences performed a series of tests on a DSRC electronic toll collection system to determine the extent to which electromagnetic compatibility problems may be experienced when operated in proximity to various radar systems in the 5-GHz spectrum. During the tests, simulated radar signals were coupled into the DSRC beacon receiver, both on the beacon frequency (co-channel) and off the beacon frequency (off-channel). Radar signals were selected to represent the range of parameters used by both existing radars and possible future radar designs.

Thresholds at which radar signals caused adverse impact on DSRC system operations were determined for each set of radar signal parameters, and these thresholds were determined for both co-channel and off-channel radar interference. Statistical data sets were acquired to quantify the effects of these interference thresholds. The measured interference thresholds for various combinations of interference pulse widths and pulse repetition rates were used to compute minimum interference power levels at which existing 5-GHz radars would be expected to produce interference to DSRC systems at deployment locations in the United States. For each type of 5-GHz radar, the distance at which the radar would be expected to cause interference to this type of DSRC system (coordination distance) was determined for various conditions of electromagnetic isolation between the systems. This analysis yielded the conclusion that, for typical coupling conditions, the DSRC system coordination distances for most 5-GHz radars are often substantially less than 1 km, and usually do not exceed several kilometers.

Only one type of radar—associated with U.S. test range facilities and used at approximately 15-20 locations in the United States for tracking rockets, aircraft, and balloons—appears to require larger coordination distances. This occurs because this radar type can be tuned to co-channel frequencies with DSRC systems. However, if the test range radars and the DSRC systems are not co-channel, and if these tracking radars do not directly illuminate the DSRC locations, then the coordination distances can become relatively short for this case, as well. The key to achieving electromagnetic compatibility is coordination (e.g., frequency coordination) at these test range locations.

Based on these measurement and analysis results, no engineering modifications are recommended for the type of DSRC system that was tested. It is recommended that DSRC systems deployed in close proximity to various U.S. test range facilities perform coordination with those facilities to avoid co-channel operations and direct illumination by the test range radars identified in this report. Such coordination should ensure electromagnetically compatible operations between such radars and the deployed DSRC systems.

ELECTROMAGNETIC COMPATIBILITY TESTING OF A DEDICATED SHORT-RANGE COMMUNICATION SYSTEM

Roger A. Dalke, Frank H. Sanders, and Brent L. Bedford[1]

Dedicated short-range communication systems have been proposed for operation at locations across the United States in the 5850- to 5925-MHz band. Various search and tracking high-power radars operate at or near this frequency band and are a source of potential interference. The successful operation of such digital communication systems is dependent upon compatible operation and coexistence with these radars. The Institute for Telecommunication Sciences has performed a series of interference tests to determine the electromagnetic compatibility of DSRC systems used for automatic toll collection and high-power 5-GHz radars. The methods used to perform the tests and results are presented in this report.

Key words: dedicated short-range communications (DSRC) systems; high-power radars; electromagnetic compatibility; interference; electronic toll collection; access control systems

1. INTRODUCTION

This report describes the methodology and results of tests in which a dedicated short-range communication (DSRC) system was tested by the Institute for Telecommunication Sciences (ITS) for its response to high-power incident field strengths in the 5850- to 5925-MHz band, and also for its response to strong signals in the radiolocation band between 5250 and 5850 MHz. The DSRC system was tested to determine the interference thresholds at which performance was degraded, up to and including total failure of the DSRC communications link. Physical burn-out of the DSRC system under test was not performed.

Using the results of these tests in conjunction with previous measurements of emissions (in both frequency-domain and time-domain) from high-power radars in the 5250- to 5925-MHz portion of the spectrum (e.g., [1-4]), ITS engineers performed an analysis to determine the extent of electromagnetic compatibility problems the DSRC device under test may encounter if it is deployed in the United States in the proposed 5850- to 5925-MHz band. The results of the tests, measurements, and electromagnetic compatibility analysis for this DSRC system, are presented in this report.

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1.1 Background

Wireless communication systems, called dedicated short-range communications (DSRC) systems, have been designed for operation in highway environments. The purpose of the DSRC systems is to enhance efficiency of highway travel by providing motorists with, for example, such services as automated, wireless-interrogation stations that would collect tolls electronically as vehicles pass through such stations without stopping. Anticipated deployment of such DSRC systems in the United States has led to a search by system designers, spectrum engineers, and spectrum managers for spectrum bands in which the devices may be deployed. Taking into account both technical and administrative restrictions on the use of various portions of the spectrum, as well as the fact that DSRC systems have already been designed to operate in particular spectrum bands in Europe, the portion of the spectrum between 5850 and 5925 MHz has been identified as a likely band for DSRC deployment in the United States. This band is part of a larger band (5250-5925 MHz) that is allocated on a primary basis in the United States for radiolocation (radar) operations. An industrial, scientific, and medical (ISM) band also has been established between 5725 and 5875 MHz.

As detailed in Section 3, the 5-GHz radiolocation band is occupied in the United States by high-power radar systems that present the potential for interference with DSRC devices in roadway environments. These radars typically use transmitters that produce between 0.25 and 1 MW peak power, with antennas that produce effective isotropic radiated power (EIRP) values that are 30-40dB higher than transmitter output power. These radars operate with duty cycles (pulse width divided by pulse repetition interval) that are on the order of 1:1000. The radar antennas typically scan across any given point in space repetitively, approximately every 3-10 s, although shorter and longer intervals do occur. Radar beams typically illuminate any given point (such as a typical DSRC station) for about 20 ms during each beam-scan period. The radar antennas often keep the main-beam power in the sky, with power levels somewhat lower than main-beam values being produced at ground level. However, some 5-GHz radars, such as maritime navigation/surface search units, do directly illuminate the ground, where DSRC systems may be located along highways.

ITS has measured electromagnetic emissions from various 5-GHz high-power radar systems and has accumulated extensive data on important radar emissions parameters such as radiated power levels, time waveforms, and antenna patterns. The interference testing and measurement strategy described in this report were largely based on an analysis of this data. A review of the 5-GHz radar emission data revealed the following important points:

1. field strengths are not likely to exceed +165 dBμV/m in the 5250- to 5925-MHz frequency range. This represents the maximum level to which the 5-GHz DSRC systems need to be tested;

2. DSRC systems need to be tested under conditions that allow for strict control of the interference frequency, incident power, pulse repetition rate, and pulse width. These variables cannot easily be controlled at actual radar locations, where environmental conditions tend to interfere with efficient testing programs; and hence,

3. the most effective method of determining DSRC electromagnetic compatibility with 5-GHz radar signals is to acquire an operational DSRC system and operate it in the presence of interference signals that simulate those produced by radars. This report describes the results of such a series of tests on a DSRC system designed for electronic toll collection.

1.2 Approach

The tests were performed at the ITS laboratory in Boulder, Colorado. The overall goal of the tests was to determine:

1. the interference levels, for various interference modulations, at which co-channel interference would occur; and

2. the interference thresholds for off-frequency interference.

Interference modulations were both continuous-wave (CW) and pulsed. The interference pulse parameter combinations used in the tests are shown in Table 1, below. The pulse parameters were selected as representative of the parameters for 5-GHz radars in the United States and are described in terms of pulse width and duty cycle. The related parameters pulse repetition frequency (PRF) and pulse repetition interval (PRI) are given for reference.

Table 1. Radar Parameters Used for DSRC Interference Signal Testing

Radar Interference Parameters	Pulse width (PRF = 300 Hz, PRI = 3.3 ms)	Pulse width (PRF = 1 kHz, PRI = 1 ms)	Pulse width (PRF = 3 kHz, PRI = 330 µs)
Duty cycle: -20 dB (1%)	----------	10 µs	3.3 µs
Duty cycle: -30 dB (0.1%)	3.3 µs	1 µs	0.33 µs
Duty cycle: -40 dB (0.01%)	0.33 µs	---------	---------

For each interference signal modulation that was tested, the interference level was initially adjusted to a very low amplitude, well below the DSRC beacon interference threshold. The amplitude was then gradually increased, while the beacon was operating, until an adverse effect on beacon operation was noted. Interference amplitude was increased beyond the level of minimal interference, first by 10 dB and then by 20 dB, to ascertain effects of increasing interference in excess of the minimum. The interference thresholds (minimal adverse effect and 10 dB and 20 dB above the minimum) were recorded for each interference modulation, for both co-channel and off-channel interference.

Subsequent to determining the set of interference thresholds, the beacon operations were monitored for extended numbers of beacon/tag information exchanges at each interference threshold and each beacon modulation. For each threshold, diagnostic histograms related to beacon performance parameters were produced to obtain a quantitative measure of the adverse impact of interference on the beacon at each threshold.

1.3 Experimental Configuration

The hardware configuration used for the DSRC testing is shown as a block diagram schematic in Figure 1. The units under test, consisting of a DSRC roadside beacon unit and a DSRC tag, were mounted on separate, telescoping masts that were, in turn, mounted at opposite corners of a metallic vehicle rooftop that itself measured about 2 m by 2 m. The vehicle rooftop was 2.7 m above the ground, and the two masts were elevated to a height of 1.5 m above the rooftop, equal to 4.2 m above the ground. The vehicle was parked at an outdoor location during the tests. Thus, the DSRC beacon and tag were effectively suspended in free space at a height of 4.2 m above the ground, with a metallic plane 1.5 m below them, and stretching between them.

An important consideration for this arrangement was that the measurements approximate to what would be obtained if the DSRC system were operating in free space, i.e., the receiver was in the *far field* and the effects of multipath were minimal. Since the largest dimension of the transmitting antennas is about 15 cm, the physical separation between the beacon and tag was sufficient to produce far field results. Given the relatively high directive gain of the beacon antenna and the height of the beacon and tag above the roof of the measurement van, it was expected that the effects of multipath would be negligible. For the short wavelengths used in this experiment (about 5 cm), interference due to multipath would be apparent and vary significantly with small changes in the relative positions of the transmitter and receiver. Such tests were performed by moving a calibrated horn antenna to various locations between the beacon and tag. Significant fluctuations in the signal strength that would accompany multipath were not observed.

The beacon transmitter and receiver were physically integrated into a single, weather-proof housing, but are shown separately in Figure 1 for purposes of schematic clarity. During testing, the DSRC beacon was operated from a laptop personal computer inside the van, via an RS-232 cable. DSRC control software (described in Section 2) was used to control all beacon functions. The beacon transmitted interrogations to the tag at a frequency of 5850 MHz. The tag would then, in normal operation, respond to the beacon at two frequencies: 5848 MHz and 5852 MHz.[2] The tag operated autonomously, its only external connections being for power [3] and the mast-mount.

[2] The beacon was only using the response from the upper channel during the tests, but future expansion of beacon capabilities may result in the use of the second frequency.

[3] The tag is normally powered by a battery when used in a vehicle, but for purposes of these tests, batteries were exhausted quickly, and marginal power from a battery near the end of its life could adversely affect test results; therefore power was supplied via a BNC cable from a DC source.

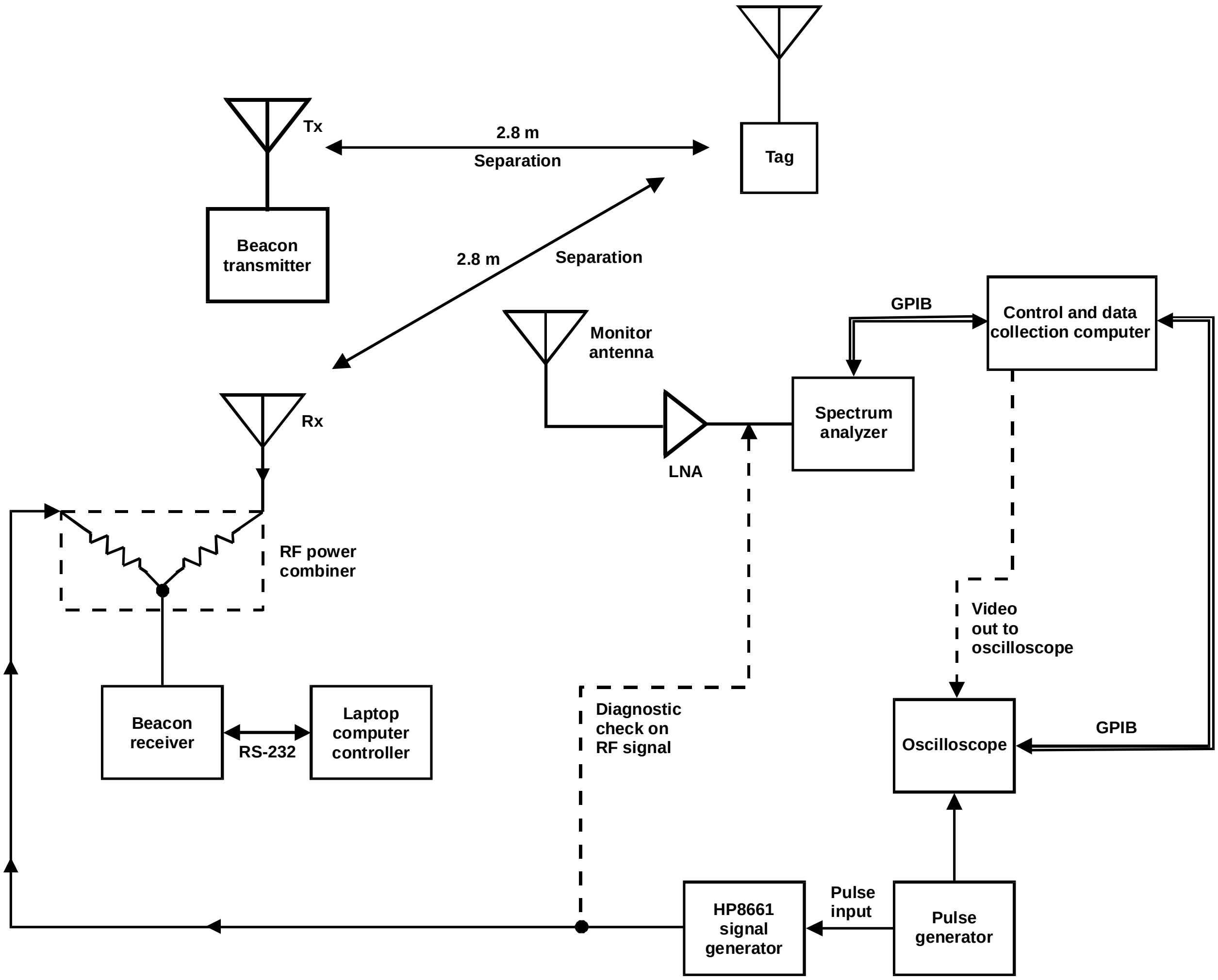

Figure 1. Block diagram of interference testing arrangement.

Since the major goal of the testing was to determine the thresholds at which DSRC performance was adversely affected for various types of interfering signals, and because separate theoretical and engineering considerations demonstrate that interference effects should be manifested as a result of interference signals that are received at the beacon rather than at the tag, interference signals were coupled into the beacon receiver. The signals were coupled via hardline, rather than via RF radiation, so as to better control the amplitudes at which the interfering signals were injected into the beacon receiver. To achieve this coupling, an RF power combiner was used between the beacon receiver antenna and the beacon receiver, as shown in Figure 1.

Interference signals were generated by adjusting modulation parameters on a pulse-waveform generator; that output was then routed to a modulation input on an HP-8661 signal generator. Pulse parameters were verified by observing pulse generator outputs on an oscilloscope. RF spectrum output from the signal generator was measured on a spectrum analyzer (Figure 1 and Section 3). The signal generator was used to generate RF energy at the proper amplitudes and frequencies for the tests. The interfering signal was coupled into the beacon receiver via a broadband combiner, along with the desired signal from the beacon receiver antenna.

While tests were in progress, a monitoring antenna was mounted on the rooftop, to the side of the beacon-to-tag propagation path. The monitor antenna output was connected to a spectrum analyzer, and the spectrum analyzer's detected video output was in turn monitored on an oscilloscope (Figure 1). This monitor provided the capability to observe both the frequency-domain and time-domain emissions from the beacon and the tag during the tests. This monitoring proved to be a useful diagnostic while tests were in progress, showing the effects of injected interference on the transmissions between the beacon-tag pair. Data from the spectrum analyzer and the oscilloscope were recorded via a GPIB bus interface to these instruments. These data served to document various aspects of the testing effort.

1.4 Calibration and DSRC System Performance Parameters

The nature of these tests and measurements required that the amplitudes of both the interference signals and the signals transmitted by the beacon and the tag be accurately measured. This required, in turn, that all measurement system components be accurately calibrated for gains and losses. Calibrations were performed in two ways: noise diode Y-factor calibration technique and injection of CW signals into various components, such as RF cabling. Both techniques depend upon measurement of the difference in power between two different system states. In the case of the noise diode Y-factor technique, a noise source of accurately known and calibrated equivalent noise temperature (in this case, a noise diode) is turned on at some point in the system (usually at the point that an antenna is normally attached to an RF line) and the power that reaches a device at the other end of the path (in this case, a spectrum analyzer) is measured. Then, the noise diode is turned off, and the power at the other end of the path is again measured. The difference between these two measured values is called Y. Measurement of Y, together with knowledge of the noise temperature of the noise source, makes possible the calculation of the system noise figure and the total gain through the system. For this set of tests, the noise diode calibration technique was used to determine gain and noise figure of various test system paths as a function of frequency between 4 and 8 GHz.

