RTCA Paper No. 086-01/PMC-139

Second Interim Report to the Department of Transportation:

Ultra-Wideband Technology Radio Frequency Interference Effects to Global Positioning System Receivers and Interference Encounter Scenario Development

Prepared by
RTCA Special Committee 159

March 27, 2001

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CORRIGENDUM

to

Second Interim Report to the Department of Transportation:

Ultra-Wideband Technology Radio Frequency Interference Effects to Global Positioning System Receivers and Interference Encounter Scenario Development (RTCA Paper No. 086-01/PMC-139)

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This corrigendum corrects the Executive Summary, page 5, fourth paragraph to be consistent with the conclusions stated in paragraph 4.3.1.5 - Summary and Conclusions, on page 55.

- **Executive Summary, page 5, fourth paragraph –**

  - Delete the last sentence: “The E-911 case…below the proposed Part 15 limits.”

- **The Executive Summary, page 5, fourth paragraph, should read:**

  New scenario development work since the first interim RTCA report (Sept. 2000) reported here are initial descriptions of aeronautical mobile satcom safety communications, on-board aircraft personal electronic device RFI to enroute navigation and GPS-based enhanced-911 position reporting through cellular telephone. E-911 relies heavily on GPS for position reporting. Furthermore, indoor, urban canyon and foliage make certain GPS operations much more sensitive to interference. UWB Wireless Local Area Networks have already been announced, using very high PRFs and may be used widely. The Part 15 EIRP limit of –71.3 dBW/MHz results in a received level at 3 meter separation 24.3 dB above the GPS receiver noise floor. Unless UWB device EIRP values are reduced below that level, excessive interference to GPS-based E-911 operations may result. Further work is needed to quantify the scenario.

April 13, 2001

RTCA Paper No. 101-01/PMC-140

1.0 EXECUTIVE SUMMARY

The Global Positioning System (GPS) is significant because it is a key element in the development of the "Free Flight" air traffic management structure of the future which is needed to enable the expected growth of air travel and alleviate the currently overcrowded air routes. It is also fast becoming the technology of choice in other public safety positioning and navigation applications (e.g., E-911, maritime, IVHS) and has become imbedded in the national AC power and telecommunications infrastructure. GPS uses, however, a set of rather weak radio signals from satellites in 20,200 kilometer high orbits and, as such, is susceptible to being overpowered by strong terrestrial interference. It operates in one of the "restricted frequency bands" of Title 47 C.F.R. Part 15 and requires protection from harmful interference by international treaty. The FCC in its May 2000 Notice of Purposed Rule Making (on ET Docket 98-153) proposed to allow intentional ultra-wideband (UWB) transmissions across the GPS and several other restricted frequency bands of key importance to aviation and other public safety applications. The proposed power level had previously been allowed only for unintentional spurious emissions.

Since its June, 2000 tasking by the Department of Transportation, RTCA has followed and reviewed 5 major activities relating to UWB radio frequency interference (RFI) to aviation systems, in general, and GPS, in particular. They are the DOT-sponsored UWB RFI tests at Stanford University, The Time Domain Corp.-sponsored RFI data collection effort at Applied Research Labs: University of Texas (ARL:UT), and data analysis effort at Johns Hopkins University Applied Physics Lab (JHU/APL), and two National Telecommunications and Information Administration (NTIA) RFI test and analysis efforts (one on UWB characterization and non-GPS system impact assessment, and the other on GPS RFI impact).

RTCA has also developed RFI encounter scenarios necessary in the impact assessments in particular for aviation precision approach and non-precision approach. RTCA has acted as a forum to help development of other public safety operational scenarios such as cell phone embedded GPS E-911 and maritime navigation in harbors and inland waterways.

Results from the various test programs have been reported and discussed at RTCA. From the Stanford tests on an aviation approach-grade GPS receiver, three different types of UWB RFI effects are observed: CW-like, noise-like, and pulse-like. These are categorized by similarity to previous RTCA published (RTCA/DO-235) susceptibility study results from conventional RFI signals. The degree of UWB RFI impact is observed to depend on UWB signal characteristics such as pulse repetition frequency (PRF), waveform gating and modulation in relation to the GPS receiver bandwidth. Stanford quantified the degree of RFI impact by a "noise equivalency factor" for later use by RTCA in an RFI link analysis.

