SECTION 1.0
INTRODUCTION

1.1 BACKGROUND

The National Telecommunications and Information Administration (NTIA) is the Executive Branch agency principally responsible for developing and articulating domestic and international telecommunications policy. NTIA's responsibilities include establishing policies concerning spectrum assignments, allocation in use, and providing various departments and agencies with guidance to ensure that their conduct of telecommunication activities is consistent with these policies.[7] Accordingly, NTIA conducts technical studies and makes recommendations regarding telecommunication policies and presents Executive Branch views on telecommunications matters to the Congress, the Federal Communications Commission (FCC), and the public.

NTIA is responsible for managing the Federal Government's use of the radio frequency spectrum. The FCC is responsible for managing the spectrum used by the private sector, and state and local governments. In support of its responsibilities, the NTIA has undertaken numerous spectrum-related studies to assess spectrum utilization, examined the feasibility of reallocating spectrum used by the Federal Government or relocating Federal Government systems, identified existing or potential electromagnetic compatibility (EMC) problems between systems, provided recommendations for resolving any EMC conflicts, and recommended changes to promote efficient and effective use of the radio frequency spectrum and to improve Federal spectrum management procedures.

In February, 2001, NTIA released Special Publication 01-45, assessing the compatibility between ultrawideband (UWB) systems and Global Positioning System (GPS) receivers.[8] This publication was also submitted to the FCC for inclusion in the public record concerning revision of Part 15 of the FCC Rules.[9] This publication reported on measurement and analysis results obtained for two GPS receiver architectures (C/A code tracking and semi-codeless), and indicated ongoing efforts to measure and analyze the interference potential for two additional receivers (a C/A code tracking receiver employing multiple narrowly-spaced correlators, and a Technical Standard Order (TSO)-C129a compliant aviation receiver). This report serves as an addendum to NTIA Report 01-45, and presents the results obtained for the two remaining receivers, and also provides a comparison to other data sets that are on the public record.

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[7] NTIA, *Manual of Regulations and Procedures for Federal Radio Frequency Management*, National Telecommunications and Information Administration (Jan. 2000 Edition with revisions).

[8] NTIA Special Publication 01-45, *Assessment of Compatibility Between Ultrawideband (UWB) Systems and Global Positioning System (GPS) Receivers*, National Telecommunications and Information Administration, (Feb. 2001) (hereinafter "NTIA Report 01-45").

[9] *Revisions of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems,* Notice of Proposed Rulemaking, ET Docket No. 98-153, FCC 00-163 (rel. May 11, 2000) (hereinafter "UWB NPRM").

1.2 OBJECTIVE

The objective of this assessment was to define the maximum allowable UWB equivalent isotropically radiated power (EIRP)[10] levels that can be tolerated by GPS receivers used within various operational applications without causing degradation to their operations. These EIRP levels will then be compared to the existing Part 15 emission limits[11] to assess the applicability of these limits to UWB devices.

1.3 APPROACH

A two-part approach consisting of a measurement and an analysis component was adopted for this assessment. First, a measurement effort was undertaken to determine the interference threshold for different GPS receiver architectures for a set of UWB waveforms. Utilizing the measured GPS receiver interference thresholds, analyses were performed for various operational scenarios to determine the maximum allowable UWB EIRP level, in the radionavigation satellite service (RNSS) frequency bands, that can be tolerated by a GPS receiver before performance degradation is realized.

The measurement component of this assessment was conducted by NTIA's Institute for Telecommunication Sciences (ITS) and the analyses portion was performed by the NTIA Office of Spectrum Management (OSM). This document provides a description of the methods used and the results obtained from these measurements and analyses. A separate report, prepared by ITS, that presents the measured data in post-processed format and provides details of the measurement procedures and equipment used to acquire the data, is available and is referenced throughout this report.[12]

1.3.1 Measurement Approach

The first activity associated with this project was the development of a plan to guide the measurement of GPS receiver susceptibility to UWB signals. In the formulation of a measurement plan, NTIA considered a number of factors including which GPS receivers to

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[10] The computation of EIRP is in terms of the average power of the UWB signal for all cases considered in this report. This average power is based on root-mean-square (RMS) voltage.

[11] The existing Part 15 measurement procedure uses an average logarithm detector process and is not equivalent to measurements using an RMS detector process. *See* NTIA Special Publication 01-43, *Assessment of Compatibility Between Ultrawideband Devices and Selected Federal Systems* (Jan. 2001) (hereinafter "NTIA Report 01-43") at 2-1 for discussion of the differences in measuring average power versus log average power.

[12] NTIA Report 01-389, *Addendum to Report 01-384-Measurements to Determine Potential Interference to GPS Receivers from Ultrawideband Transmission Systems*, National Telecommunications and Information Administration, Institute for Telecommunication Sciences (Oct. 2001) (hereinafter "ITS Report 01-389").

measure, what UWB signal parameters to examine, and what GPS receiver performance metrics and criteria to apply. Also as a part of the formulation of the measurement plan, a set of measurement procedures were developed with the intent that if followed, these procedures would lead to repeatable measurement results.

After the measurement plan was completed and made available to other Government agencies for review and comment, NTIA sought public comment in a notice published in the Federal Register.[13] The following seven parties submitted comments to the Federal Register notice:

- Air Transport Association
- ANRO Engineering, Inc.
- Multispectral Solutions, Inc.
- National Aeronautics and Space Administration (NASA) Glenn Research Center
- RAND Science and Technology Policy Institute
- Time Domain Corporation
- United States GPS Industry Council

NTIA considered the comments, made appropriate changes to the measurement plan, and provided a response for each commenter for the public record. The initial measurement plan, the Federal Register notice, the public comments received, and the NTIA responses to the comments can be obtained from the NTIA website or directly from NTIA/OSM upon request.

One of the immediate difficulties encountered in establishing a methodology for measuring the impact of UWB emissions to GPS receivers was the lack of documented performance criteria for GPS receivers intended for applications other than aviation. After researching available technical standards and other open literature, a set of criteria that was not application specific was adopted for assessing the performance of the GPS receivers in this measurement effort. The two performance criteria examined were "break-lock" and "reacquisition." Break-lock refers to the loss of signal lock between the GPS receiver and a GPS satellite. This condition occurs when an interfering signal reduces the carrier-to-noise density (C/N_0) ratio (i.e., an increase in the undesired signal level, N_0, relative to the desired signal level, C) to such an extent that the GPS receiver can no longer adequately determine the pseudorange (the initial/uncorrected measure of distance from a single GPS satellite to a receiver) for the given satellite signal. Within this measurement effort, the occurrence of a break-lock condition was as reported by the receiver. Depending on the receiver application, this condition could be a function of cycle slips, or a loss of carrier lock or phase lock. The reacquisition threshold refers to the UWB power level at which an abrupt increase from the nominal reacquisition time was observed.

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[13] National Telecommunications and Information Administration, Notice, Request for Comments on Global Positioning System/Ultrawideband Measurement Plan, Federal Register, Vol. 65, No. 157 (Aug. 14, 2000) at 49544.

To determine the impact on reacquisition time, the signal from the GPS satellite of interest was interrupted for 10 seconds and a 50-meter step in pseudorange was introduced. This was done to simulate a GPS-equipped vehicle passing behind a building or other obstacle in the satellite-to-receiver path, causing a temporary loss-of-lock between the GPS receiver and the satellite of interest. As the vehicle clears the obstacle and the satellite again becomes visible, the GPS receiver must be able to reacquire the lost satellite in the presence of UWB energy in a time consistent with that associated with no UWB energy present. In order to determine the maximum UWB level at which this can be accomplished, the UWB signal was reduced from the power level at which break-lock occurred until the receiver was able to reacquire the lost satellite in a time correspondent with the nominal receiver reacquisition time with no UWB signal present.