Losses through RF cabling in the measurement system were determined by injecting a CW signal into each cable and measuring the difference in RF power levels with and without the cable. A spectrum analyzer was used to measure the power levels. The two calibration techniques (CW signal and noise diode) were used to produce independent calibration results. No calibration difficulties were encountered with the ITS measurement and test system, and the calibration data were used to determine directly, among other parameters, the gain of the beacon antennas.

A desired calibration of the beacon receiver noise figure and front-end preselection roll-off proved impossible to perform. These two parameters were not specified in the manufacturer's documentation, and at the time this report was written, this information was not available from the manufacturer. In an effort to measure these parameters directly, the beacon receiver box was opened to obtain access to the receiver front-end. The goal was to perform a noise diode calibration through the front-end, thus yielding gain and noise figure of the receiver front-end as a function of RF frequency. However, inspection of the opened receiver unit revealed that no mechanical connections were available for such a calibration effort.

2. DSRC SYSTEM SOFTWARE DESCRIPTION

The DSRC system that was tested could not be operated under any sort of manual control; all DSRC beacon operations were performed under the control of software, while the DSRC tag device operated autonomously. All test results were obtained through outputs from the DSRC software control program.

2.1 Automated Fee-Collection Mode

The beacon was operated in a mode called automated fee-collection (AFC) transaction. This mode is used to collect identifying information from a tag as the tag passes through the beacon's beam. One transaction is composed of five separate messages, as listed in Table 2. The messages are:

Beacon Service Table (BST) - This message is transmitted by the beacon at regular time intervals when the communication channel is error free. This regular interval may be disrupted when a tag is in the beacon's beam and certain messages are retransmitted.

Private Window Request (PrWRq) - This message is transmitted by the tag in response to a BST from the beacon. The tag decodes the beacon's identification number from the BST and responds with a PrWRq if a transaction with that identification number has not occurred recently. Upon receiving a PrWRq, the beacon will attempt to complete a transaction with the tag within a BST time interval.

Private Window Allocation (PrWA) - This message is transmitted by the beacon in response to a PrWRq from a tag. This message defines three time windows. The tag may choose to respond in any of the three windows.

Vehicle Service Table (VST) - This message is transmitted by the tag in response to a PrWA from the beacon. This message contains information that identifies that particular tag to the beacon.

Release - This message is transmitted by the beacon in response to a VST from the tag. This message closes the DSRC link. The tag knows that the beacon received its VST and the tag will not respond to further BST's for a set time limit.

The order of occurrence of messages to form a complete transaction is shown in Table 2 for an error-free channel.

Table 2. Message Type as a Function of Transmitter Unit in the DSRC System

Transmitting Device	Message Type
Beacon	BST
Tag	PrWRq
Beacon	PrWA
Tag	VST
Beacon	Release

2.2 Software Algorithm for the Tests

The DSRC beacon has a serial port interface that allowed it to communicate with a computer using a specific set of commands to which the beacon responded. Using these commands, a software algorithm was developed to allow the computer to collect statistical information about the RF link. The algorithm was designed to measure a parameter called the *wait time*. Wait time as used in this report refers to the time interval starting with the transmission of the first beacon service table (BST) when the tag is in the communication zone, and the successful reception of a VST by the beacon. The wait time is effectively a measure of how long it takes for a beacon to collect a tag's identification information after the tag enters the beam of a beacon. The algorithm recorded the wait time for a predefined number of trials. The results were stored in a file on the computer's hard disk.

The algorithm consisted of a series of commands that are sent to the beacon from the computer in a defined sequence. The first few commands set the beacon for measurements. First, a command was sent that performed a soft-reset on the beacon firmware. The beacon assumed a well-defined, known state with this command. Next, the beacon transmit frequency was tuned to 5.850 GHz, the frequency used in these measurements. The beacon was instructed to send to the computer, via the serial interface, each VST that was received by the beacon via the RF interface.

In normal operation, the tag is designed to remain silent for a period of time after successfully completing a transaction. (At an operational DSRC station, this feature prevents the beacon from recording the tag's presence in a given location more than once as a vehicle passes a beacon.) In the measurement setup, the tag remained in the beam of the beacon continuously and in normal operation, the tag would respond once, then remain silent. For the tests, it was necessary to have the tag respond repeatedly in this situation in order to measure the statistical behavior of the link; hence, a software command was used to instruct the beacon to change its identification after each wait time measurement. During a wait time measurement, the beacon identification was locked. After a transaction was completed, and a wait time was obtained, the beacon was instructed to change its identification. A 4-s delay was used before beginning the next measurement to ensure that the beacon had time (nominally 3 s) to change its identification number before starting the wait time measurement timer.

To start a wait time measurement, the beacon was commanded to send BST's at a rate of 1 BST per 60 ms and the personal computer timer (DOS user timer) was started. This timer has a resolution of approximately 55 ms. The computer waited for a VST to arrive (from the beacon) at the serial port interface. The content of the received VST was compared to the expected content. If the contents were identical, the timer was stopped, and the wait time was calculated and recorded. In an interference-free environment, the wait time can be on the order of several ms to 20 ms, which is the equivalent of zero on our time scale. Resolution of these short wait times is unimportant, since they are an indication of normal operation. As the interference power level increases, the wait times increase substantially, to values ranging from hundreds of milliseconds to seconds. Therefore, the 55-ms timer resolution is more than adequate to measure the wait times in the presence of interference.

After a successful wait time measurement, the beacon was commanded to stop sending BST's. The beacon identification number was unlocked to allow this number to change. After a 4-s delay, the next wait time measurement was initiated. The computer executed this loop for a user-defined number of trials (usually about 500).

3. MEASUREMENT RESULTS AND DATA ANALYSIS

In this section, system performance measurements and statistical data obtained from interference testing are presented. System performance measurements were made to determine the spectral characteristics of the downlink and uplink signals and to estimate the sensitivity of the beacon receiver in the absence of interference. Measurements of the time required for a successful transaction between the beacon and tag in an interference-free channel were also performed and are included with the statistical data given below. The measurement configuration shown in Figure 1 was used for all of the results described in this section. Statistical measurements were made with the interference RF frequency coincident with the tag RF frequency. Frequency offset measurements were also made to determine interference power levels that effectively disrupt operations. In all cases, the DSRC system was operated in the AFC mode.

3.1 System Performance Measurements

Figure 2 shows the beacon and tag spectra measured with a calibrated 10-dBi horn antenna located 1 m from and aimed at the beacon transmitter antenna. Note that the tag transmits two sidebands offset from the beacon RF carrier by 2 MHz. Using this measurement configuration, we found that the power delivered by the beacon to the transmit antenna was 16 dBm. This power level was maintained for all measurements described in this section.

Figure 3 shows the power spectra measured at the beacon RF input terminal. This measurement was made by direct connection to the input terminal using a power splitter while the DSRC system was operating in AFC mode. The total power received at the beacon terminal was then obtained by integrating the power spectrum and removing the gain (or losses) of the measurement system. The measured power received from the tag at the beacon RF input terminal was −63 dBm.

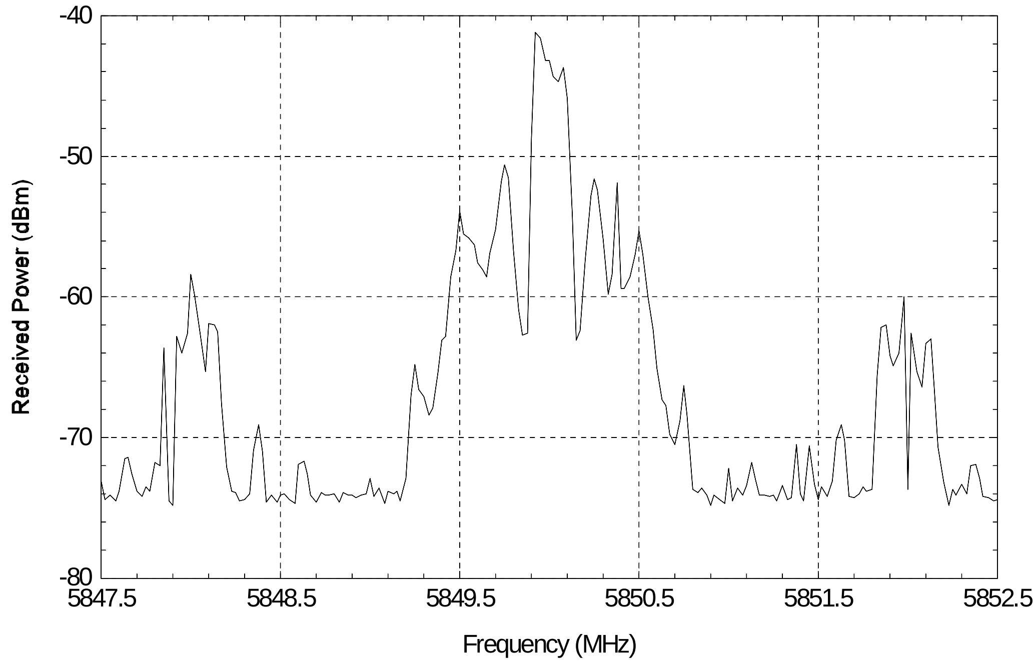

Figure 2. Beacon (center) and tag (± 2 MHZ) spectra measured with a 10-dB horn antenna 1 m from and aimed at the beacon transmitter (30-kHz resolution bandwidth).

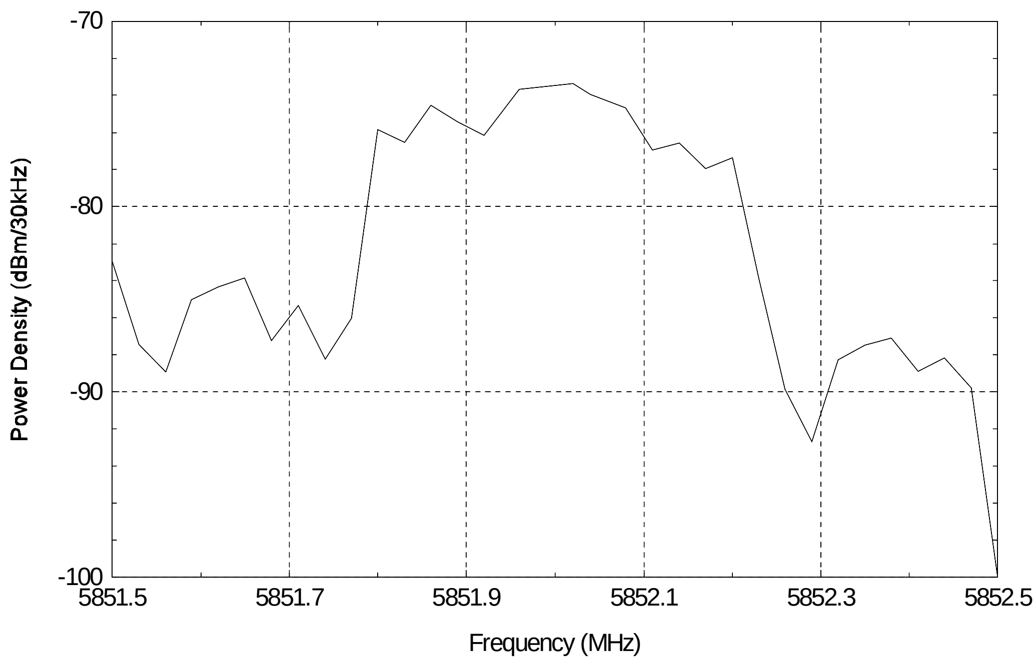

Figure 3. Tag spectra measured at the beacon receiver RF input terminal (30-kHz resolution bandwidth).

As noted in Section 1, the beacon construction precluded a quantitative measure of beacon receiver sensitivity. A qualitative measurement of the beacon receiver sensitivity was obtained by connecting attenuators to the beacon RF input. When the signal level at the beacon RF input terminal was reduced to −79 dBm, there was a noticeable degradation in the system performance, and at −89 dBm, the system completely failed to operate. This would indicate a system sensitivity of greater than -79 dBm to achieve a bit error ratio of 10^{-6}.

3.2 Statistical Measurements of DSRC System Performance

The primary goal of this measurement effort was to determine the effects of various C-band pulsed radars on the operation of the DSRC system. When operating in AFC mode, the DSRC system protocol allows for the retransmission of frames (e.g., the vehicle service table; VST) if a transaction is not completed due to bit errors resulting from, for example, pulsed radar interference. In addition, both the *arrival time* of the pulsed radar signal as well as its *phase* are random with respect to a particular AFC mode transaction. As a consequence, the time it takes for a complete transaction in the presence of radar interference, previously defined (Section 2.1) as *wait time*, is a random variable.

If the distribution of wait times is such that an unacceptably large percentage (to be determined) of vehicles will traverse the communication zone before a successful transaction can be accomplished, then clearly the DSRC system and the interferer are not compatible. Such a determination requires a statistical characterization of the wait time random process. Using the measurement equipment

and methods described in the previous sections of this report, we measured the wait time statistics based on several hundred (usually 500) independent trials for the pulsed radar parameters shown in Table 1.

The wait time statistics in the absence of interference are presented in Figures 4 and 5. For the most part, the wait time is less than the resolution of the measurement system or nominally 0 s, as would be expected. The few wait times exceeding 0 s are most likely due to errors resulting from the precision used in the floating point arithmetic. Measurement resolution and errors based on floating point number precision while evident for the relatively short wait time observed in the absence of interference, are expected to have an imperceptible effect on the statistics of the much longer wait times resulting from interference.

The measured wait time statistics in the presence of interference are given in Appendix A in the form of both histograms and cumulative distribution functions. In each case, statistics were obtained at several levels of peak RF interference power. For each pulse parameter set, statistics were measured at three interference power levels: the lowest power level where the wait time obviously starts to increase relative to an interference-free channel, and two additional measurements at 10 and 20 dB above this minimum. The percentage of trials that exceed a desired wait time can be evaluated directly from the cumulative distribution plots.

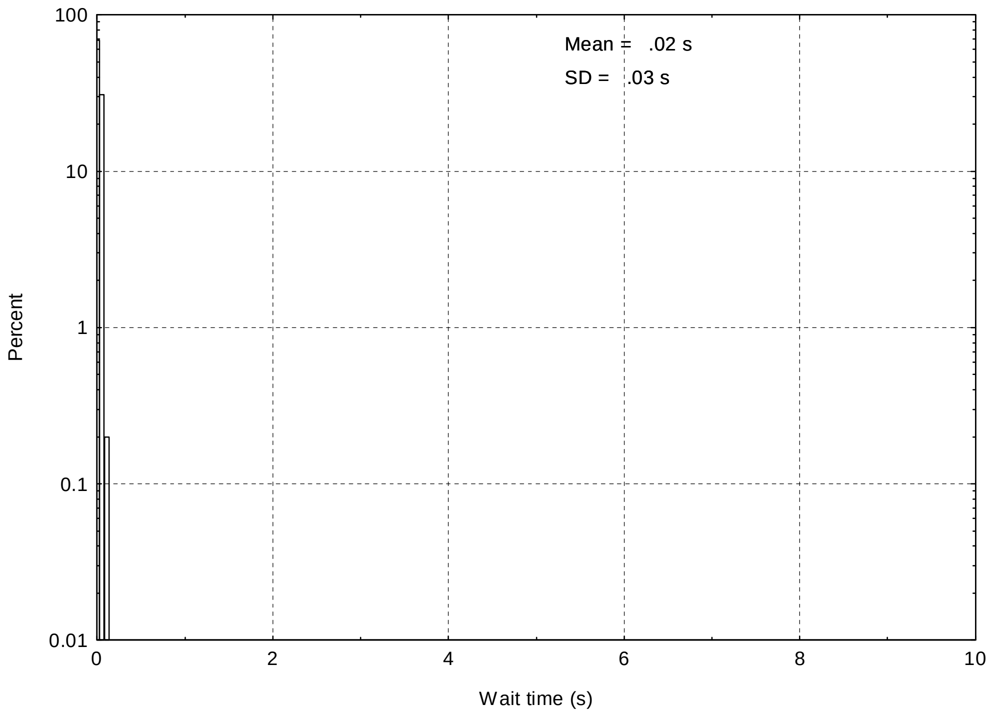

Figure 4. Wait time histogram, no interference.