RTCA developed aviation approach scenarios for Category II/III precision approach and Non-precision approach. The Category II/III scenario was based on previous work for Category I which was recorded in DO-235. From the scenario parameters, an RFI link analysis was performed and yielded the result that maximum allowed UWB RFI emission level must be less than –100 dBW/MHz (28.7 dB below the proposed Part 15 limit of –71.3 dBW/MHz). The non-precision approach case fell within the bounds of the precision approach cases.

NTIA UWB characterization efforts show the usefulness of the RMS spectral density technique in measuring UWB emissions. NTIA non-GPS assessment results showed UWB RFI impact at Part 15 levels to several key Federal systems (up to 6 km spacing required from air route surveillance radars).

Similar to Stanford, NTIA GPS results on a set of general purpose GPS receivers also showed the CW-like, noise-like, pulse-like UWB RFI impacts depending on UWB PRF, waveform gating and modulation in relation to the GPS receiver bandwidth. Susceptibility values were in agreement with RTCA and ITU published standards (-140.5 dBW/MHz broadband, and –150.5 dBW discrete line, relative to a GPS received signal level of –164.5 dBW) even though test criteria were somewhat different than those on which the standards was based. Link analyses for the scenarios used in their compatibility assessments showed UWB low-end power values similar to the RTCA precision approach cases.

JHU/APL concluded from their analysis of the ARL:UT data collection that UWB RFI impact is also waveform-dependent though their results do not bring out the receiver dependence aspect. Furthermore, they concluded that "for UWB devices with average powers that are compliant with the current FCC Part 15 regulations, the performance of GPS receivers exhibits severe degradation when the separation between the GPS receiver and UWB devices is less than about 3 meters." As described in more detail in the body of this RTCA report, RTCA took issue with that conclusion and some related ones. It noted that a device emitting at the Part 15 emission limit in the GPS band 3 meters from a GPS receiving antenna causes the received interference to be more than 200 times the internationally-recognized value for unacceptable interference. This is equivalent to a noise density that is 24.3 dB above the thermal noise density for a typical GPS receiver.

New scenario development work since the first interim RTCA report (Sept. 2000) reported here are initial descriptions of aeronautical mobile satcom safety communications, on-board aircraft personal electronic device RFI to enroute navigation and GPS-based enhanced-911 position reporting through cellular telephone. The E-911 case RFI link analysis shows that indoor GPS-based E-911 is probably one of the most stringent of all the scenarios and requires a UWB power reduction of more than 60 dB below proposed Part 15 limits.

It is clear from the results summarized above and discussed in this report that UWB RFI impact to GPS and other key systems is not negligible as some of its proponents claimed. Due to the complexity of the interaction, considerable care and further work will likely be needed before rules for UWB can be drafted. Since some of the UWB RFI studies are on-going, the RTCA study group will continue to review new study material as it becomes available. Final reports for the original GPS L5 RFI environment study and for the update to the RTCA DO-235 study report on the GPS L1 environment are planned for release early in 2002.

2.0 INTRODUCTION

In October, 1999, at the request of the Department of Transportation (DOT), the RTCA undertook an effort to investigate the radio frequency interference (RFI) environment in the vicinity of the new Global Positioning System (GPS) L5 frequency (1176.45 ± 12 MHz) and determine appropriate receiver susceptibility criteria and related RFI unwanted emission limits for the use with new civil signal. Aviation-related issues were acknowledged to be of primary importance, but the group was encouraged to seek significant involvement and input from non-aviation GPS uses, especially public safety applications (e.g., maritime, E-911, police, fire fighting). By June 2000 the pace had intensified on regulatory and business activities related to ultra-wideband (UWB) transmission technology. As a result the DOT requested the RTCA enlarge the study to explicitly treat UWB RFI effects and operational scenarios for the GPS L1 frequency (1575.42 ± 12 MHz) as well as L5.