The UWB power level that results in receiver break-lock is not the preferred criterion for determining the interference threshold because it represents an extreme penalty to the performance of a GPS receiver. Thus, the interference threshold adopted for these measurements was the UWB signal level that resulted in an abrupt increase in the reacquisition time.[14] However, for some UWB signal permutations (e.g., those deemed to be CW-like signals), a statistical parameter such as reacquisition time could not be obtained due to limitations associated with the available test equipment (see discussion in Section 2.1.1 of this report). Initial reacquisition measurements for the narrowly-spaced correlator receiver architecture showed a two-level reacquisition effect. The receiver would either reacquire in a relatively short period of time (an actual reacquisition) or the receiver would not reacquire in the test time allotted for each reacquisition trial. This could indicate that the code acquisition search algorithm, as implemented in this receiver, was such that if code lock was not obtained within a very limited search window then the receiver was forced into a mode where a much broader acquisition strategy, requiring much more time, was used. Because of the uncertainty associated with this two level (bimodal) reacquisition effect, it was decided to not continue reacquisition measurements for the narrowly-spaced correlator receiver architecture. Thus, for the subsequent evaluation of the measured data, the break-lock interference threshold was used in those cases where a reacquisition threshold could not be determined.

The next challenge encountered was how to determine a representative sample of GPS receivers. Since GPS receivers are used in a myriad of applications, including navigation (aviation, space, maritime, rail, and vehicular), position determination (surveying, asset tracking, E-911), and timing (banking, power distribution, Internet synchronization), to name but a few, it is not feasible to attempt to measure a representative receiver from each possible application. Instead, NTIA decided to select candidate GPS receivers based upon the various available GPS receiver architectures. One receiver from each of three basic receiver architectures were

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[14] It should be noted that initial acquisition of a GPS satellite signal is an even more stringent performance criterion for GPS operations. However, this is an extremely difficult criteria to measure and is also highly dependent on manufacturer-specific receiver algorithms. Therefore, it was not considered feasible for use in this effort. A 6 dB factor is often used in GPS interference analyses to account for the greater sensitivity of initial satellite acquisition over the satellite tracking mode of operation.

identified for inclusion in the measurements: coarse acquisition (C/A)-code tracking receivers, which make up a significant share of the GPS receivers in use today, semi-codeless receivers used in low-dynamic applications requiring high precision (e.g., surveying and reference stations), and C/A-code tracking receivers employing multiple, narrowly-spaced correlators to enhance accuracy and mitigate the effects of multipath. These three GPS receiver architectures encompass most of the existing civil GPS applications.[15] In order to address particular concerns related to an aviation use of GPS, a TSO-C129a compliant aviation receiver (as currently used in en-route and non-precision approach) was also included. The assessment of potential UWB interference to aviation precision approach operations is addressed in a Department of Transportation sponsored study and therefore is not considered in the scope of this effort. Measurement and analysis results have already been presented for the C/A code tracking and the semi-codeless receivers in NTIA Report 01-45. This report focuses on the C/A code tracking receiver employing multiple narrowly-spaced correlators, and the TSO-C129a compliant aviation receiver.

A third question to be addressed concerned defining the UWB signal(s) to be generated. Since there was little information revealed in the public record with regard to the proposed signal structure of UWB devices, no single UWB signal structure could be identified that would be representative of a typical UWB transmission system. Therefore, NTIA identified 32 distinct UWB signal structures as being representative of those expected to be used in UWB applications. Those UWB signal permutations identified for examination considered various pulse repetition frequencies (PRFs), modulation schemes, and gating percentages. Each combination of the UWB signal parameters shown in Table 1-1 was used to represent a distinct UWB signal permutation.

TABLE 1-1. UWB Permutations Considered in Measurements

UWB Parameter	Parameter Value
PRF	0.1, 1, 5, and 20 MHz (nominal)
Modulation	None, OOK, 2% relative dither, 50% absolute dither
Gating	100% (always on), 20% (4 ms on, 16 ms off)

The PRF defines the number of pulses transmitted per unit time (one second). The PRF effects the spectral line magnitude and spacing, and the percentage of time that pulses are present.

Gating refers to the process of distributing pulses in bursts by employing a programmed set of periods where the UWB transmitter is turned on or off for a period of pulses. For the measurements performed in this assessment, the gated UWB signal utilized a scheme where a

[15] This effort did not consider the potential impact of UWB operations to military GPS receivers.

burst of pulses lasting 4 milliseconds (ms) was followed by a 16 ms period when no pulses were transmitted. This is referred to as 20% gating, because the UWB pulses are transmitted 20% of the time. The signal permutations depicted within this report as 100% gating, define a signal where pulses are transmitted 100% of the time.

On-Off Keying (OOK) refers to the process of selectively turning off or eliminating individual pulses to represent data bits.

Dithering refers to the random or pseudo-random spacing of the pulses. Two forms of dithered UWB signals were considered in this effort. These are an absolute referenced dither, where the pulse period is varied in relation to the absolute clock, and a relative referenced dither, where the pulse spacing is varied relative to the previous pulse. The PRF of a relative dithered pulse train is equal to the reciprocal of the mean pulse period. Dithering of the pulses in the time domain spreads the spectral line content of a UWB signal in the frequency domain making the signal appear more noise-like.

A GPS satellite simulator was used to provide simulated GPS signals from a four satellite constellation (five satellites were used for the TSO-C129a compliant receiver in order to meet receiver autonomous integrity monitoring (RAIM) requirements) based on ephemeris data taken from an actual GPS constellation present on December 16, 1999. In the test constellation, one satellite was located at or near the zenith while the remaining three satellites were positioned near the horizon. The GPS receiver channel processing the signal from the near-zenith satellite was monitored for these measurements. This satellite was selected as the satellite to monitor because it has the least Doppler shift during the duration of the measurements. For the measurements performed on the C/A-code receiver, the simulator power representing the near-zenith satellite was set to the minimum specification level of -160 dBW at the GPS receiver input.[16] The simulator power representing the remaining three satellites was set 5 dB higher (-155 dBW at the GPS receiver input). The higher power level was used for the remaining satellites so that a break-lock condition would not occur for these signals prior to break-lock of the monitored signal. The value of 5 dB was selected so that UWB power increments of 3 dB could be used to induce break-lock only on the receiver channel being monitored. All of the conducted measurements in this effort were performed over a 55-minute evolution of the constellation. The constellation was then reset for the subsequent test condition (e.g., another UWB signal permutation). More detailed information on this test constellation is presented in ITS Report 01-384.[17]

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[16] Global Positioning System Standard Positioning Service Signal Specification, 2nd Edition, GPS NAVSTAR (June 2, 1995) at 18.

[17] NTIA/ITS Report 01-384, *Measurements to Determine Potential Interference to GPS Receivers from Ultrawideband Transmission Systems*, National Telecommunications and Information Administration, Institute for Telecommunication Sciences (Feb. 2001).

A broadband noise signal was generated using a noise diode to represent the noise contribution from the cross-correlation phenomenon associated with the use of the relatively short Gold Codes in the GPS C/A signal. This cross-correlation noise arises because within a GPS receiver channel, the signals generated from GPS satellites other than the one being monitored by that channel, appear as undesired noise. This phenomenon is well documented in the open literature and the value used in this analysis is based upon work done within the International Telecommunication Union-Radiocommunications Sector (ITU-R).[18] This broadband noise was input to the GPS receiver at a level of -93 dBm/20 MHz (as derived for the minimum C/N_0 of 34 dB-Hz identified in the ITU-R work) in the measurements of the GPS receiver employing multiple narrowly-spaced correlators and the TSO-C129a compliant receiver.