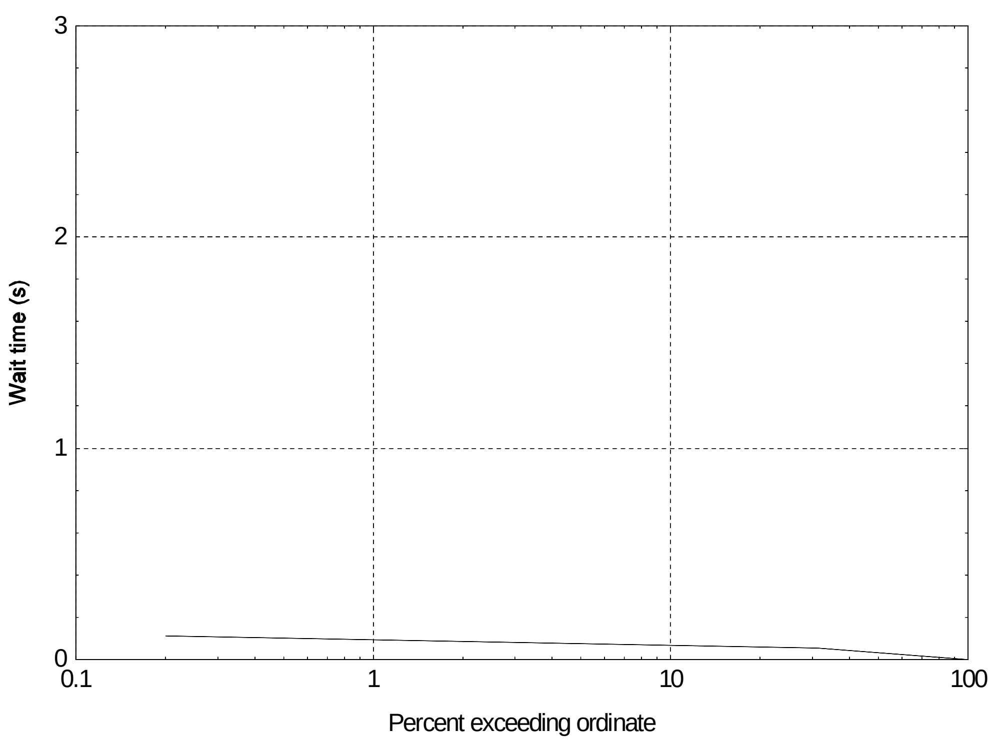

Figure 5. Wait time cumulative distribution, no interference.

3.3 Frequency Offset Measurements

The measurements described in the previous section can be considered to be *worst case* since the interference center frequency is equal to the center frequency for the upper-side band of the tag. To ascertain the DSRC system performance when the interferer is offset in frequency, several measurements were made at various frequency offsets using a pulsed signal as well as a continuous RF signal (CW). The results of these measurements are given in Table 3 below.

The interference power levels given in Table 3 correspond to mean wait times that exceed tens of seconds and for practical purposes completely disrupt effective communications. The CW interference has a very narrow bandwidth and is expected to interfere through the mechanism of RF front-end overload. It is interesting to note that while frequency offsets provide a margin in terms of allowable interference levels, the interference still disrupts operation for both the pulsed interference and CW.

3.4 Analysis of Measurements

Using the measurement results described above, the interference effects of typical pulsed radars operating in-band or nearly in-band with respect to the DSRC system were analyzed. First, it was necessary to estimate the maximum amount of time that might be allowed for a DSRC system transaction (*maximum allowable wait time*). For a particular installation, this will be approximately equal to the ratio of the length (along the roadway) of the communication zone and the speed of vehicle. Using the measured statistics for wait time, the percentage of vehicles that may exceed the maximum allowable wait time were estimated for various radar pulse parameters. The results are presented in Table 4.

Table 3. Deleterious Peak Interference RF Power Levels as a Function of Frequency Offset

Frequency Offset (MHZ)	CW (dBm)	Pulse width 3.3 µs 1% Duty Cycle (dBm)
−300	−5	−15
−200	−10	−15
−100	−20	−10
−50	−20	−20
−20	−20	−35
0	−98	−91

The communication zone for DSRC systems is typically defined as the volume of space where a reference bit error ratio (BER) of 10^{-6} can be achieved. In addition, it is required that the minimum power incident on the tag (relative to a 0-dB receiver antenna) within the communication zone is

−40 dBm [5]. Using this requirement, the upper bound or maximum length of a communication zone along a roadway can be estimated using the following expression for the power received by the tag:

$$W_{received} = EIRP + G_{receiver} - L_{free space} - A$$
$$L_{free space} = 32.45 + 20\log_{10} F_{MHz} D_{km} \quad \textbf{(1)}$$

where $W_{received}$ = −40 dBm is the power received by the tag, $EIRP$ is the effective isotropic radiated power, $G_{receiver}$ = 0 dB is the gain of the tag antenna, F_{MHz} = 5850 MHZ, D_{km} is the distance in km, and A is the attenuation of the radio channel. Assuming a free space propagation path (A=0 dB) and an effective isotropic radiated power of 32 dBm (16 dBm delivered to transmitter antenna plus 16 dB antenna gain) the maximum length of the communication zone is about 16 m. Note that this calculation assumes that the tag is in the main beam of the antenna when it is 16 m from the beacon along the roadway. The length of the communication zone may be somewhat less for a particular installation, however, 16 m should provide a reasonable upper bound.

Assuming that a vehicle travels for 16 m in the communication zone at a constant speed, Table 4 shows the peak RF interference power levels that resulted in wait times in excess of the maximum allowable wait times for vehicle speeds of 96.6-32.2 km/hr (20-60 mph). The percentage of trials that exceeded the maximum wait times are shown in parenthesis.

Table 4. Peak Pulsed Interference Power Levels Resulting in Wait Times that Exceed the Maximum Allowable Wait Time as a Function of Vehicle Speed in the Communication Zone (PW = Pulse Width, DC = Duty Cycle)

Vehicle Speed km/hr (mph)	Max Allowable Wait Time (s)	PW=1 ms DC=0.1% PRF= 1 kHz*	PW=3.3 µs DC=1% PRF= 3.03 kHz*	PW=10 µs DC=1% PRF= 1 kHz*	PW=.33 µs DC=0.1% PRF= 3.03 kHz*	PW=3.3 µs DC=0.1% PRF= 303 Hz*
96.6 (60)	0.6	−68 dBm (2%)	−91 dBm (1%)	−89 dBm (9%)	−61 dBm (17 %)	−14 dBm (1%)
80.5 (50)	0.72	−68 dBm (1%)	−91 dBm (0.4%)	−89 dBm (5%)	−61 dBm (12.5 %)	−14 dBm (0.8%)
64.4 (40)	0.89	−68 dBm (0.5%)	−91 dBm (0.2%)	−89 dBm (2.7%)	−61 dBm (6 %)	−14 dBm (0.4%)
48.3 (30)	1.19	−58 dBm (3.3%)	−81 dBm (43.5%)	−89 dBm (0.8%)	−61 dBm (2.6 %)	not measured
32.2 (20)	1.79	−58 dBm (0.4%)	−81 dBm (28.3%)	−89 dBm (0.2%)	−61 dBm (0.25 %)	not measured

* The percentage of trials exceeding the maximum are shown in parenthesis.

Typically, the radars operating at or near the proposed DSRC system center frequency have peak (EIRP) in the range of 113-133 dBm. The worst case interference had a pulse width of 3.3 μs, a duty cycle of 1%, and interferes with the DSRC system at power levels as low as −91 dBm at the beacon receiver. For this case, at least 220-240 dB of isolation is required. The best case interference (on frequency, from the Table 4) occurs for a pulse width of 3.3 μs and a duty cycle of 0.1% requiring 143-163 dB of isolation. It is clear that if the DSRC system and the interfering radar operate at about the same RF frequency, the required isolation is quite significant.

In general, the required isolation can be achieved by a variety of techniques including the use of a highly directive DSRC beacon receiver antenna, offsetting the operating frequencies of the radar and DSRC system, and allowing sufficient physical separation between the DSRC system and radar to achieve a specified *basic transmission loss*. It is estimated that 15 dB of isolation may be achieved in cases where the DSRC system can be installed so that the radar is well out of the beacon receiver antenna main beam. Also, when the DSRC system is well out of the main beam of the radar (e.g., due to installation or rotation) it may be possible to obtain 25 dB of isolation. The most optimistic case would then give 40 dB of isolation for antenna alignment. The measurement results for interference as a function of frequency offset (Table 3) indicate that about 75-80 dB of additional isolation may be achieved for offsets of a few hundred megahertz. This in combination with antenna sidelobe attenuation and basic transmission loss for distances of several hundred meters may be sufficient to allow effective operation of the DSRC system in most cases.

The required physical separation for the general ranges of best case (−143 to −163 dB of required isolation) and worst case (−220 to −240 dB of required isolation) interference scenarios was calculated for the following cases:

Case 1- isolation is achieved via physical separation only.

Case 2- isolation is achieved via physical separation and antenna alignment that provides an additional 40 dB of isolation.

Case 3- isolation is achieved via physical separation and frequency offset that provides approximately 80 dB of additional isolation.

Case 4- isolation is achieved via physical separation and frequency offset plus antenna alignment that provides an additional 120 dB of attenuation.

The basic transmission loss as a function of distance was calculated using the ITS Irregular Terrain Model [6] and is shown in Figure 6. The parameters used to determine the basic transmission loss are given in Table 5. The calculated separation distances are given in Table 6.

Table 5. ITM Parameters Used to Calculate Basic Transmission Loss

Parameter	**Value**
Frequency	5850 MHZ
Antenna Heights	13 m (radar), 6.1 m (DSRC)
Polarization	Vertical
Terrain Irregularity	90 m
Surface Refractivity	301 N-units (4/3 earth)
Climate	Continental temperate
Electrical Ground Constants	σ = 0.001 S/m ϵ_r = 15
Time Reliability, Location Reliability, and Confidence Level	90%, 90%, 50%

Table 6. Required Separation for Best Case and Worst Case Interference Pulses

Required Isolation (dB)	Case 1 Required Separation (km)	Case 2 Required Separation (km)	Case 3 Required Separation (km)	Case 4 Required Separation (km)
−143	17	0.6	<0.1	<0.1
−163	44	4	<0.1	<0.1
−220	379	64	14	<0.4
−240	621	203	40	<3.0

For example, if the interfering radar transmits 3.3 µs pulses with a 1% duty cycle at an EIRP of 133 dBm (worst case interferer), the received interference power (at the beacon receiver) should not exceed −91 dBm (from Table 4). Equation 1 can be used to calculate the basic transmission loss L_b required to obtain −91 dBm:

$$W_{received} = 133 + 16 - L_{freespace} - A = -91 \ \ (dBm)$$
$$L_b = L_{freespace} + A = 240 \ \ (dB). \qquad \textbf{(2)}$$

From Figure 6, the required basic transmission loss is achieved at a distance of 621 km as given in Table 6. If 40 dB of isolation is achieved by antenna alignment (Case 2), then 203 km of separation is required to obtain a basic transmission loss of 200 dB.

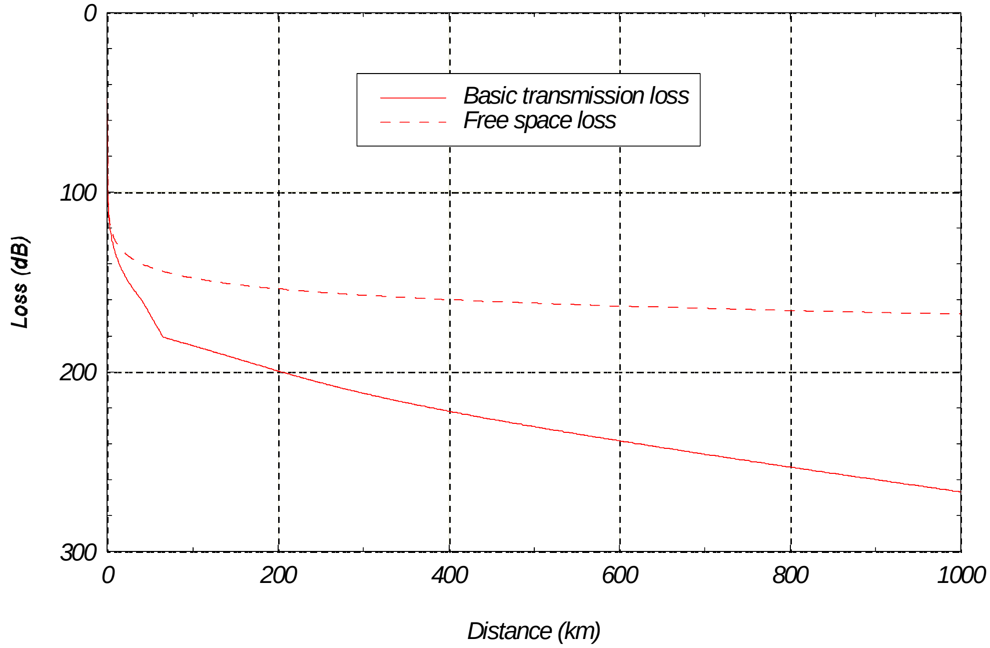

Figure 6. Basic transmission loss as a function of distance.

These results indicate that when the DSRC system and the radar antennas are aligned such that the radar is viewed with the minimum directive gain for both antennas, and the center RF frequencies are offset by a few hundred MHZ, the systems should be compatible at separation distances of 3 km or more for the worst-case required isolation of 240 dB (EIRP = +133 dBm). If only 220 dB of isolation is required (EIRP = + 113 dBm), then the systems should be compatible at separation distances of 0.4 km or more. The condition for minimum directive gain should be realized for rotating high-gain radar antennas with rotation rates of a few seconds, in which case the DSRC system would be in the main beam for only about 20 ms.

In Table 7, we give the results of interference calculations for specific existing radars that may potentially interfere with the operation of DSRC systems. This table shows specifically the radars that can reasonably coexist with the DSRC system and those where additional efforts will be required to improve compatibility. The radars and operating characteristics were taken from the Government Master File,[4] and should include all of the radars that may potentially interfere with the implementation of DSRC systems in the 5850- to 5925-MHZ band.

In the first column, we give the specific radar identification, pulse parameters (pulse width in μs and pulse repetition frequency; PRF), and the measured minimum interference power (MIP) for the pulse parameters. These were matched as closely as possible to the measurement results (Table 4) to estimate the MIP for that particular radar. In most cases, there is a range of possible pulse widths

[4] The file of all United States Government frequency assignments. This file is updated monthly.

and repetition frequencies resulting in large differences in the required isolation. In such cases, we have shown the best and worst cases associated with possible pulse parameters for each radar.

In the following columns of Table 7, we give the results for each previously defined case and an additional case (Case 5) where the DSRC system antenna sidelobe is in the main beam of the radar antenna and the isolation due to antenna alignment is 15 dB. There are two table entries for all cases: the required isolation for interference free operation, and the separation distance required to achieve that isolation. For Case 3, there is an additional entry showing the value of Δf that was used to estimate the isolation due to frequency offset (from Table 3). The frequency offset used is the minimum offset based on the radar RF frequency range and the proposed DSRC system RF frequency range.

For most existing radars, Case 4 should be achievable. As discussed previously, maximum isolation due to antenna alignment is likely for most rotating radars. Furthermore, installation of the DSRC system so as to achieve maximum antenna alignment isolation should be possible in many cases. The results show that for Case 4, the required separation distance is less than 1 km except for the *test radar* which has a required separation distance of 2 km. Case 5 may occur when the DSRC system is in the main beam of the radar for prolonged periods of time. This will occur, for example, if a nonrotating radar happens to be pointed at the DSRC system antenna sidelobe. This case, while somewhat unlikely, is possible and does significantly increase the required separation distance relative to Case 4.

Cases 1 and 2 only occur when the DSRC system and the radar are co-channel resulting in quite large required separation distances. These cases are only applicable to the FPS-16 and RIR-778C tracking radars. A map showing their locations is given in Figure 7. For these radars, a significant decrease in the required isolation is achieved when antenna alignment and frequency offset are possible (see Case 4). In cases where maximum isolation due to antenna alignment and frequency offset are difficult to achieve, coordination between the radar facility and DSRC system operations may be required to ensure electromagnetic compatibility. Such efforts could include RF frequency coordination and/or spatial masking.