Each UWB signal permutation was generated and combined with the simulated GPS satellite signals, and the broadband noise. The combined signal was injected into the GPS receiver at the antenna input. The UWB power level was increased until either the receiver broke lock with the satellite of interest or until the maximum available output power level from the UWB generator was reached. Plots of GPS receiver performance criteria (e.g., break-lock and reacquisition interference levels) were produced for each UWB signal permutation measured. From these plots, the UWB average power level wherein the performance criteria was realized was determined from these plots.

Both the measurement plan and ITS Report 01-384 contain more detail on these measurement procedures, including information on the measurement equipment used, test set-ups, and calibration procedures. These are available on the NTIA and ITS websites or directly from NTIA/OSM upon request.

1.3.2 Analysis Approach

In order to calculate the maximum allowable EIRP, a source-path-receiver analysis must be performed. The basic parameters that must be defined for this type of analysis are the receiver interference threshold, the source output power and antenna gain, the propagation path between the transmitter and the receiver, and the antenna gain of the receiver in the direction of the source transmitter. The data obtained from the ITS measurements defines the interference threshold level at the input of the GPS receiver as a function of UWB signal structure (e.g., power, PRF, modulation scheme) for each of the GPS receiver architectures examined. The UWB output power and antenna gain combined define the EIRP, which is the variable to be determined from the analysis. In order to make reasonable assumptions regarding the remaining values needed for the analysis, information regarding how the transmitter and receiver can interact within their operating environment is necessary. Collectively, this information defines an operational scenario, which establishes how close the two systems may come to one another under actual

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[18] Recommendation ITU-R M.1477, *Technical and Performance Characteristics of Current and Planned RNSS (Space-to-Earth) and ARNS Receivers to be Considered in Interference Studies in the Band 1559-1610 MHz,* at Section 3.2 (hereinafter "ITU-R M.1477").

operating conditions, and the likely orientation of the antennas. This information is then used to compute the propagation loss and the GPS antenna gain in the direction of the UWB transmitting device. The operational scenario can also be used to determine the applicability of factors such as building attenuation, aggregate allowance, and safety margins.

NTIA hosted a series of public meetings to develop operational scenarios to be considered for GPS and envisioned UWB applications. The meetings were announced in the Federal Register on August 31, 2000.[19] Participation was encouraged within the UWB and GPS communities and among representatives of the interested Federal Agencies. Multispectral Solutions Inc., the National Oceanic and Atmospheric Administration/National Ocean Service/National Geodetic Survey, Time Domain Corporation, the United States Coast Guard (USCG), the U.S. GPS Industry Council, and NTIA submitted pertinent documents. Specific proposals for operational scenarios to be considered included GPS receivers used in the following applications: terrestrial[20] (e.g., public safety applications such as cellular phone embedded E-911 and emergency response vehicle navigation, geographic information systems, precision machine control, and general operations); maritime navigation (in constricted waterways, harbors, docking, and lock operations); railway operations (positive train control); surveying; and aviation (en-route navigation and non-precision approach). The input received at these meetings was used to develop the operational scenarios that were then used in the analyses documented in this report. These scenarios do not represent all possible applications of GPS, however, they do represent a reasonable bound on the parameters necessary to perform the broadly based analyses. For example, the separation distances represented in these scenarios range from a minimum of 2 meters for the embedded E-911 scenario, to a maximum of approximately 300 meters (1000 feet) for the en-route aviation scenario.

An analysis was also performed to determine the distance separations that are required to preclude interference to the different GPS receiver architectures, if the UWB device is operating at the current Part 15 level of -71.3 dBW/MHz. The measured UWB interference thresholds for both single-entry and multiple-entry UWB device interactions were considered.

1.4 COMPARISON TO OTHER MEASUREMENT EFFORTS

This report also compares the results of the NTIA measurements and analyses with those collected and performed by other parties with interests in the current FCC proceeding. Specifically, the NTIA measurement data were compared with data collected by Stanford

[19] National Telecommunications and Information Administration, Notice of Public Meeting to Develop Global Positioning System/Ultrawideband Operational Scenarios, Federal Register Vol. 65, No. 170 (Aug. 31, 2000) at 52989 (hereinafter "NTIA Notice").

[20] Within the context of this report, terrestrial refers to land-based operations.

University (SU) under contract to the Department of Transportation,[21] and with the data collected by the University of Texas Applied Research Laboratory (ARL:UT)[22] which has been analyzed by Johns Hopkins University/Applied Physics Laboratory (JHU/APL)[23] and the Department of Defense (DoD) Joint Spectrum Center (JSC).[24] These comparisons were conducted in order to assess consistency and agreement in the data sets available in the public record.

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[21] Stanford University, *Potential Interference to GPS from UWB Transmitters Phase II Test Results* (March 16, 2001) (hereinafter "Stanford Report").

[22] University of Texas at Austin Applied Research Laboratories, *Final Report Data Collection Campaign for Measuring UWB/GPS Compatibility Effects* (Feb. 26, 2001).

[23] Johns Hopkins University/Applied Physics Laboratory, *Final Report UWB-GPS Compatibility Analysis Project* (March 8, 2001) (hereinafter "JHU/APL Report").

[24] JSC-CR-01-036, *Observations Regarding Test Data Collected at University of Texas Applied Research Laboratory On GPS Receivers Operating in the Presence of Ultrawideband Emissions*, Department of Defense Joint Spectrum Center (May 2001) (hereinafter "JSC Report").

SECTION 2.0
MEASUREMENT RESULTS

2.1 SUMMARY OF ANALYSIS OF MEASUREMENT RESULTS

As explained in NTIA Report 01-45, measured data and analysis results for the narrowly-spaced correlator and the TSO-C129a compliant GPS receivers are provided in this addendum to that report.[25] This section of the addendum report presents a summary and analysis of the data collected by ITS on the narrowly-spaced correlator and the TSO-C129a compliant GPS receivers. As appropriate, data from NTIA Report 01-45 on the C/A code receiver will also be considered in this analysis. The three GPS receivers considered use the GPS C/A code L1 signal to determine a navigation solution. This analysis includes a comparison of the measured data sets across the three C/A code receivers to gain insight into the variability, reliability, and accuracy of the measured data.

The NTIA data analyzed herein was extracted from the measurement plots documented in measurement reports published by ITS.[26] There are two methods for performing radio interference measurements; those where the desired and undesired signal are conducted into the test receiver via a cable connection, and those where the signals are radiated into the test receiver via the propagation medium and antenna assembly. In this effort, conducted measurements were used to evaluate the performance of the GPS receivers.

As part of this analysis, NTIA measured receiver susceptibility values are also compared to those from the GPS/UWB measurements carried out by SU and by ARL:UT. Because of some differences in test procedures, interference criteria and UWB signals tested, only a limited number of tests were similar. Measured susceptibility data are compared in those cases of similar test conditions.

2.2 SINGLE-ENTRY CONDUCTED MEASUREMENTS

The data in Tables 2-1 through 2-3 summarize the receiver susceptibility measurements, collected by ITS, used in this analysis. The data for the C/A code receiver in Table 2-1 is the same information that was presented in NTIA Report 01-45 and is included here for completeness.[27] The table entries correspond to the maximum tolerable UWB interference levels (referenced to the receiver input) associated with the GPS receiver performance criteria adopted for this program. These points are extracted from the data curves presented in the ITS Reports.

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[25] NTIA Report 01-45 at v.

[26] ITS Report 01-384 at Appendix F; ITS Report 01-389 at Appendix B.

[27] NTIA Report 01-45 at 2-3.

Although each individual data plot is not reproduced within this report, a representative plot is provided in Figure 2-1 to illustrate how the data points associated with the GPS receiver performance criteria are obtained.

The break-lock and reacquisition threshold data points are taken from the ITS plots as illustrated in Figure 2-1. The break-lock level is represented by the heavy vertical line in Figure 2-1. This value is read directly from the scale on the horizontal axis, and has the units of dBm/20 MHz. There are two curves which represent reacquisition data. The lower curve is the mean reacquisition time for the successful reacquisition measurements over 10 trials. The upper curve is the maximum time for all successful reacquisition measurements within these 10 trials. The interference threshold level for the reacquisition performance criterion is determined by locating the point on the lower curve (mean reacquisition time) corresponding to a sharp increase in the reacquisition time. The threshold level is then read directly from the scale on the horizontal axis, and has the units dBm/20 MHz. The power levels are average values for all single-entry UWB measurements except for the 20% gated signal[28] where the level represents the average power for the time when the signal is gated on. In a limited number of cases, the reacquisition threshold level that is determined by these methods is at a higher interference signal level than the break-lock level. This is attributable to the break-lock measurement being carried out in conjunction with measurements such as pseudo-range error, accumulated delta-range (ADR) and code-minus-carrier (CMC) error. Certain of these, other than break-lock, measurements require a large sample size for each input UWB signal level to define statistically significant test data. If a break-lock condition occurs at any time during the longer sampling period, break-lock is declared. However, in a limited number of cases, the break-lock condition did not occur during the shorter time period used in the reacquisition measurements. In these instances (when the measured break-lock point was at a lower power than reacquisition), the reacquisition level threshold is set equal to the break-lock threshold.

The data collected by ITS is represented in Tables 2-1 through 2-3. These tables list the break-lock and reacquisition interference threshold levels for each UWB permutation measured. The tables are organized according to the GPS receiver architectures considered in the analysis.

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[28] 100% gating is a continuous uninterrupted PRF, 20% gating is a pulse train that is on for 4 ms in a 20 ms period.

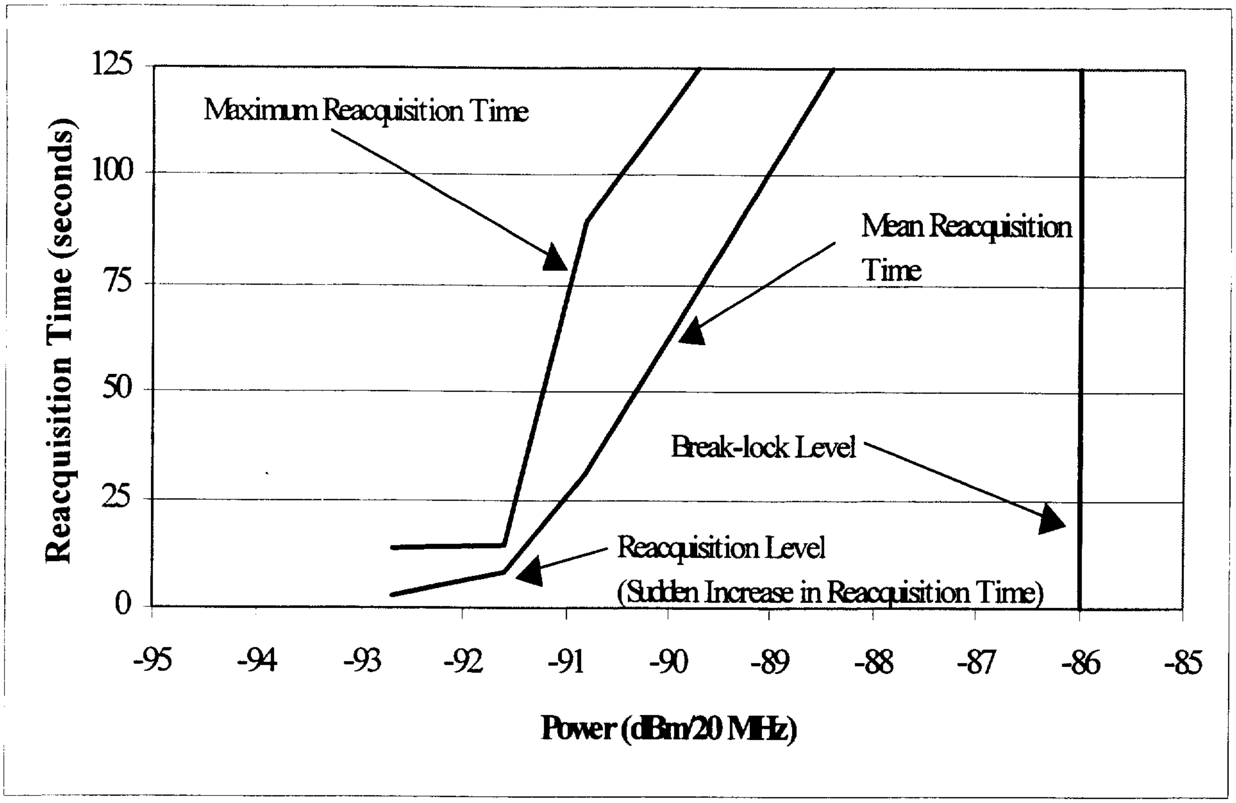

Figure 2-1. Illustration of Power Levels Resulting in Break-lock and Reacquisition

For those UWB signal permutations that produced spectral lines within the GPS receiver passband, the measurement of a statistical parameter such as reacquisition time, or pseudo-range error was not reliable or repeatable given the nature of the moving GPS constellation. To obtain 10 trials of reacquisition time can take as long as 20 minutes. During this time period, the statistics of GPS performance are non-stationary because the Doppler shift of the GPS C/A-Code lines causes them to, at some point, align with the UWB spectral lines. A GPS simulator with the capability of setting the Doppler shift to zero would facilitate collection of the reacquisition data for those UWB signal permutations containing spectral line components. The simulator used in this measurement effort did not have this capability. For this reason, entries in Tables 2-1 through 2-3 which contain an "x" indicate that the performance metric could not be measured with statistical reliability, and therefore is not reported.

Initial reacquisition measurements for the narrowly-spaced correlator receiver showed a two level reacquisition effect. The GPS receiver would either reacquire in a relatively short period of time (an actual reacquisition) or the receiver would not reacquire in the test time allotted (120 seconds) for each reacquisition trial. This could indicate the code acquisition search algorithm, as implemented in this receiver, was such that if code lock was not obtained within a very limited search window then the receiver was forced into a mode where a much broader acquisition strategy, requiring much more time, was used. Because of the uncertainty associated with reacquisition, it was decided to not continue reacquisition measurements for the narrowly-spaced correlator receiver. Thus, only break-lock levels are reported for this receiver in Table 2-2.

Other entries in these tables contain a power level in brackets. This indicates that for some of the UWB signal permutations, the total available power from the UWB simulator was used without resulting in a loss of lock or an impact on reacquisition time for the GPS receiver and the satellite of interest.