Table 7. Required Separation Distances Between Specific Interfering Radars and the DSRC System for Different Isolation Cases

Specific Radar	Case 1: Isolation by physical separation only	Case 2: Isolation by physical separation and 40 dB from antenna alignment	Case 3: Isolation by physical separation and frequency offset	Case 4: Isolation by physical separation, frequency offset, and 40 dB from antenna alignment	Case 5: Isolation by physical separation, frequency offset, and 15 dB from antenna alignment
RIR-778C/FPS-16 1μs, 1 kHz MIP* =−68 dBm	348 km 217 dB	61 km 177 dB	20 km Δf=50 MHZ 146 dB	0.8 km 106 dB	8 km 131 dB
Test radar 10 μs, 1 kHz MIP =−89 dBm	505 km 231 dB	140 km 191 dB	32 km Δf=180 MHZ 155 dB	2 km 115 dB	14 km 140 dB
Test radar 3.3 μs, 303 Hz MIP =−14 dBm	34 km 156 dB	2.2 km 116 dB	0.05 km Δf=180 MHZ 80 dB	<0.001 km 40 dB	0.008 km 65 dB
SPS-10 1 μs, 1 kHz MIP=−68 dBm	182 km 197 dB	35 km 157 dB	13 km Δf=25 MHZ 139 dB	0.4 km 99 dB	5 km 124 dB
SPS-10 3.3 μs, 303 Hz MIP=−14 dBm	17 km 143 dB	0.6 km 103 dB	.08 km Δf=25 MHZ 85 dB	<0.001 km 45 dB	0.015 km 70 dB
SPS-67 1 μs, 1 kHz MIP=−68 dBm	196 km 199 dB	39 km 159 dB	15 km Δf=25 MHZ 141 dB	0.5 km 101 dB	6 km 126 dB
SPS-67 .33 μs, 3.03 kHz MIP=−61 dBm	147 km 192 dB	28 km 152 dB	10 km Δf=25 MHZ 134 dB	0.2 km 94 dB	3 km 119 dB
WSR-74C 1 μs, 1 kHz MIP=−68 dBm	266 km 208 dB	50 km 168 dB	9 km Δf=200 MHZ 132 dB	0.17 km 92 dB	2.5 km 117 dB
WSR-74C 3.3 μs, 303 Hz MIP=−14 dBm	31 km 154 dB	2 km 114 dB	0.04 km Δf=200 MHZ 78 dB	<0.001 km 38 dB	0.006 km 63 dB

*Minimum interference power (MIP).

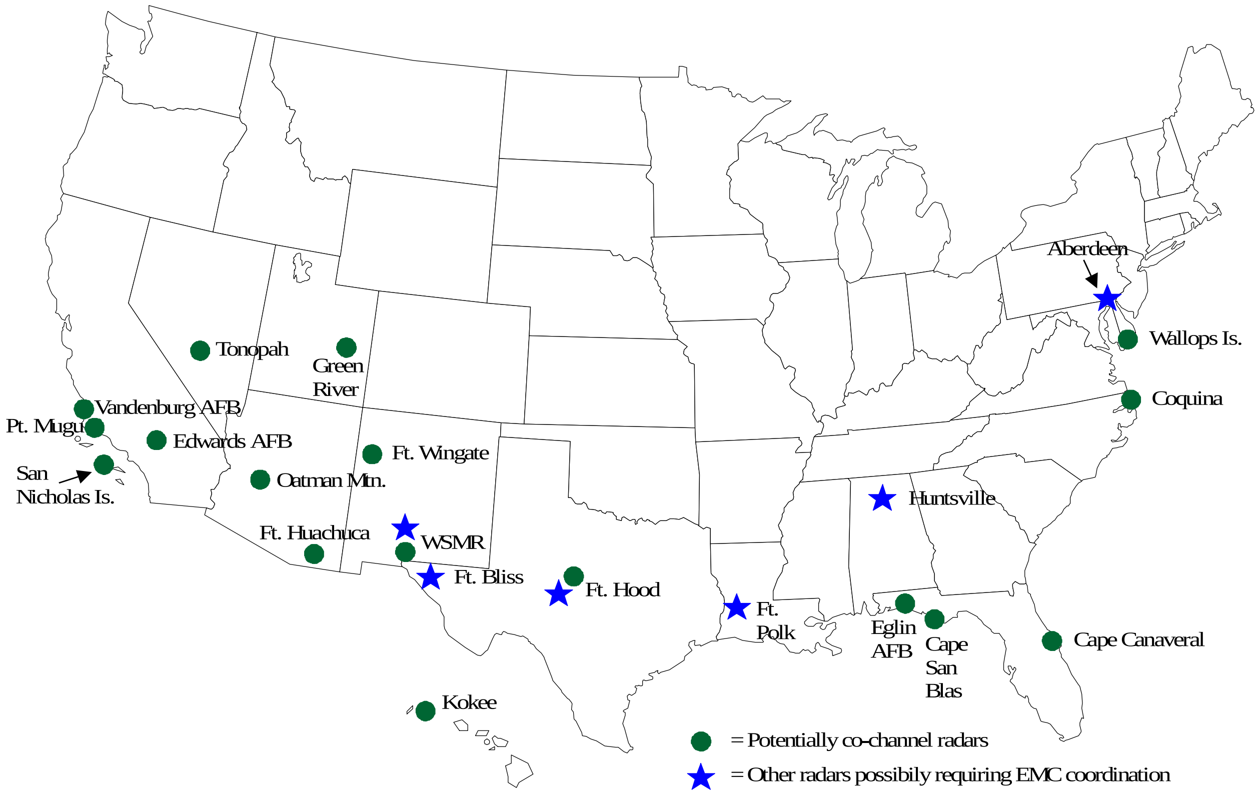

Figure 7. U.S. locations possibly requiring EMC coordination for DSRC deployment.

4.0 SUMMARY AND RECOMMENDATIONS

The tests and measurements performed on the DSRC system resulted in quantitative determinations of the adverse impact that various C-band radar transmissions produce on beacon operations. These adverse impacts were quantified as a function of both the interference amplitude and the interference modulation parameters. This section summarizes the results of the tests, and also makes recommendations to improve electromagnetic compatibility where required.

4.1 Summary

DSRC beacon operations were found to be significantly affected by co-channel radar signals that use pulse widths and pulse repetition rates that are representative of actual 5-GHz radars, and that are expected to be representative of radars that may operate in the 5-GHz band in the future. For co-channel operations between DSRC stations and radar stations, mitigation of adverse effects due to radar signals may require separation distances of up to a few hundred kilometers to achieve the necessary isolation. Our results further indicate that significant isolation can be achieved when the RF frequencies are offset by more than 25 MHZ. When combined with the expected maximum isolation achieved by antenna alignment (about 40 dB), we found that for all but one radar type, the DSRC system and existing C-band radars should be compatible at distances of 1 km, (or less) with the exceptional case requiring a 2-km separation.

It is expected that for most radar installations, coordination with DSRC systems operations will allow the required isolation resulting from frequency offset and antenna alignment to be achieved. Possible modifications that can be used to enhance compatibility in the event that the required isolation cannot otherwise be achieved are given below.

4.2 Recommendations for Enhanced DSRC Electromagnetic Compatibility

Taking into account the results of the DSRC tests and data analysis, we make the following recommendations for design modifications to the DSRC to improve electromagnetic compatibility with both current and future radiolocation operations in the 5-GHz portion of the spectrum:

1. The electromagnetic compatibility between DSRC stations and radar stations within the 5850- to 5925-MHZ spectrum band can be enhanced through the incorporation of modified DSRC data-encoding schemes.

It was noted during the course of the tests and measurements that deleterious interference effects were more pronounced when the duty cycle was increased, and that pulse repetition rate was particularly important as an interference factor. This dependence implies that significantly improved DSRC performance in the presence of radar interference may be achievable through the use of shorter DSRC data packets, and possibly through the use of forward error correction (FEC) in the DSRC coding scheme. Shorter DSRC data packets would reduce the probability of the loss of data bits due to simultaneous occurrence with radar pulses. We believe that shorter data packets would have the same effect as lower radar duty cycle. FEC should be useful in recovering individual bits that might be lost due to radar pulse interference as well, but the effectiveness of both of these approaches is beyond the scope of this report, and need to be studied separately.

2. Even with the suggested changes to the DSRC system protocol, there remains one possible electromagnetic compatibility problem that cannot be solved by modifying the DSRC design: the case in which a radar is co-channel to the DSRC receiver frequency, and the radar signal is received at such a high amplitude that front-end overload occurs in the DSRC beacon receiver front-end. This may happen if a DSRC station is within close proximity to a very high-power radar, such as an FPS-16. In such a case, electromagnetic compatibility can only be achieved by installing a notch filter in the DSRC front-end at the radar frequency (or a band-reject filter that is effective across the range of selectable radar frequencies), or else by tuning the radar below 5850 MHZ (where the interference will be mitigated by the DSRC 5250- to 5850-MHZ band-reject filter). At such locations, long-term coordination will be required to ensure that the DSRC and radar frequencies do not coincide. Locations in the United States where we anticipate that such coordination may be required are

Wallops Island, Patuxent Naval Air Test Center, Cape Canaveral Air Force Station, Eglin Air Force Base, White Sands Missile Range, Edwards Air Force Base, China Lake Naval Weapons Center, Vandenburg Air Force Base, and Point Mugu.

4.3 Recommended Additional Analysis

Our measurements indicate that there is a strong likelihood that DSRC system performance in the presence of radar interference can be substantially improved through the use of data encoding schemes. The tests and analysis that were performed were not adequate to make that determination definitively. Further analysis needs to be performed to determine, quantitatively, to what extent DSRC electromagnetic compatibility can be improved through the use of such a design modification, and indeed what data encoding modifications would be most effective. Therefore, we recommend that additional resources be devoted to determining engineering changes in DSRC data transfer protocols that would effectively mitigate co-channel, pulsed interference from radar stations.

5. REFERENCES

[1] F.H. Sanders and V.S. Lawrence, “Broadband spectrum survey at Denver, Colorado,” NTIA Report 95-321, Sep. 1995.

[2] F.H. Sanders, B.J. Ramsey, and V.S. Lawrence, “Broadband spectrum survey at San Diego, California,” NTIA Report 97-334, Dec. 1995.

[3] F.H. Sanders, R.L. Hinkle, and B.J. Ramsey, “Analysis of electromagnetic compatibility between radar stations and 4 GHz fixed-satellite earth stations,” NTIA Report 94-313, Jul. 1994.

[4] R.J. Matheson, J.D. Smiley, G.D. Falcon, and V.S. Lawrence, “Output tube emission characteristics of operational radars,” NTIA Report 82-92, Jan. 1992.

[5] European Committee for Standardization (CEN), “Dedicated short-range communications physical layer,” Predraft Standard, Dec. 1995.

[6] G.A. Hufford, A.G. Longley, and W.A. Kissick, “A guide to the use of the ITS Irregular Terrain Model in the area prediction mode,” NTIA Report 82-100, Apr. 1982.

APPENDIX A: MEASURED WAIT TIME STATISTICS

The measured wait time statistics in the presence of interference are presented in this appendix. These data are presented in Figures A-1 through A-30 in the form of both histograms and cumulative distribution functions for the interference pulse parameters given in Table 1 of this report. In each case, statistics were obtained at several levels of peak RF interference power. For each pulse parameter set, statistics were typically measured at three interference power levels: the lowest power level where the wait time obviously starts to increase relative to an interference-free channel, and two additional measurements at 10 and 20 dB above this minimum. The percentage of trials that exceed a desired wait time can be evaluated directly from the cumulative distribution plots.

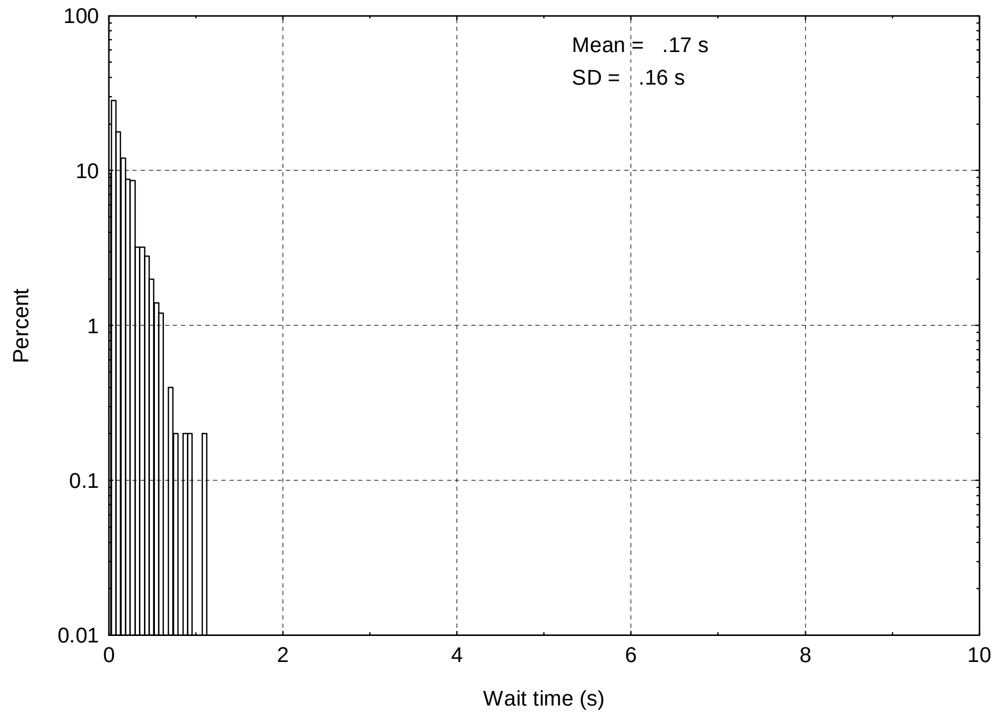

Figure A-1. Wait time histogram, interference pulse parameters: pulse width = 1 μs, pulse period = 1 ms, peak RF power = −68 dBm.

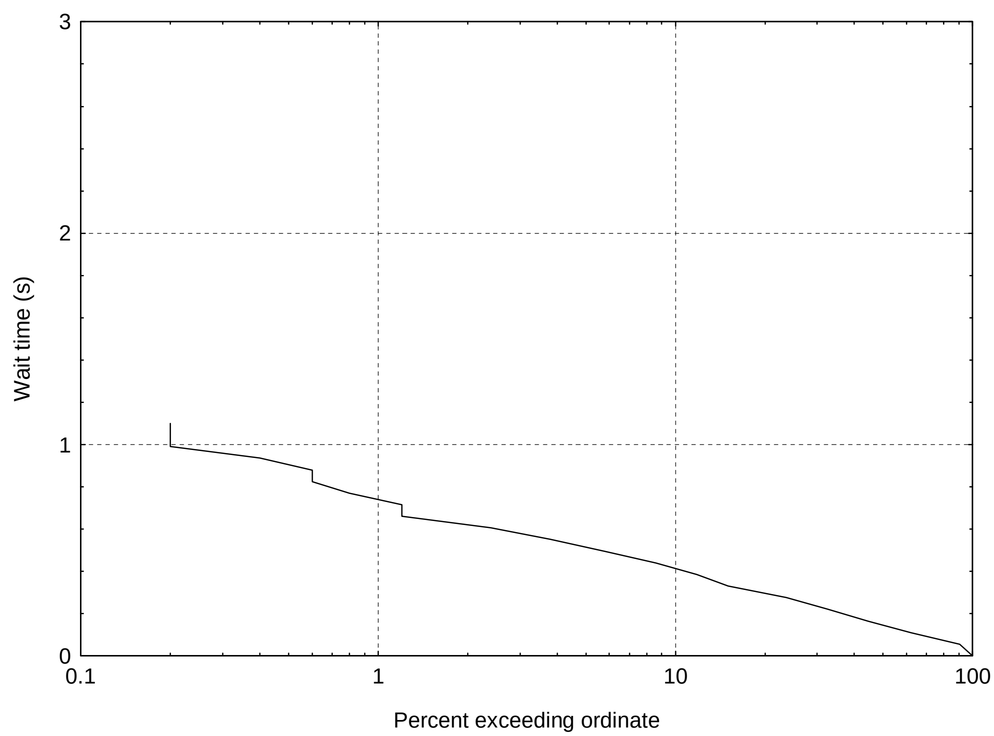

Figure A-2. Wait time cumulative distribution, pulse parameters: pulse width = 1 μs, pulse period = 1 ms, peak RF power = −68 dBm.

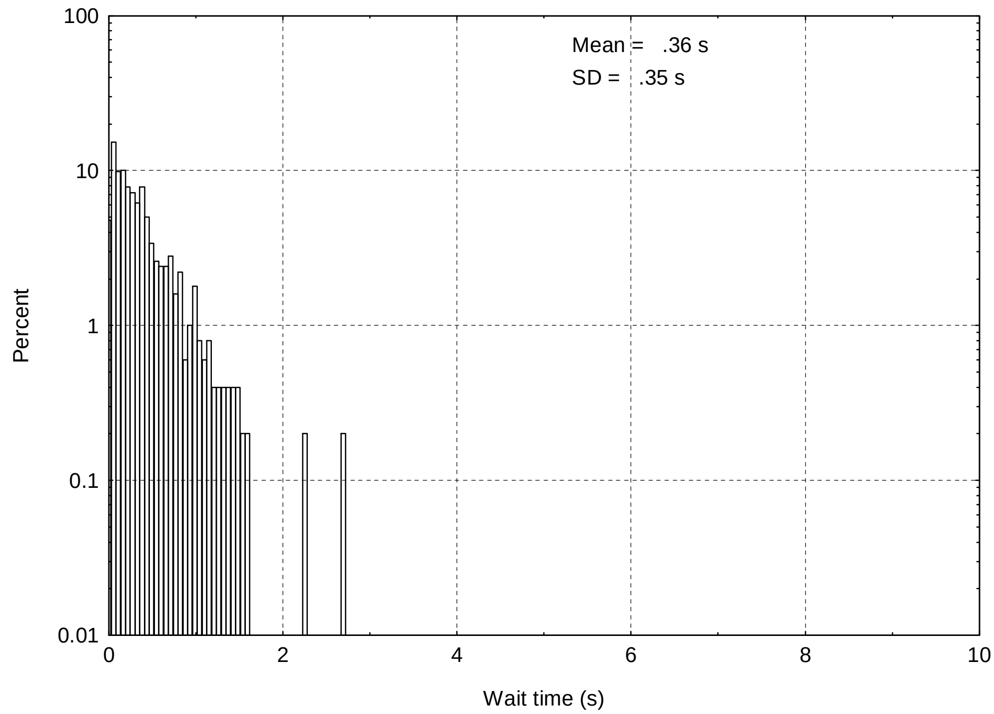

Figure A-3. Wait time histogram, interference pulse parameters: pulse width = 1μs, pulse period = 1 ms, peak RF power = −58 dBm.

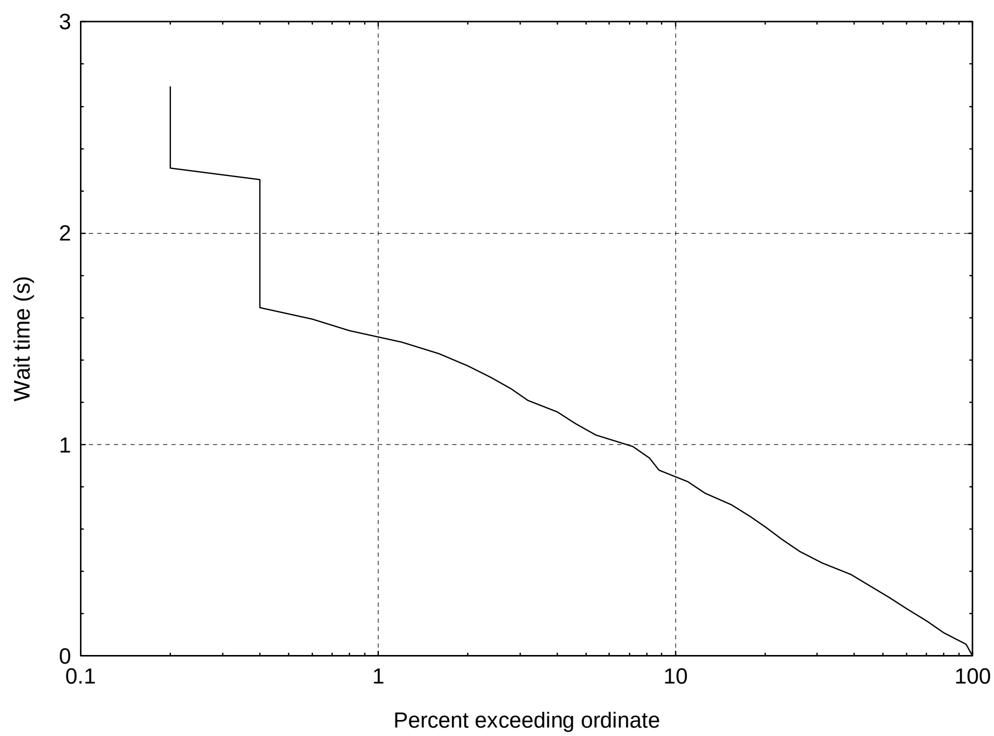

Figure A-4. Wait time cumulative distribution, pulse parameters: pulse width = 1μs, pulse period = 1 ms, peak RF power = −58 dBm.

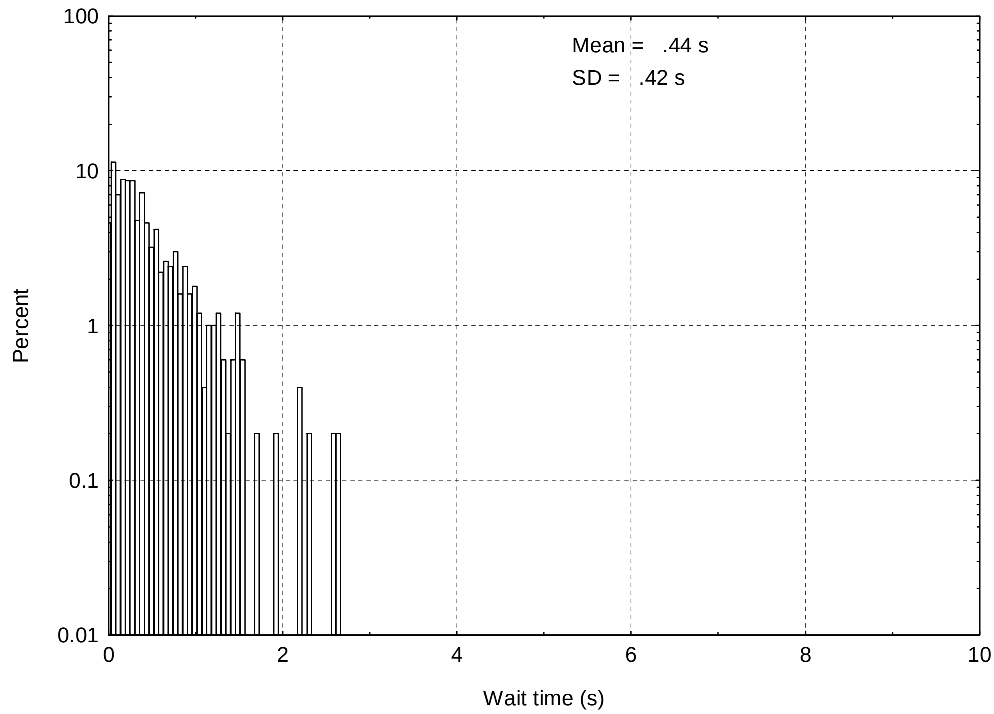

Figure A-5. Wait time histogram, interference pulse parameters: pulse width = 1μs, pulse period = 1 ms, peak RF power = −48 dBm.

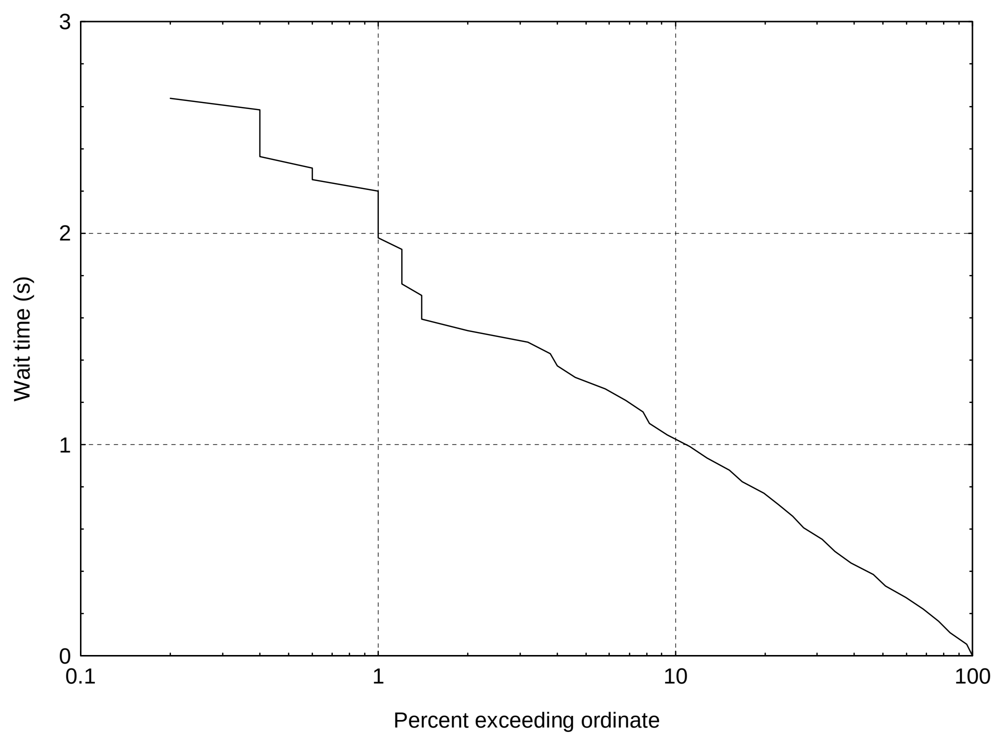

Figure A-6. Wait time cumulative distribution, pulse parameters: pulse width = 1μs, pulse period = 1 ms, peak RF power = −48 dBm.

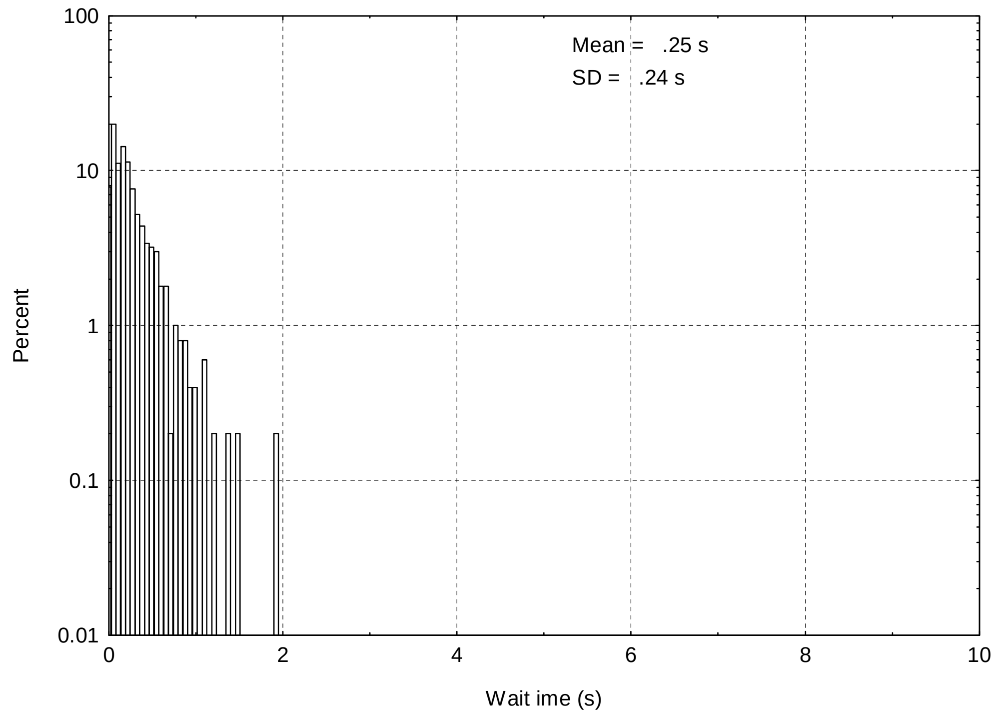

Figure A-7. Wait time histogram, interference pulse parameters: pulse width = 10μs, pulse period = 1 ms, peak RF power = −89 dBm.

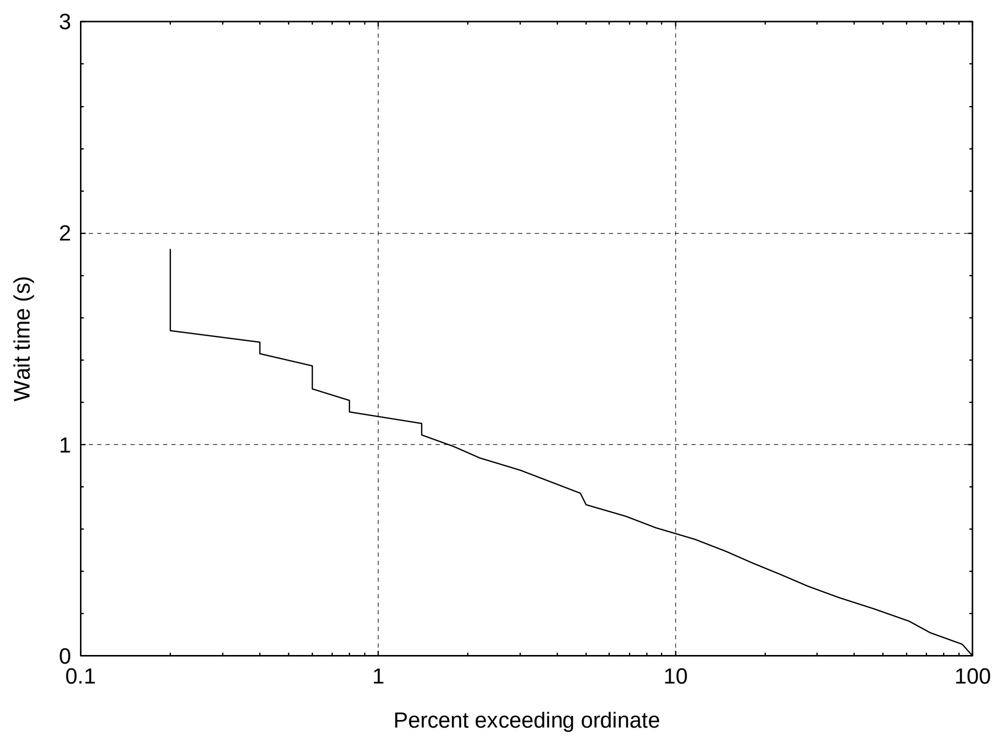

Figure A-8. Wait time cumulative distribution, pulse parameters: pulse width = 10μs, pulse period = 1 ms, peak RF power = −89 dBm.

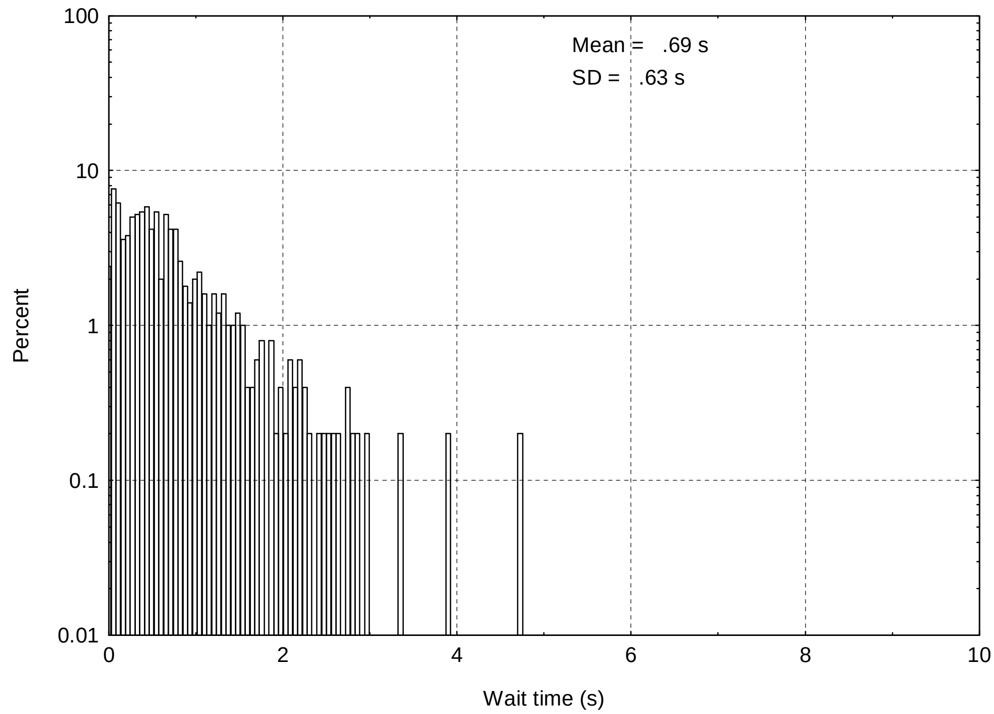

Figure A-9. Wait time histogram, interference pulse parameters: pulse width = 10μs, pulse period = 1 ms, peak RF power = −79 dBm.