TABLE 2-1. Measurement Results for C/A-Code Receiver

Interfering Signal Structure	Interference Susceptibility Levels* (dBm/20 MHz)	
	Break-Lock	Reacquisition
Broadband Noise	-87	-91.5
0.1 MHz PRF, No Mod, 100% Gate	-70	x
0.1 MHz PRF, No Mod, 20% Gate	[-57]	x
0.1 MHz PRF, OOK, 100% Gate	[-60]	x
0.1 MHz PRF, OOK. 20% Gate	[-59.5]	x
0.1 MHz PRF, 50% abs, 100% Gate	[-57]	[-57]
0.1 MHz PRF, 50% abs, 20% Gate	[-56.5]	[-56.5]
0.1 MHz PRF, 2% rel, 100% Gate	[-57]	[-57]
0.1 MHz PRF, 2% rel, 20% Gate	[-57]	[-57]
1 MHz PRF, No Mod, 100% Gate	-100.5	x
1 MHz PRF, No Mod, 20% Gate	[-47.5]	x
1 MHz PRF, OOK, 100% Gate	-78	x
1 MHz PRF, OOK, 20% Gate	[-51]	x
1 MHz PRF, 50% abs, 100% Gate	[-47]	-70
1 MHz PRF, 50% abs, 20% Gate	[-47.5]	[-47.5]
1 MHz PRF, 2% rel, 100% Gate	[-47.5]	-88
1 MHz PRF, 2% rel, 20% Gate	[-47.5]	-47
5 MHz PRF, No Mod, 100% Gate	-108.5	x
5 MHz PRF, No Mod, 20% Gate	-94.5	x
5 MHz PRF, OOK, 100% Gate	-104.5	x
5 MHz PRF, OOK, 20% Gate	-90.5	x
5 MHz PRF, 50% abs, 100% Gate	-86.5	-94
5 MHz PRF, 50% abs, 20% Gate	[-40]	-55
5 MHz PRF, 2% rel, 100% Gate	-85.5	-93.5
5 MHz PRF, 2% rel, 20% Gate	[-39]	[-39]
20 MHz PRF, No Mod, 100% Gate	-115	x
20 MHz PRF, No Mod, 20% Gate	-102	x
20 MHz PRF, OOK, 100% Gate	-111.5	x
20 MHz PRF, OOK, 20% Gate	-99.5	x
20 MHz PRF, 50% abs, 100% Gate	-89.5	-95
20 MHz PRF, 50% abs, 20% Gate	[-34]	-85
20 MHz PRF, 2% rel, 100% Gate	-87	-93
20 MHz PRF, 2% rel, 20% Gate	[-33]	-83

* No measurable effect up to the power level shown in brackets.

TABLE 2-2. Measurement Results for the Narrowly-Spaced Correlator Receiver

Interfering Signal Structure	Interference Susceptibility Levels* (dBm/20 MHz)
	Break-Lock
Broadband Noise	-89.2
0.1 MHz PRF, No Mod, 100% Gate	[-57.2]
0.1 MHz PRF, No Mod, 20% Gate	[-57.2]
0.1 MHz PRF, OOK, 100% Gate	[-60.2]
0.1 MHz PRF, OOK. 20% Gate	[-60.3]
0.1 MHz PRF, 50% abs, 100% Gate	[-57.1]
0.1 MHz PRF, 50% abs, 20% Gate	[-57.2]
0.1 MHz PRF, 2% rel, 100% Gate	[-57.1]
0.1 MHz PRF, 2% rel, 20% Gate	[-57.2]
1 MHz PRF, No Mod, 100% Gate	-100.9
1 MHz PRF, No Mod, 20% Gate	[-44.9]
1 MHz PRF, OOK, 100% Gate	-93.9
1 MHz PRF, OOK, 20% Gate	[-47.9]
1 MHz PRF, 50% abs, 100% Gate	-62.9
1 MHz PRF, 50% abs, 20% Gate	[-44.9]
1 MHz PRF, 2% rel, 100% Gate	[-44.8]
1 MHz PRF, 2% rel, 20% Gate	[-44.8]
5 MHz, No Mod, 100% Gate	-108.7
5 MHz, No Mod, 20% Gate	-95.8
5 MHz, OOK, 100% Gate	-106.7
5 MHz, No OOK, 20% Gate	-88.8
5 MHz PRF, 50% abs, 100% Gate	-84.7
5 MHz PRF, 50% abs, 20% Gate	[-38.6]
5 MHz PRF, 2% rel, 100% Gate	-84.6
5 MHz PRF, 2% rel, 20% Gate	[-38.6]
20 MHz PRF, No Mod, 100% Gate	-116.1
20 MHz PRF, No Mod, 20% Gate	-103
20 MHz PRF, OOK, 100% Gate	-113.5
20 MHz PRF, OOK, 20% Gate	-98.5
20 MHz PRF, 50% abs, 100% Gate	-90.6
20 MHz PRF, 50% abs, 20% Gate	-50.6
20 MHz PRF, 2% rel, 100% Gate	-92.5
20 MHz PRF, 2% rel, 20% Gate	-72.3

* No measurable effect up to the power level shown in brackets.

TABLE 2-3. Measurement Results for the TSO-C129a Compliant Receiver

Interfering Signal Structure	Interference Susceptibility Levels* (dBm/20 MHz)	
	Break-Lock	Reacquisition
Broadband Noise	-92	-93
0.1 MHz PRF, No Mod, 100% Gate	-74.9	-74.9
0.1 MHz PRF, No Mod, 20% Gate	[-56.9]	[-56.9]
0.1 MHz PRF, OOK, 100% Gate	[-60.1]	[-60.1]
0.1 MHz PRF, OOK. 20% Gate	[-60]	[-60]
0.1 MHz PRF, 50% abs, 100% Gate	-72	-72
0.1 MHz PRF, 50% abs, 20% Gate	[-56.9]	[-56.9]
0.1 MHz PRF, 2% rel, 100% Gate	[-54.9]	[-54.9]
0.1 MHz PRF, 2% rel, 20% Gate	[-57]	[-57]
1 MHz PRF, No Mod, 100% Gate	-97.6	x
1 MHz PRF, No Mod, 20% Gate	-89.6	x
1 MHz PRF, OOK, 100% Gate	-94.6	x
1 MHz PRF, OOK, 20% Gate	-80.6	x
1 MHz PRF, 50% abs, 100% Gate	-96.6	-99
1 MHz PRF, 50% abs, 20% Gate	-89.6	-89.6
1 MHz PRF, 2% rel, 100% Gate	-97.6	-98.5
1 MHz PRF, 2% rel, 20% Gate	-83.6	-83.6
5 MHz PRF, No Mod, 100% Gate	-101.4	x
5 MHz PRF, No Mod, 20% Gate	-92.4	x
5 MHz PRF, OOK, 100% Gate	-99.4	x
5 MHz PRF, OOK, 20% Gate	-89.5	x
5 MHz PRF, 50% abs, 100% Gate	-98.3	-99
5 MHz PRF, 50% abs, 20% Gate	-88.4	-92
5 MHz PRF, 2% rel, 100% Gate	-98.2	-100
5 MHz PRF, 2% rel, 20% Gate	-89.3	-92.5
20 MHz PRF, No Mod, 100% Gate	-109.8	x
20 MHz PRF, No Mod, 20% Gate	-103.9	x
20 MHz PRF, OOK, 100% Gate	-105.2	x
20 MHz PRF, OOK, 20% Gate	-95.2	x
20 MHz PRF, 50% abs, 100% Gate	-97.4	-98
20 MHz PRF, 50% abs, 20% Gate	-86.4	-90.5
20 MHz PRF, 2% rel, 100% Gate	-95.2	-98
20 MHz PRF, 2% rel, 20% Gate	-87.2	-90

* No measurable effect up to the power level shown in brackets.

2.3 ANALYSIS OF NTIA RECEIVER SUSCEPTIBILITY MEASUREMENTS

The analysis of the measured results contained in Tables 2-1 through 2-3 initially involves classifying the UWB interference effect on the GPS receiver for each UWB signal permutation considered as either pulse-like, CW-like, or noise-like. The procedures for making these classifications are discussed in detail in Section 2.2.2 of NTIA Report 01-45 [29] and the results of this classification are shown in Tables 2-4 through 2-6 for each of the three GPS receivers. It should be noted that the bandwidth of the band limiting filters of the narrowly spaced correlator receiver is wider (approximately 16 MHz) than the C/A code receiver (approximately 10 MHz) and the bandwidth for the TSO-C129a receiver is narrower (approximately 2 MHz). The ramifications of this are that the cases judged to be pulse-like for the TSO-C129a receiver are somewhat different than those for the other two receivers. Specifically, most of the 1 MHz PRF UWB signal permutations that are classified as having a pulse-like interference effect, for the narrowly spaced correlator and C/A code receivers, show either a CW-like or noise-like interference effect for the TSO-C129a receiver. This is because the impulse response of the TSO-C129a receiver band limiting filter is lengthening the individual impulses of the 1 MHz PRF UWB signal permutations to the point where the output of the filter is approaching a continuum in the time domain as opposed to a series of individual pulses.