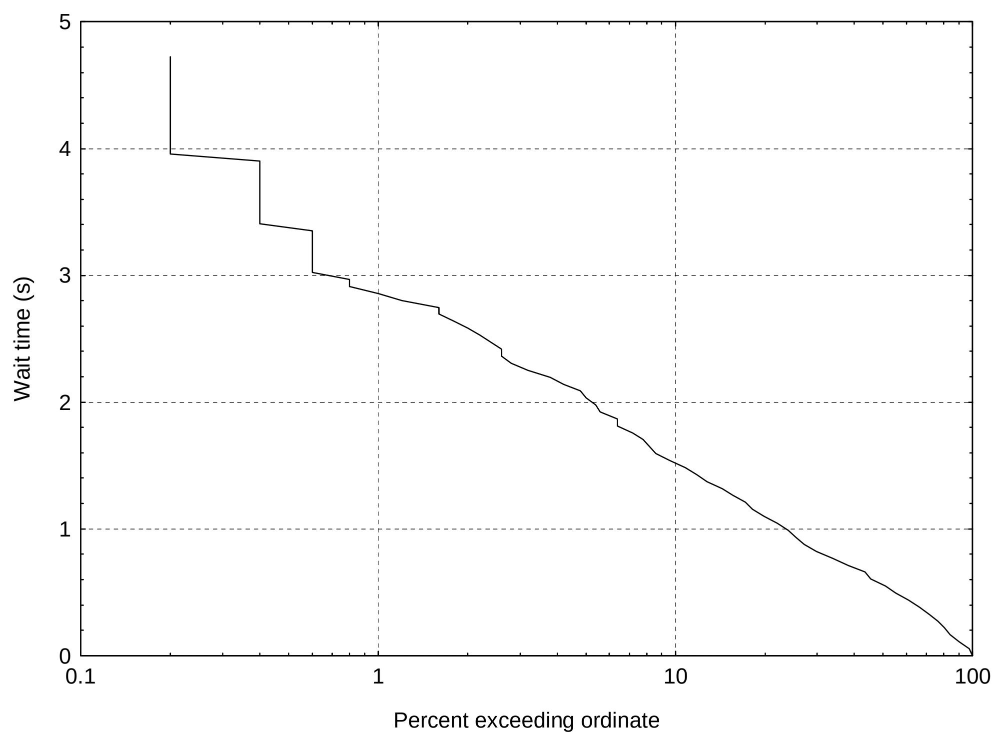

Figure A-10. Wait time cumulative distribution, pulse parameters: pulse width = 10μs, pulse period = 1 ms, peak RF power = −79 dBm.

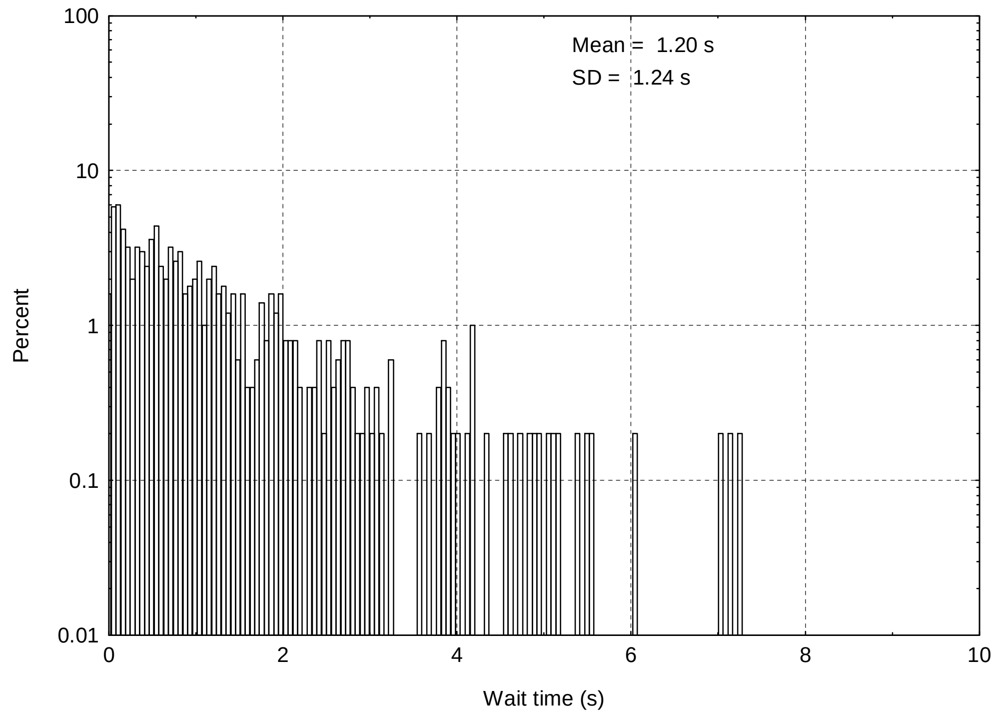

Figure A-11. Wait time histogram, interference pulse parameters: pulse width = 10µs, pulse period = 1 ms, peak RF power = −69 dBm.

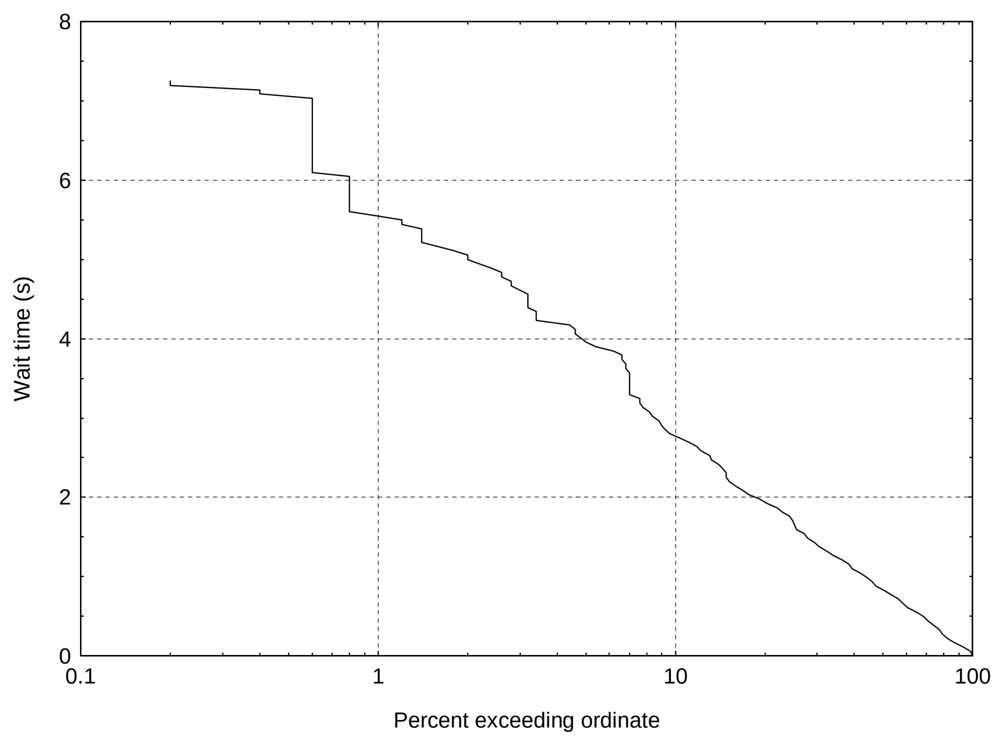

Figure A-12. Wait time cumulative distribution, pulse parameters: pulse width = 10µs, pulse period = 1 ms, peak RF power = −69 dBm.

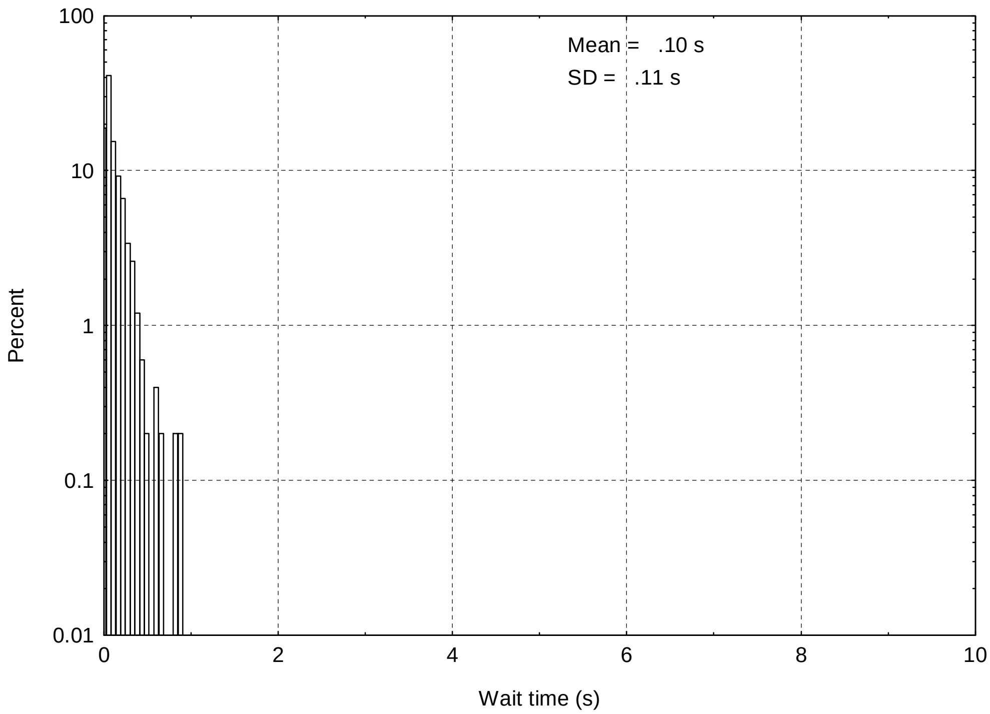

Figure A-13. Wait time histogram, interference pulse parameters: pulse width = 3.3 μs, pulse period = .330 ms, peak RF power = −91 dBm.

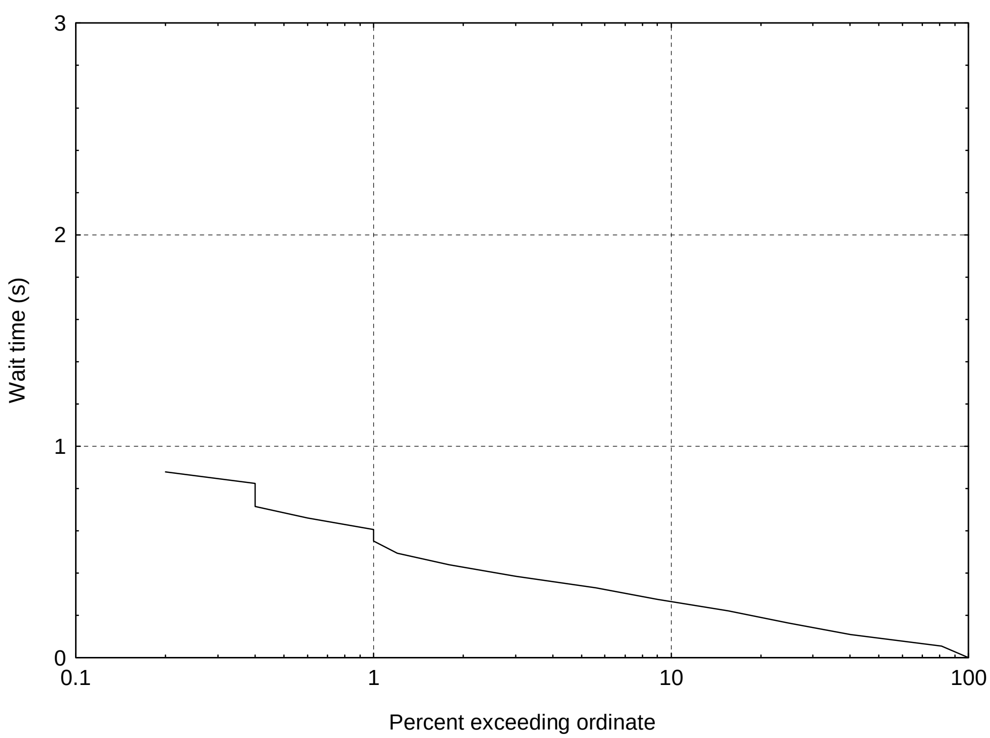

Figure A-14. Wait time cumulative distribution, pulse parameters: pulse width = 3.3 μs, pulse period = .330 ms, peak RF power = −91 dBm.

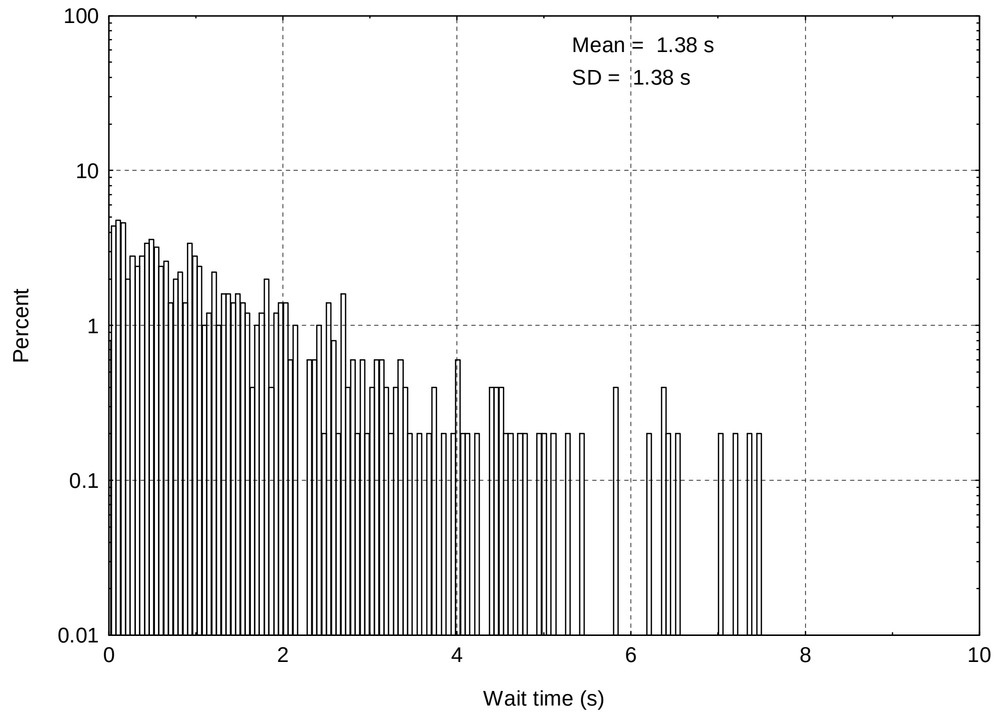

Figure A-15. Wait time histogram, interference pulse parameters: pulse width = 3.3 µs, pulse period = .330 ms, peak RF power = −81 dBm.

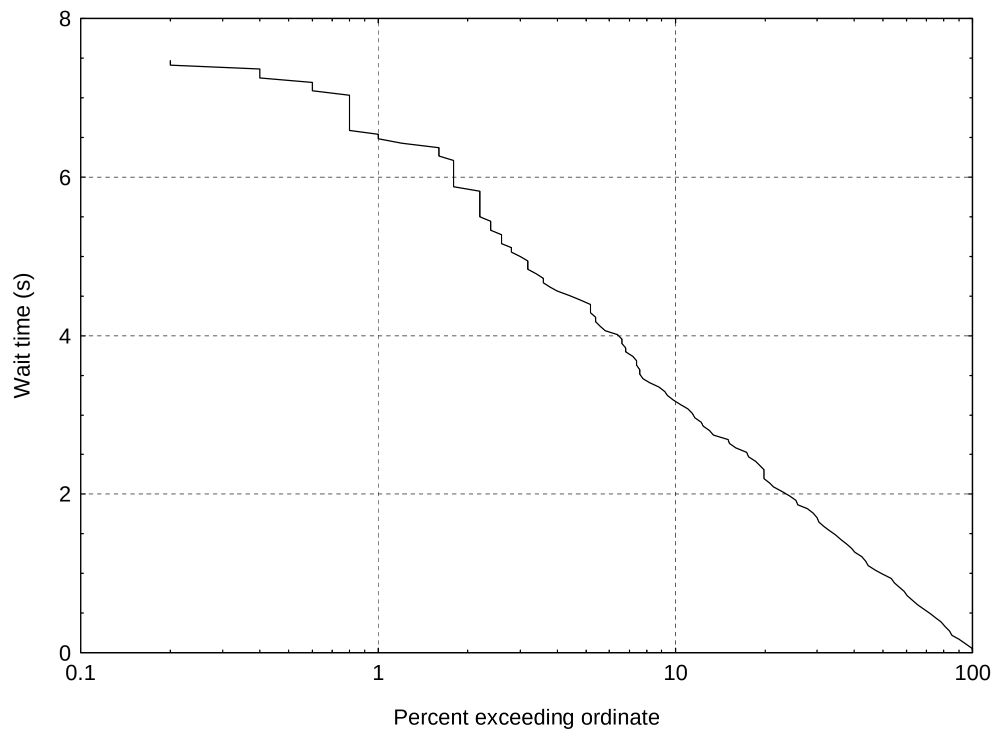

Figure A-16. Wait time cumulative distribution, pulse parameters: pulse width = 3.3 µs, pulse period = .330 ms, peak RF power = −81 dBm.

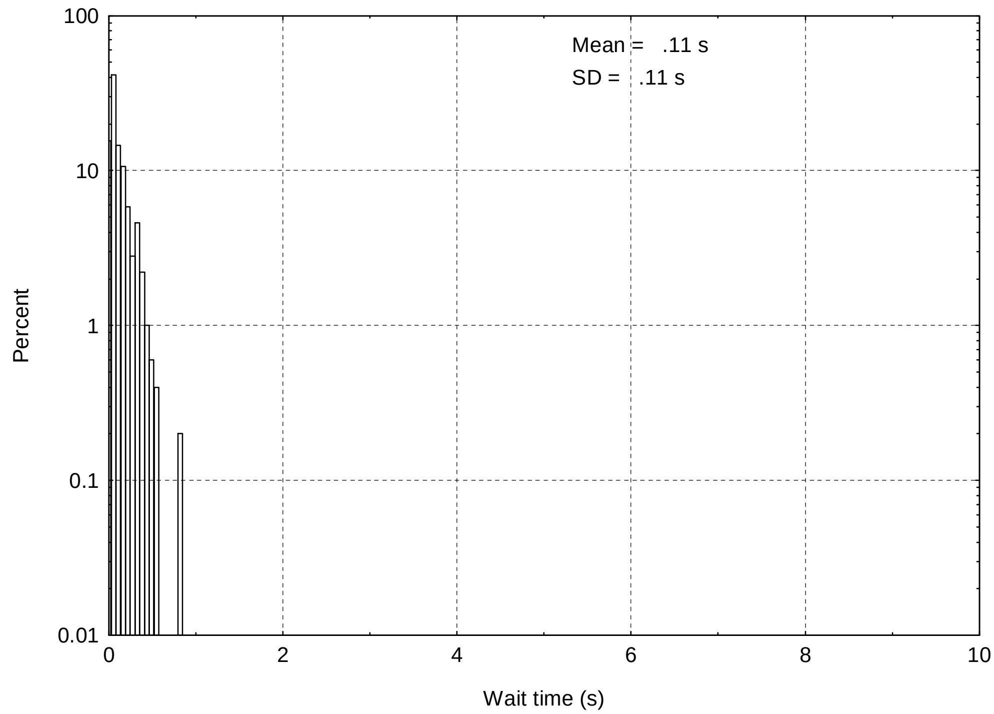

Figure A-17. Wait time histogram, interference pulse parameters: pulse width = .33 μs, pulse period = .330 ms, peak RF power = −71 dBm.

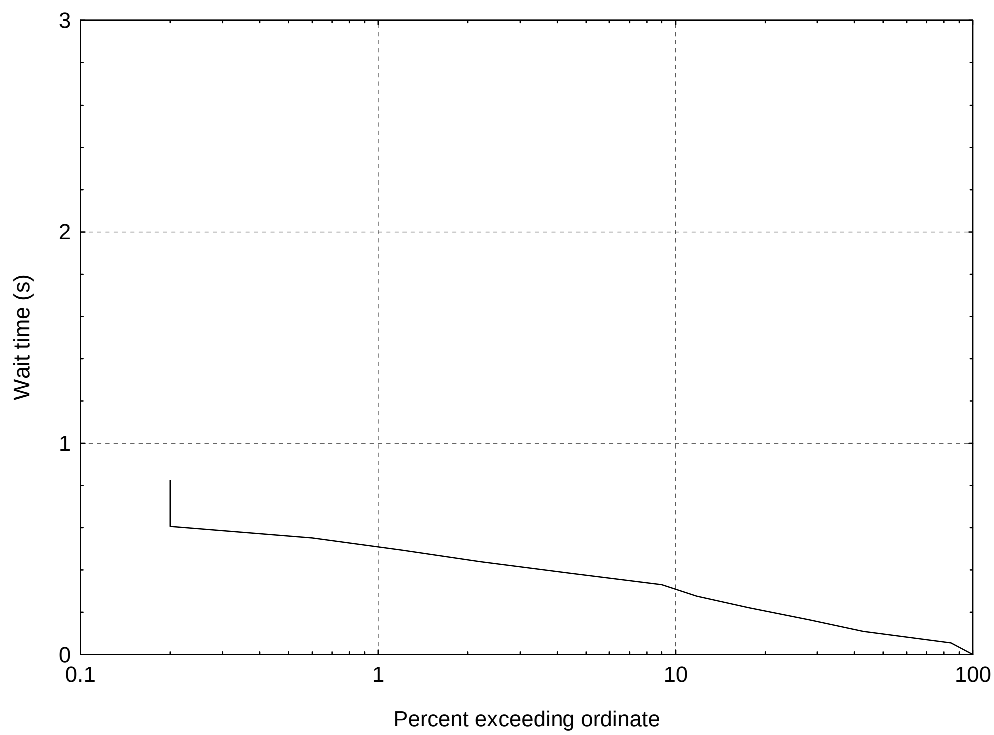

Figure A-18. Wait time cumulative distribution, pulse parameters: pulse width = .33 μs, pulse period = .330 ms, peak RF power = −71 dBm.

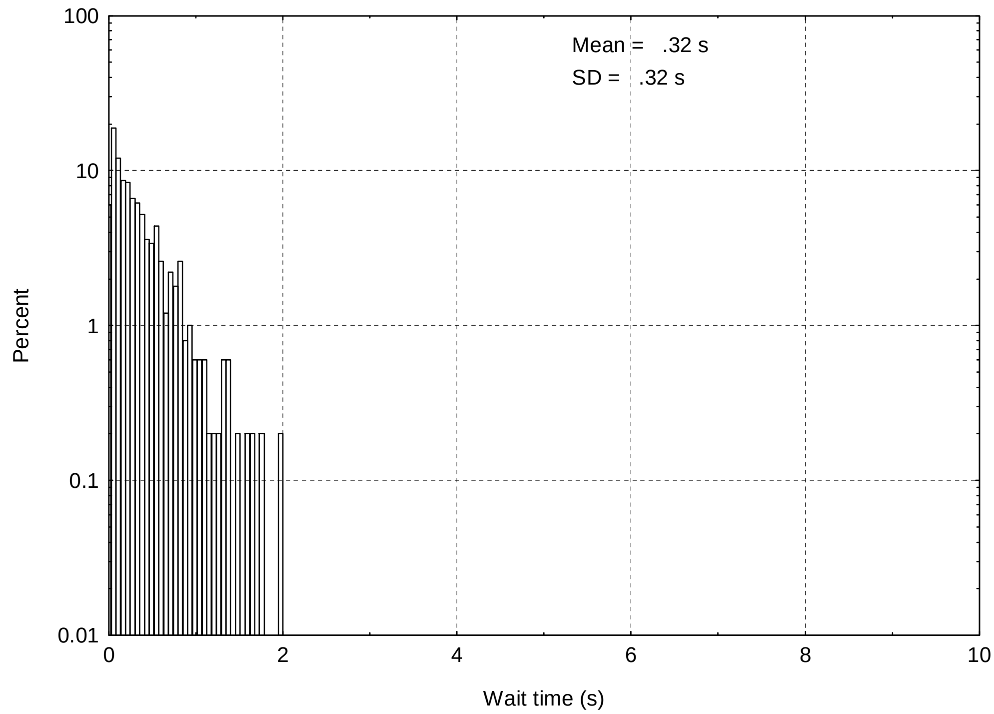

Figure A-19. Wait time histogram, interference pulse parameters: pulse width = .33 μs, pulse period = .330 ms, peak RF power = −61 dBm.

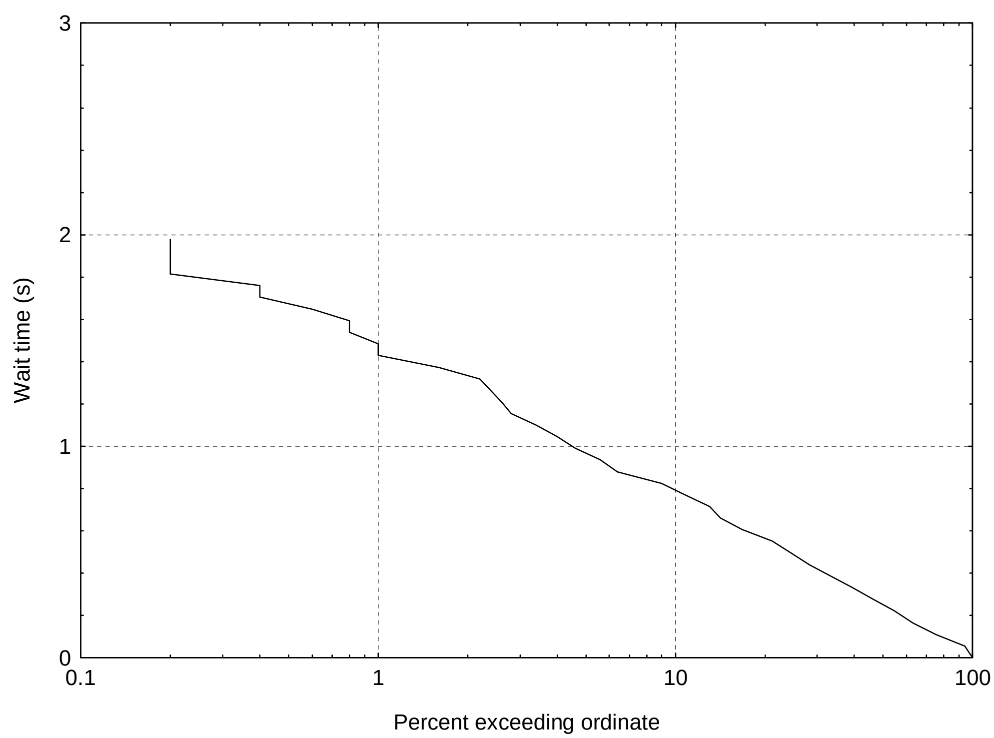

Figure A-20. Wait time cumulative distribution, pulse parameters: pulse width = .33 μs, pulse period = .330 ms, peak RF power = −61 dBm.

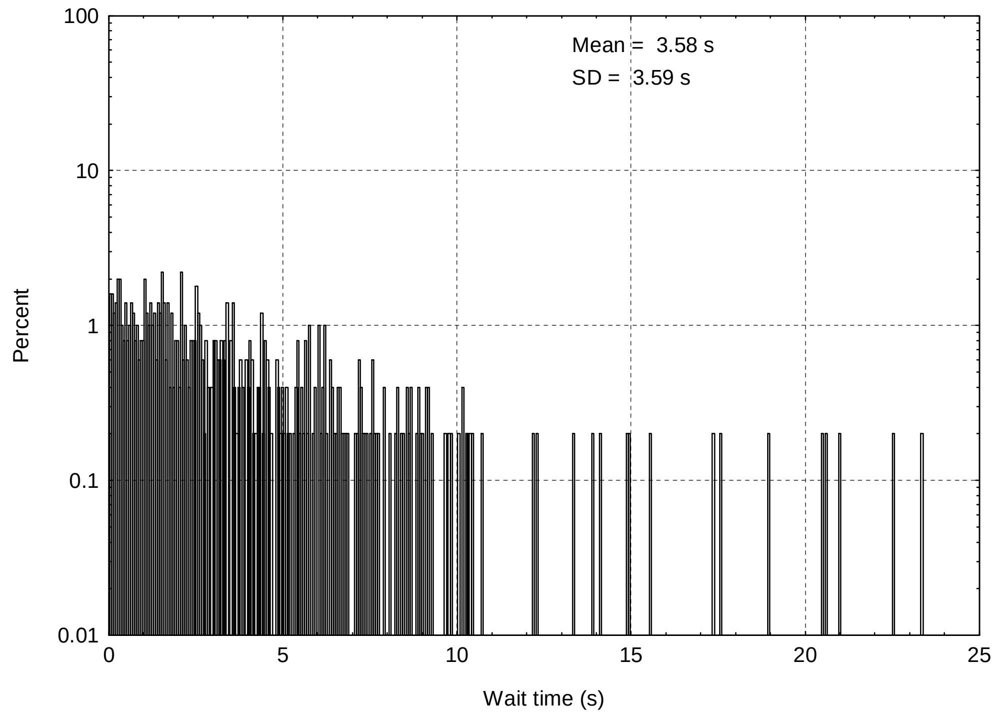

Figure A-21. Wait time histogram, interference pulse parameters: pulse width = .33 μs, pulse period = .330 ms, peak RF power = −51 dBm.

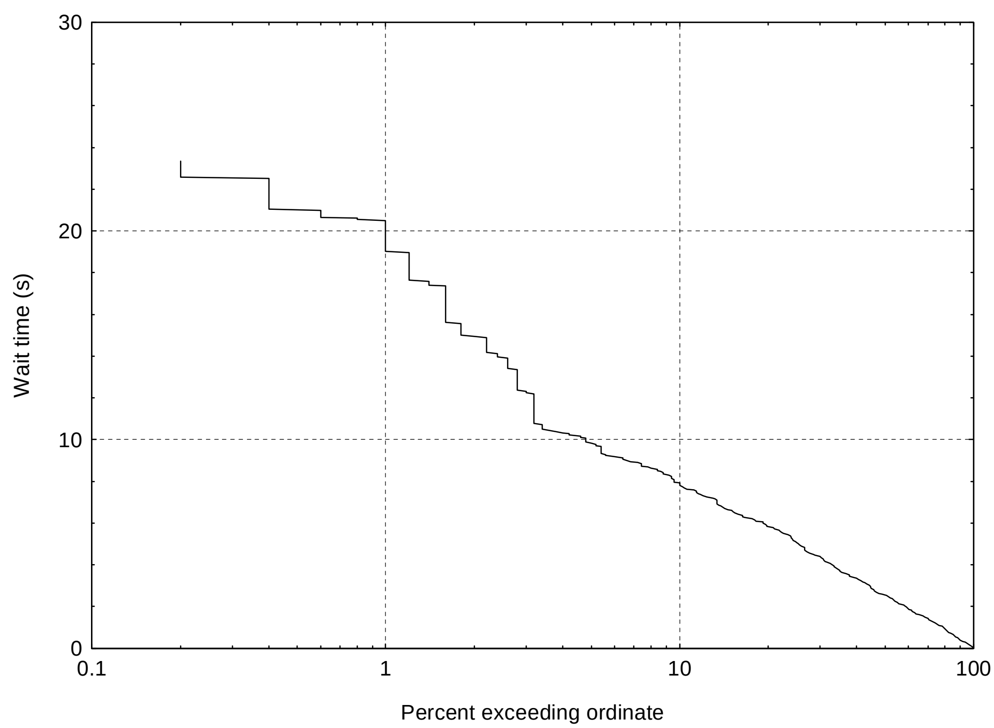

Figure A-22. Wait time cumulative distribution, pulse parameters: pulse width = .33 μs, pulse period = .330 ms, peak RF power = −51 dBm.

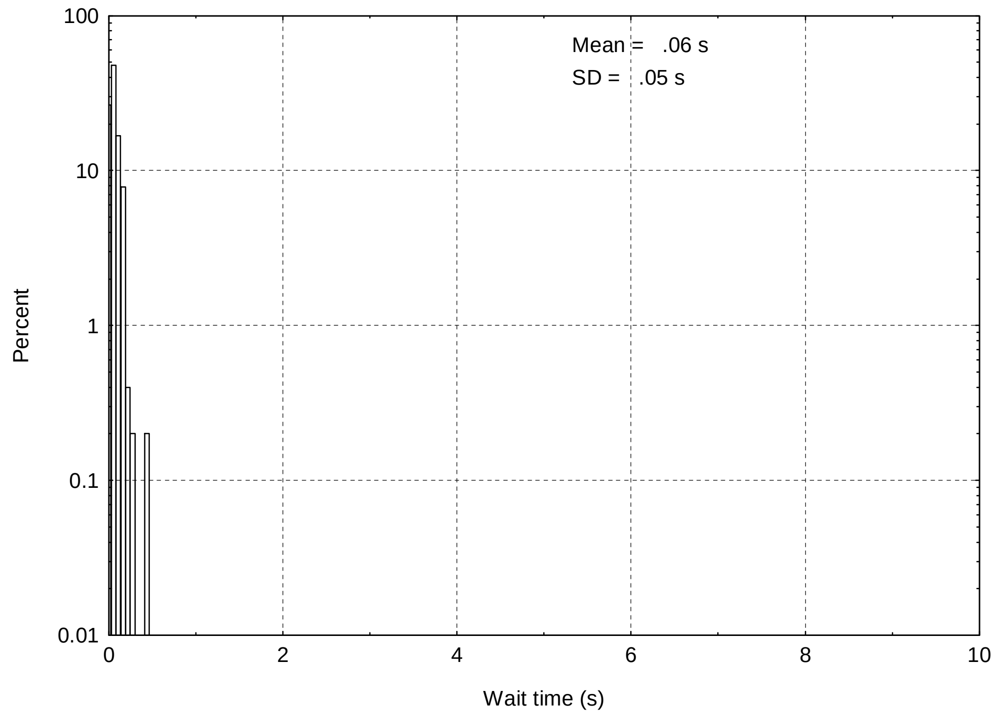

Figure A-23. Wait time histogram, interference pulse parameters: pulse width = 3.3 μs, pulse period = 3.3 ms, peak RF power = −24 dBm.