Tables 2-4 through 2-6 also contain adjusted interference threshold data to convert the noise-like interference levels to dBW/MHz and the CW-like interference levels to the power in a single spectral line expressed in dBW. The procedures followed to make these adjustments are also explained in Section 2.2.2 of NTIA Report 01-45.[30] The exception to the previous adjustments was that the interference levels in Tables 2-4 through 2-6 are relative to a GPS signal level of -130 dBm rather than -134.5 dBm as used in NTIA Report 01-45. Also, for the noise-like interference cases the power of the UWB signal is added to the -93 dBm/20 MHz noise signal that was also input to the GPS receiver. This is done to facilitate the data analysis and the comparison to data measured in the other measurement efforts.

It should be noted that the adjusted interference threshold values (Tables 2-4 through 2-6) used here in this analysis and the median values derived later in this section are not always numerically the same threshold values used in Section 3 of this report. However, the threshold values of Section 2 and Section 3 are all derived directly from the same measured data (Tables 2-2 through 2-4). These numerical differences are brought about by a need to use differing reference units to facilitate the analyses in each section.

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[29] NTIA Report 01-45 at 2-9.

[30] *Id.* at 2-12.

TABLE 2-4. Single-Entry UWB Interference Effects and Adjusted Interference Thresholds for the C/A Code Receiver

Interfering Signal Structure	Category Of Interfering Signal Effect	Adjusted Interference Threshold	
		Break-Lock	Reacquisition
Broadband Noise	Noise-Like	-130 dBW/MHz	-134.5 dBW/MHz
0.1 MHz PRF, No Mod, 100% Gate	Pulse-Like	x	x
0.1 MHz PRF, No Mod, 20% Gate	Pulse-Like	x	x
0.1 MHz PRF, OOK, 100% Gate	Pulse-Like	x	x
0.1 MHz PRF, OOK. 20% Gate	Pulse-Like	x	x
0.1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	x	x
0.1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	x	x
0.1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	x	x
0.1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	x	x
1 MHz PRF, No Mod, 100% Gate	CW-Like	-143.7 dBW	x
1 MHz PRF, No Mod, 20% Gate	Pulse-Like	x	x
1 MHz PRF, OOK, 100% Gate	Pulse-Like	x	x
1 MHz PRF, OOK, 20% Gate	Pulse-Like	x	x
1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	x	x
1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	x	x
1 MHz PRF, 2% rel, 100% Gate	Pulse-Like*	x	-129.8 dBW/MHz
1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	x	x
5 MHz PRF, No Mod, 100% Gate	CW-Like	-145.5 dBW	x
5 MHz PRF, No Mod, 20% Gate	CW-Like	-145.5 dBW	x
5 MHz PRF, OOK, 100% Gate	CW-Like	-144.5 dBW	x
5 MHz PRF, OOK, 20% Gate	CW-Like	-144.5 dBW	x
5 MHz PRF, 50% abs, 100% Gate	Noise-Like	-128.6 dBW/MHz	-133.5 dBW/MHz
5 MHz PRF, 50% abs, 20% Gate	Pulse-Like	x	x
5 MHz PRF, 2% rel, 100% Gate	Noise-Like	-127.8 dBW/MHz	-133.2 dBW/MHz
5 MHz PRF, 2% rel, 20% Gate	Pulse-Like	x	x
20 MHz PRF, No Mod, 100% Gate	CW-Like	-145 dBW	x
20 MHz PRF, No Mod, 20% Gate	CW-Like	-146 dBW	x
20 MHz PRF, OOK, 100% Gate	CW-Like	-144.5 dBW	x
20 MHz PRF, OOK, 20% Gate	CW-Like	-146.5 dBW	x
20 MHz PRF, 50% abs, 100% Gate	Noise-Like	-130.9 dBW/MHz	-133.9 dBW/MHz
20 MHz PRF, 50% abs, 20% Gate	Pulse-Like*	x	-132.5 dBW/MHz
20 MHz PRF, 2% rel, 100% Gate	Noise-Like	-129 dBW/MHz	-133 dBW/MHz
20 MHz PRF, 2% rel, 20% Gate	Pulse-Like*	x	-131.2 dBW/MHz

* These UWB parameter sets were judged to cause pulse-like interference for break-lock, which was in keeping with the measured data that showed the GPS receiver did not break-lock with maximum available UWB signal power. However, reacquisition data was obtained for these cases. These cases were categorized as noise-like to compute the adjusted thresholds as they involved dithered signals which showed noise-like spectra in the amplitude probability distribution and spectrum analyzer measurements of the UWB signals.

TABLE 2-5. Single-Entry UWB Interference Effects and Adjusted Interference Thresholds for the Narrowly-Spaced Correlator Receiver

Interfering Signal Structure	Category Of Interfering Signal Effect	Adjusted Interference Threshold
		Break-Lock
Broadband Noise	Noise-Like	-132.2 dBW/MHz
0.1 MHz PRF, No Mod, 100% Gate	Pulse-Like	x
0.1 MHz PRF, No Mod, 20% Gate	Pulse-Like	x
0.1 MHz PRF, OOK, 100% Gate	Pulse-Like	x
0.1 MHz PRF, OOK. 20% Gate	Pulse-Like	x
0.1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	x
0.1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	x
0.1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	x
0.1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	x
1 MHz PRF, No Mod, 100% Gate	CW-Like	-144.1 dBW
1 MHz PRF, No Mod, 20% Gate	Pulse-Like	x
1 MHz PRF, OOK, 100% Gate	CW-Like	-139.9 dBW
1 MHz PRF, OOK, 20% Gate	Pulse-Like	x
1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	x
1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	x
1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	x
1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	x
5 MHz PRF, No Mod, 100% Gate	CW-Like	-145.7 dBW
5 MHz PRF, No Mod, 20% Gate	CW-Like	-146.6 dBW
5 MHz PRF, OOK, 100% Gate	CW-Like	-146.7 dBW
5 MHz PRF, OOK, 20% Gate	CW-Like	-142.6 dBW
5 MHz PRF, 50% abs, 100% Gate	Noise-Like	-127.1 dBW/MHz
5 MHz PRF, 50% abs, 20% Gate	Pulse-Like	x
5 MHz PRF, 2% rel, 100% Gate	Noise-Like	-127 dBW/MHz
5 MHz PRF, 2% rel, 20% Gate	Pulse-Like	x
20 MHz PRF, No Mod, 100% Gate	CW-Like	-146.1 dBW
20 MHz PRF, No Mod, 20% Gate	CW-Like	-146.9 dBW
20 MHz PRF, OOK, 100% Gate	CW-Like	-146.5 dBW
20 MHz PRF, OOK, 20% Gate	CW-Like	-145.4 dBW
20 MHz PRF, 50% abs, 100% Gate	Noise-Like	-131.6 dBW/MHz
20 MHz PRF, 50% abs, 20% Gate	Pulse-Like	x
20 MHz PRF, 2% rel, 100% Gate	Noise-Like	-132.7 dBW/MHz
20 MHz PRF, 2% rel, 20% Gate	Pulse-Like	x

TABLE 2-6. Single-Entry UWB Interference Effects and Adjusted Interference Thresholds for the TSO-C129a Compliant Receiver

Interfering Signal Structure	Category Of Interfering Signal Effect	Adjusted Interference Threshold	
		Break-Lock	Reacquisition
Broadband Noise	Noise-Like	-135 dBW/MHz	-136 dBW/MHz
0.1 MHz PRF, No Mod, 100% Gate	Pulse-Like	x	x
0.1 MHz PRF, No Mod, 20% Gate	Pulse-Like	x	x
0.1 MHz PRF, OOK, 100% Gate	Pulse-Like	x	x
0.1 MHz PRF, OOK. 20% Gate	Pulse-Like	x	x
0.1 MHz PRF, 50% abs, 100% Gate	Pulse-Like	x	x
0.1 MHz PRF, 50% abs, 20% Gate	Pulse-Like	x	x
0.1 MHz PRF, 2% rel, 100% Gate	Pulse-Like	x	x
0.1 MHz PRF, 2% rel, 20% Gate	Pulse-Like	x	x
1 MHz PRF, No Mod, 100% Gate	CW-Like	-140.8 dBW	x
1 MHz PRF, No Mod, 20% Gate	CW-Like	-146.7 dBW	x
1 MHz PRF, OOK, 100% Gate	CW-Like	-140.8 dBW	x
1 MHz PRF, OOK, 20% Gate	CW-Like	-140.7 dBW	x
1 MHz PRF, 50% abs, 100% Gate	Noise-Like	-134.4 dBW/MHz	-135 dBW/MHz
1 MHz PRF, 50% abs, 20% Gate	Noise-Like	-134.4 dBW/MHz	-134.4 dBW/MHz
1 MHz PRF, 2% rel, 100% Gate	Noise-Like	-134.7 dBW/MHz	-134.9 dBW/MHz
1 MHz PRF, 2% rel, 20% Gate	Noise-Like	-131.6 dBW/MHz	-131.6 dBW/MHz
5 MHz PRF, No Mod, 100% Gate	CW-Like	-138.4 dBW	x
5 MHz PRF, No Mod, 20% Gate	CW-Like	-143.2 dBW	x
5 MHz PRF, OOK, 100% Gate	CW-Like	-139.4 dBW	x
5 MHz PRF, OOK, 20% Gate	CW-Like	-143.3 dBW	x
5 MHz PRF, 50% abs, 100% Gate	Noise-Like	-134.9 dBW/MHz	-135 dBW/MHz
5 MHz PRF, 50% abs, 20% Gate	Noise-Like	-134 dBW/MHz	-135 dBW/MHz
5 MHz PRF, 2% rel, 100% Gate	Noise-Like	-134.9 dBW/MHz	-135.2 dBW/MHz
5 MHz PRF, 2% rel, 20% Gate	Noise-Like	-134.3 dBW/MHz	-135.1 dBW/MHz
20 MHz PRF, No Mod, 100% Gate	CW-Like	-139.8 dBW	x
20 MHz PRF, No Mod, 20% Gate	CW-Like	-147.8 dBW	x
20 MHz PRF, OOK, 100% Gate	CW-Like	-138.2 dBW	x
20 MHz PRF, OOK, 20% Gate	CW-Like	-142.1 dBW	x
20 MHz PRF, 50% abs, 100% Gate	Noise-Like	-134.7 dBW/MHz	-134.8 dBW/MHz
20 MHz PRF, 50% abs, 20% Gate	Noise-Like	-133.2 dBW/MHz	-134.7 dBW/MHz
20 MHz PRF, 2% rel, 100% Gate	Noise-Like	-134 dBW/MHz	-134.8 dBW/MHz
20 MHz PRF, 2% rel, 20% Gate	Noise-Like	-133.6 dBW/MHz	-134.5 dBW/MHz

The data shown in Tables 2-4 through 2-6 is analyzed for consistency by determining the median along with the range of the data for break-lock and reacquisition threshold levels for noise-like and CW-like interference effects for each GPS receiver.[31] The data analysis was not applied to the pulse-like interference effects because, in most cases, the measured UWB level was the maximum power available from the UWB signal generator not the level that degraded GPS receiver performance. For the noise-like data analysis the broad-band noise measurements are included as part of the data set. The results of this analysis are shown in Table 2-7. The overall median for the combined data for the three receivers is shown in Table 2-8. As shown in Tables 2-7 and 2-8, most of the median threshold values for the individual receivers are consistent with one another and the data ranges associated with each median shows that the individual interference threshold values vary over a small range relative to the median values. The median threshold levels for the TSO-C129a receiver show this receiver to be slightly more robust, for CW-like interference effects, than the C/A code and narrowly-spaced correlator receivers. However, the data ranges are consistent. The overall median information is used for comparison with other measured data and with existing interference protection limits as discussed in the following sections.

TABLE 2-7. Median and Range of Data Values for the Interference Thresholds

Data Set	Interference Threshold Values		
	C/A Code	**Narrowly-Spaced Correlator**	**TSO-C129a Compliant**
Median for CW-Like Interference (Break-Lock)	-145 dBW	-145.9 dBW	-140.8 dBW
Range of Data	-143.7 to -146.5 dBW	-139.9 to -147 dBW	-138.2 to -147.8 dBW
Median for Noise-Like Interference (Break-Lock)	-129 dBW/MHz	-131.6 dBW/MHz	-134.4 dBW/MHz
Range of Data	-127.8 to -130.9 dBW/MHz	-127 to -132.7 dBW/MHz	-131.6 to -135 dBW/MHz
Median for Noise-Like Interference (Reacquisition)	-133 dBW/MHz	No Measured Data	-134.9 dBW/MHz
Range of Data	-129.8 to -133.9 dBW/MHz		-131.6 to -136 dBW/MHz

[31] The median is the value in an ordered set of values below and above which there is an equal number of values or which is the arithmetic average of the two middle values if there is no middle number.

TABLE 2-8. Overall Median and Range of Data Values for the Interference Thresholds

Data Set	Interference Threshold Values (Data Combined for the Three Receivers)
Median for CW-Like Interference (Break-Lock)	-144.5 dBW
Range of Data	-138.2 to -147.8 dBW
Median for Noise-Like Interference (Break-Lock)	-133.2 dBW/MHz
Range of Data	-127 to -135 dBW/MHz
Median for Noise-Like Interference (Reacquisition)	-134.6 dBW/MHz
Range of Data	-129.8 to -136 dBW/MHz

2.4 ANALYSIS OF SU RECEIVER SUSCEPTIBILITY MEASUREMENTS

The first comparison of the NTIA data is with certain data collected by SU. In order to make a comparison between the NTIA and SU data, data sets had to be identified where similar measurement procedures, interference criteria, and UWB signal characteristics are used. Where measurement procedures, interference criteria, and UWB signal characteristics were similar, appropriate comparisons are made. The comparison of the NTIA and SU data is presented in Table 2-9.

As indicated in Table 2-9, the SU GPS/UWB interference measurement program considered two types of GPS receivers. These are referred to as a high-grade GPS aviation receiver and a low-cost Original Equipment Manufacturer (OEM) receiver.[32] Several interference criteria were also used including break-lock and pseudo-range accuracy. The interference effects for the SU data examined in this analysis can be characterized as noise-like or CW-like. The SU measured interference threshold data is reported in units of dBm (average power) as measured in a 24 MHz bandwidth filter. For comparison purposes the SU data is adjusted to units of dBW/MHz for noise-like interference cases and referenced to a GPS signal level of -130 dBm using the methods described in Section 2.2.2 of NTIA Report 01-45.[33] The SU measurements were carried out using a GPS signal level of -131.3 dBm. Similarly, the CW-like cases are adjusted using the method described in Section 2.2.2 of NTIA Report 01-45, to determine power in a single

[32] Stanford Report at 1.