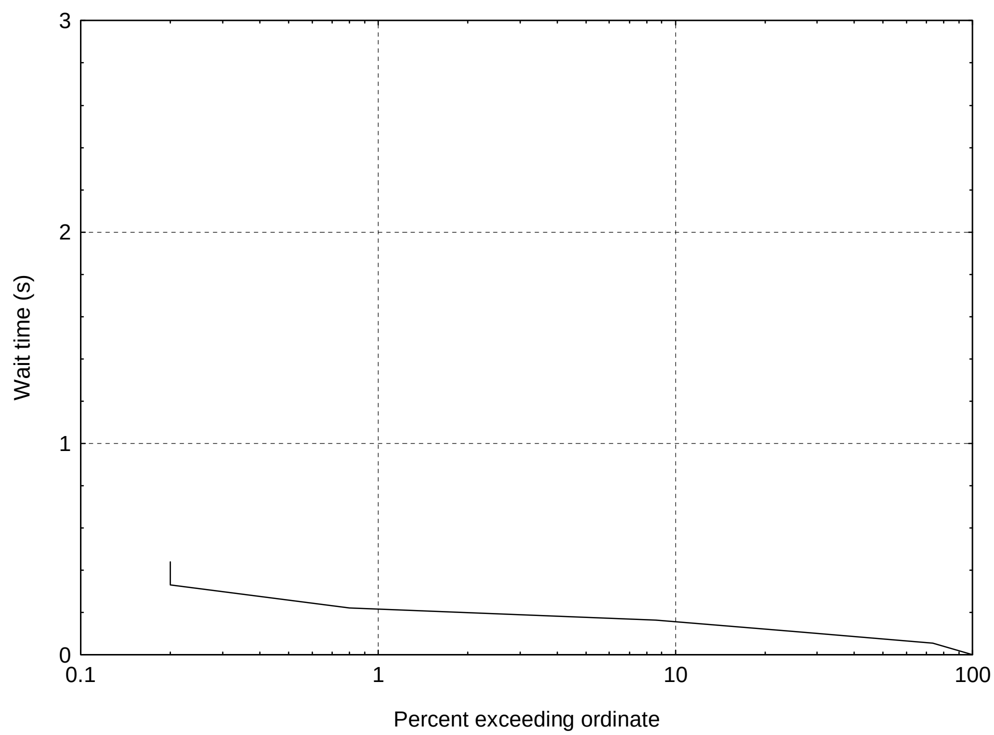

Figure A-24. Wait time cumulative distribution, pulse parameters: pulse width = 3.3 μs, pulse period = 3.3 ms, peak RF power = −24 dBm.

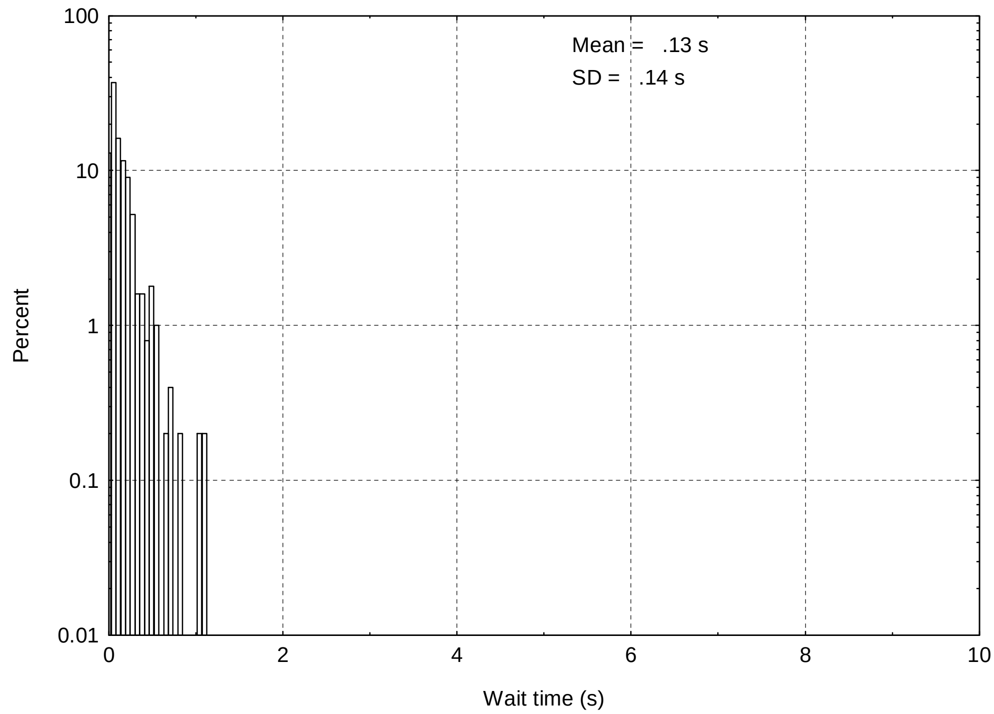

Figure A-25. Wait time histogram, interference pulse parameters: pulse width = 3.3 μs, pulse period = 3.3 ms, peak RF power = −14 dBm.

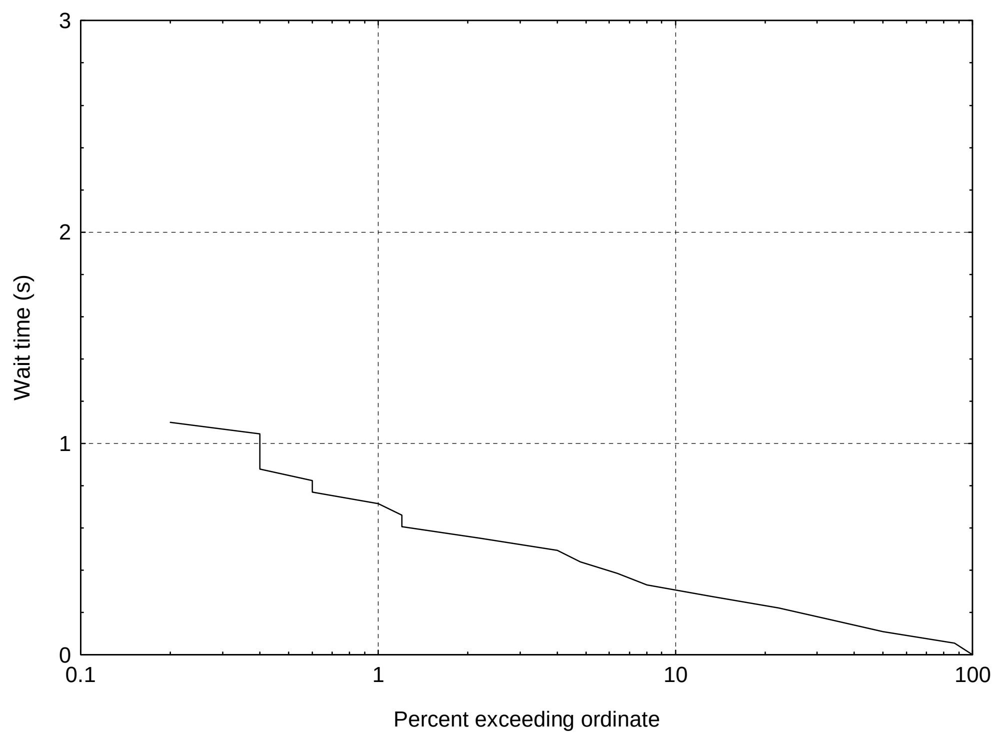

Figure A-26. Wait time cumulative distribution, pulse parameters: pulse width = 3.3 μs, pulse period = 3.3 ms, peak RF power = −14 dBm.

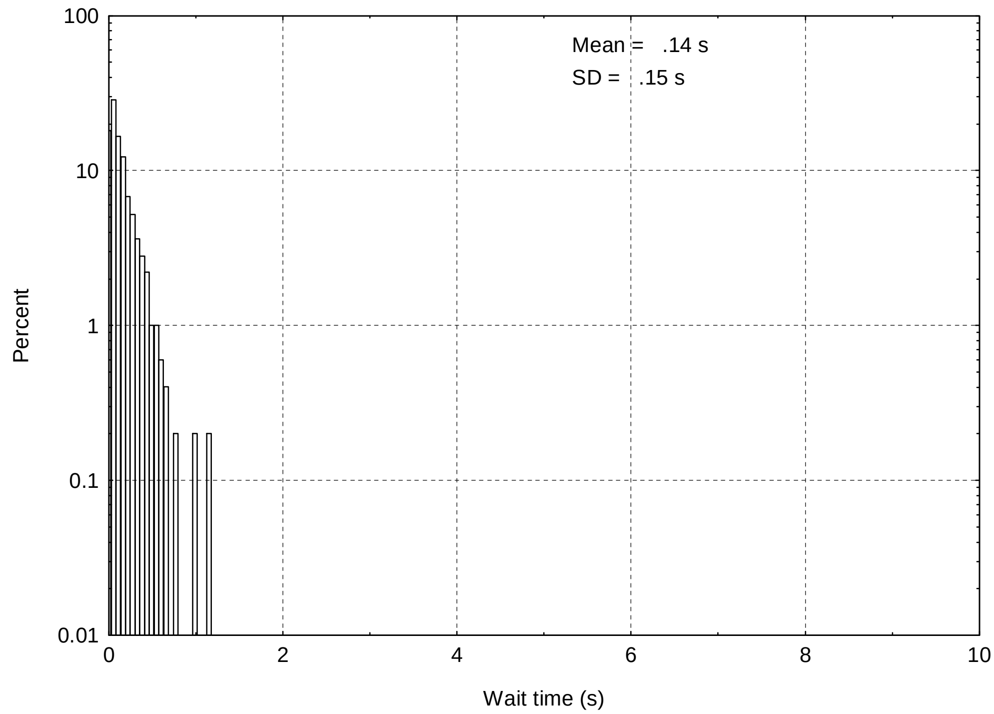

Figure A-27. Wait time histogram, interference pulse parameters: pulse width = 3.3 µs, pulse period = 3.3 ms, peak RF power = −4 dBm.

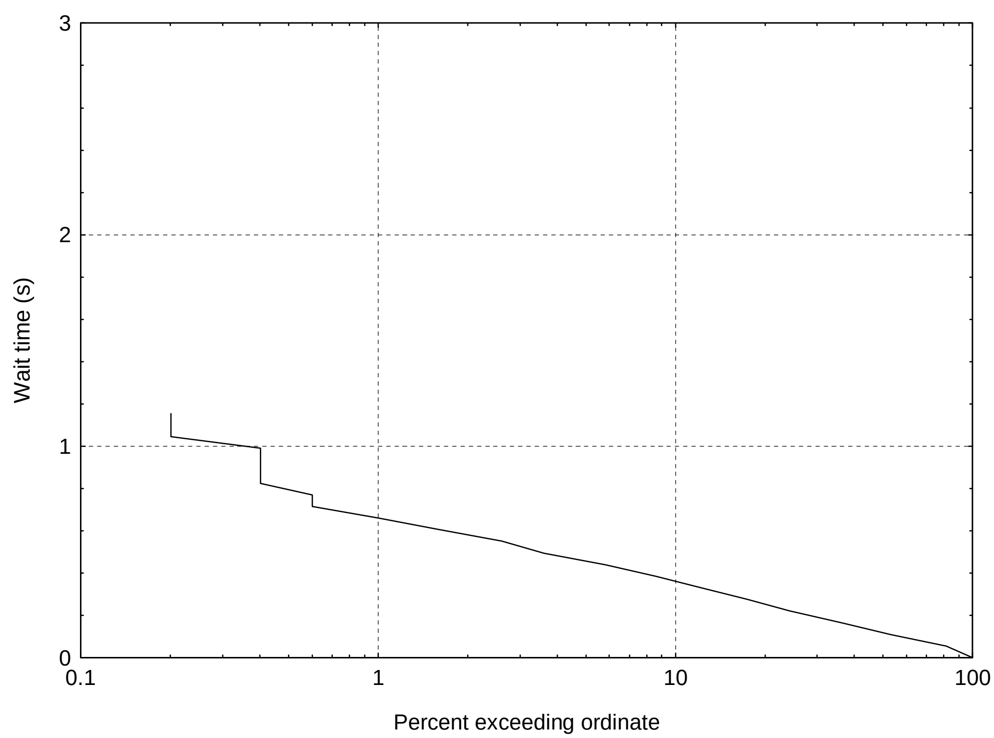

Figure A-28. Wait time cumulative distribution, pulse parameters: pulse width = 3.3 µs, pulse period = 3.3 ms, peak RF power = −4 dBm.

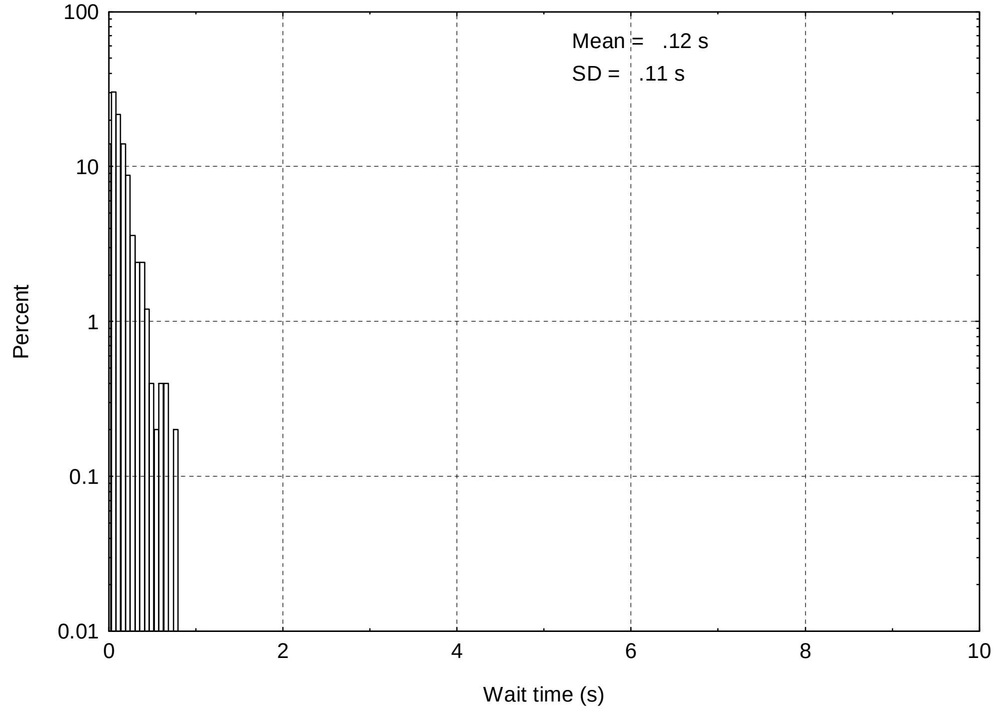

Figure A-29. Wait time histogram, interference pulse parameters: pulse width = .33 μs, pulse period = 3.3 ms, peak RF power = −21 dBm.

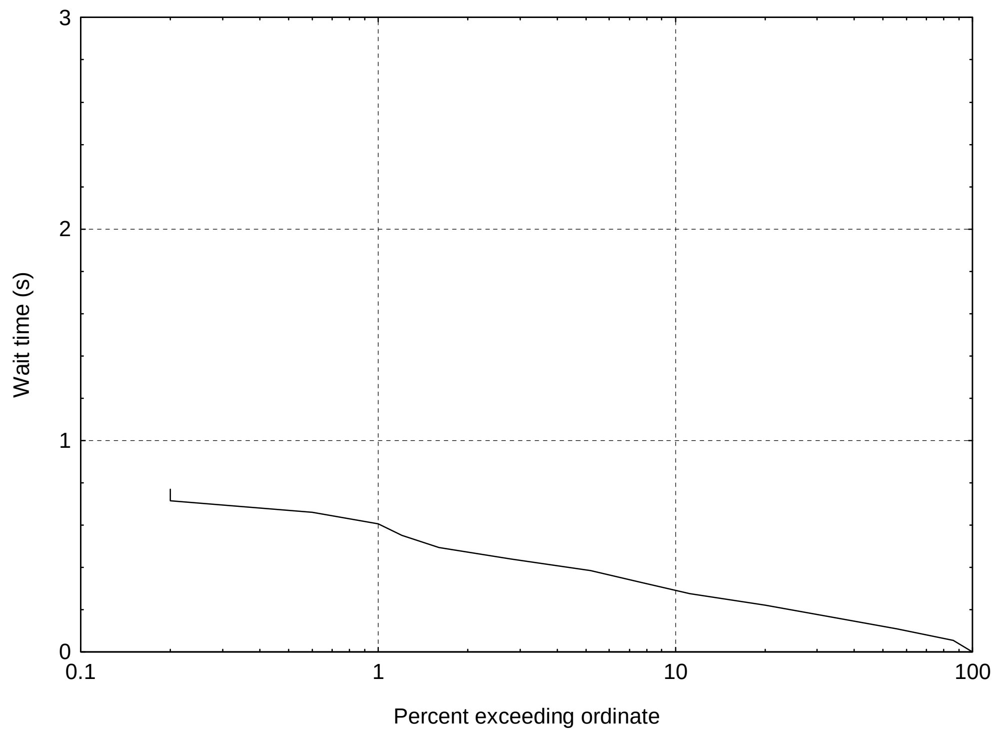

Figure A-30. Wait time cumulative distribution, pulse parameters: pulse width = .33 μs, pulse period = 3.3 ms, peak RF power = −21 dBm.