[33] NTIA Report 01-45 at 2-16.

TABLE 2-9. Comparison of SU and NTIA Interference Threshold Levels

SU Receiver Type	Interference Criteria	Category of Interfering Signal Effect	SU Report Threshold Level	SU Adjusted Threshold Level	Comparable NTIA Adjusted Threshold Overall Median Level	Range of Data Associated with NTIA Median Levels
Aviation	Break-Lock	Noise-like	-83.8 dBm/24 MHz[34]	-126.3 dBW/MHz	-133.2 dBW/MHz	-127 to -135 dBW/MHz
	Break-Lock	CW-like	-101.27 dBm/24 MHz[35]	-136.5 dBW	-144.5 dBW	-138.2 to -147.8 dBW
	15 cm Pseudo-Range Error	Noise-like	-89.7 dBm/24 MHz[36]	-132.2 dBW/MHz	-134.6 dBW/MHz	-129.8 to -136 dBW/MHz
OEM	Break-Lock	Noise-like	-87.8 dBm/24 MHz[37]	-130.3 dBW/MHz	-133.2 dBW/MHz	-127 to -135 dBW/MHz
	Break-Lock	CW-like	-104.27 dBm/24 MHz[38] (4 dB back off)	-139.5 dBW	-144.5 dBW	-138.2 to -147.8 dBW

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[34] Stanford Report at 30.

[35] *Id.*

[36] *Id.* at 21.

[37] *Id.* at 39.

[38] *Id.* at 40.

spectral line in dBW and referenced to a GPS signal level of -130 dBm.[39] Both SU measured CW-like interference cases in Table 2-9 used a UWB signal that resulted in only one line within the 24 MHz measurement filter. In the case of the OEM receiver with the CW-like interference effect, the measured break-lock level for the 4 dB noise back off condition is used in Table 2-9. This back off condition is selected because the SU injected noise level (-93.5 dBm/24 MHz) is closer to the NTIA injected level (-93 dBm/20 MHz) than the 2 dB back off condition. The adjusted interference threshold levels are shown in Table 2-9. The NTIA data shown in Table 2-9 is primarily for the break-lock condition either for CW-like or noise-like interference effects and is compared to the SU data for CW-like and noise-like interference effects as appropriate. For the SU test that used pseudo-range accuracy as the interference criterion, the NTIA median interference threshold value for reacquisition was used for comparison. This is used because pseudo-range accuracy is more a performance based criterion (than break-lock) and reacquisition is somewhat a performance rather than a failure criterion. Table 2-9 also contains the range of data associated with each NTIA median threshold level.

A review of the Table 2-9 information indicates that the SU data is consistent (comparing the adjusted threshold level columns) with the NTIA receiver input threshold data. The high-grade aviation receiver is slightly more robust than the receivers tested by NTIA under break-lock conditions. However, the SU break-lock thresholds are within 2 dB of the range of the NTIA data. For the aviation receiver pseudo-range measurement and both the OEM receiver measurements, the SU data is within the range of the NTIA data.

2.5 ANALYSIS OF ARL:UT RECEIVER SUSCEPTIBILITY MEASUREMENTS

Certain interference threshold data reported in the ARL:UT report as analyzed by the JSC are also compared to the NTIA data.[40] Again, because of differences in the measurement approach and the interference threshold criteria, only a subset of the ARL:UT data can be used in this comparison. These differences in measurement approach are explained in the JSC Report.[41] The comparison of NTIA data with ARL:UT data is shown in Table 2-10. The interference thresholds in Table 2-10 for the ARL:UT results are the values shown in the JSC Report with an appropriate correction (-43 dB) to convert from dBm/20 MHz to dBW/MHz for comparison purposes. The referenced values in the JSC report were modified (by JSC) to adjust the ARL:UT UWB power levels, measured using a log average procedure, to an RMS power level and to adjust UWB power levels to a reference GPS signal level of -130 dBm. Most of the ARL:UT cases shown in Table 2-10 are consistent with the NTIA data particularly if one compares the ARL:UT data to the range associated with the NTIA median value. A possible exception to this

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[39] NTIA Report 01-45 at 2-13.

[40] JSC Report at 4-7.

[41] *Id* at 4-1.

consistency is for Receiver Number One with UWB interference and a performance metric of a loss of one space vehicle (SV) (-142.3 dBW/MHz for UWB Mode 7 and -142.7 dBW/MHz for UWB Mode 13). For these conditions, the receiver seems to be more susceptible to UWB interference. As discussed in Section 5 the JSC Report, there is evidence for possible CW-like interference effects having occurred with Receiver Number One during the ARL:UT tests for these conditions.[42] As shown in many of the GPS interference tests, these receivers are more susceptible to CW-like interference than noise-like interference. The NTIA data shows a median value of -144.5 dBW for CW-like interference for a break-lock condition. This is consistent with the ARL:UT test results for these two cases.

Table 2-10. Comparison of ARL:UT and NTIA Interference Threshold Levels

ARL:UT Receiver	Interference Effects[a]	ARL:UT Interference Signals and Threshold Interference Levels			Comparable NTIA Median Threshold Levels with Associated Range of Data
		White Noise (dBW/MHz)	UWB Mode 7 (dBW/MHz)	UWB Mode 13 (dBW/MHz)	
1	Loss of 1 SV	-126.8	-142.3[b]	-142.7[b]	-133.2 dBW/MHz Median Break-Lock Level for Noise-Like Interference
	Loss of Multiple SVs	-124.8	-131.3	-133.7	
2	Loss of 1 SV	-126.2	-129.7	-131.1	-127 to -135 dBW/MHz Range of Data Associated with Median
	Loss of Multiple SVs	-126.2	-127.7	-129.1	
3	Loss of 1/Multiple SVs	-127.9	-127.4	-128.8	
4	Loss of 1 SV	-129.9	-129.4	-133.8	
	Loss of Multiple SVs	-127.9	-129.4	-133.8	

a. The ARL:UT data shows, among many other performance measures, the interference power level at the input of the GPS at which the signal from one and/or more than one GPS SV cannot be tracked. This performance metric measure compares with the break-lock metric used by NTIA.
b. In reviewing the data there is evidence of possible CW-like interference effects in this receiver for these UWB modes.

[42] JSC Report at 5-1

2.6 COMPARISON OF MEASURED RESULTS WITH EXISTING GPS C/A CODE INTERFERENCE LIMITS

Finally, if one subtracts 4.5 dB from the median values of Table 2-8 to correct the GPS reference signal from -130 dBm to -134.5 dBm, the NTIA data can be compared to the existing RTCA and ITU-R GPS interference limits.[43] The adjusted median value for CW-like interference would be -149 dBW and for noise-like interference for reacquisition would be -139.1 dBW/MHz. These values are consistent with the existing protection limits for GPS receivers of -150.5 dBW for CW-like interference and -140.5 dBW/MHz for noise-like interference.

2.7 SUMMARY

In summary, the GPS receiver interference threshold data is consistent across the three receivers tested in the NTIA measurement program. These receivers are those that process the C/A code L1 signal. The NTIA data was also shown to be consistent with the SU and ARL:UT test results. These comparisons can only be made for a subset of the SU and ARL:UT data because of differences in the UWB characteristics considered and the measurement procedures used. Finally, the NTIA data was shown to be consistent with existing interference protection limits for GPS. For the parameter sets tested, this data defines the power level of the UWB signal that can be tolerated at the GPS receiver input without causing break-lock or increasing reacquisition time. This body of susceptibility data can be used in source-path-receiver analysis (such as that in Section 3) to determine the interference impact to GPS receivers from UWB emissions in various operational scenarios.

[43]NTIA Report 01-45 at 2-8.