Two interim reports were requested on the RTCA study effort. In September, 2000 RTCA Special Committee 159 released its first interim report[1] to the DOT on its study of UWB transmitter RFI testing on GPS receivers and RFI encounter scenario development. That report covered the study activities through early August 2000. Since that time efforts to complete further RFI testing, refine scenarios, and perform RFI link analyses encountered difficulties and delays that forced a 3 month delay in second interim report. To provide policymakers an early update on the aviation-related portion of the continuing RTCA RFI study effort, a preliminary aviation approach segment of the second interim report[2] was released in early February 2001, and covered study progress through the end of January. Among the information on key activities unavailable at that time were the National Telecommunications and Information Administration (NTIA) GPS RFI study results and the Johns Hopkins University Applied Physics Lab (JHU/APL) analysis of the Applied Research Labs: University of Texas (ARL:UT) UWB RFI tests raw data. Some aviation and non-aviation public safety interference scenario descriptions were also unavailable.

The information missing at the end of January has largely been supplied to RTCA by mid March so the full second interim report could be released. This second interim report will cover in Section 3.1 the latest update of the Stanford University/DOT-sponsored RFI test results and include an explanation of the observed UWB discrete spectral line RFI. Section 3.2 contains summaries of the Time Domain Corp.-sponsored ARL:UT UWB RFI data collection and JHU/APL analysis of that data. Section 3.3 on the NTIA UWB characterization and non-GPS system RFI impact assessment is unchanged from the aviation approach segment report. However, Section 3.4 has been added to contain summaries of the newly released NTIA GPS

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[1] RTCA SC-159, "Ultra-Wideband Technology Radio Frequency Interference Effects to GPS and Interference Scenario Development, First Interim Report to Department of Transportation," RTCA Paper No. 289-00/PMC-108, 12 September 2000, http://rtca.org/comm/reports/pmcSC159report.PDF, "RTCA First Interim Report"

[2] RTCA SC-159, "Preliminary Aviation Approach Segment for the Second Interim Report to Department of Transportation: Ultra-Wideband Technology Radio Frequency Interference Effects to Global Positioning System Receivers and Interference Encounter Scenario Development," RTCA Paper No. 039-01/PMC-128, 2 February 2001, http://www.rtca.org/comm/reports/UWB%20P-Aviation%20Final%2002%2013%202001.pdf, "RTCA Aviation Approach Segment Report"

RFI reports.[3,4] The aviation precision approach scenarios and RFI link budget in the aviation segment report Section 4.1 remain unchanged. New scenario descriptions have been added in Section 4.2 to discuss potential UWB RFI to aeronautical mobile satellite (route) service and on-board UWB personal electronic device RFI to enroute navigation. Section 4.3 contains a new description of scenarios for Enhanced-911 cell phone position reporting with GPS and an RFI link budget. Appendix B contains corrections for some typographical errors from the preliminary aviation approach segment.

The RTCA study group will continue to incorporate new input material as it becomes available. Final reports for the original GPS L5 RFI environment study and the update to the RTCA DO-235 study report on the GPS L1 environment are planned for release early in 2002.

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[3] National Telecommunications and Information Administration, U.S. Department of Commerce, NTIA Special Publication 01-45, "Assessment of Compatibility Between Ultrawideband (UWB) Systems and Global Positioning System Receivers," Feb. 2001, "NTIA 01-45".
[4] National Telecommunications and Information Administration, U.S. Department of Commerce, NTIA Report 01-384, "Measurements to Determine Potential Interference to GPS Receivers from Ultrawideband Transmission Systems," Feb. 2001, "NTIA 01-348"

3.0 UWB RFI EFFECTS TESTS ON GPS RECEIVERS

3.1 Department of Transportation-Sponsored Tests at Stanford University

3.1.1 Noise Equivalency Factor Measurement and Analysis Method

A typical set of measurements from the DoT-Stanford University UWB RFI test program on GPS receivers is illustrated below (Fig. 3.1). The curve labeled "BB Noise Only" plots the baseline GPS receiver pseudorange measurement error standard deviation with broadband noise RFI. As indicated, the total interference input power at the accuracy limit is N_{ACC}.

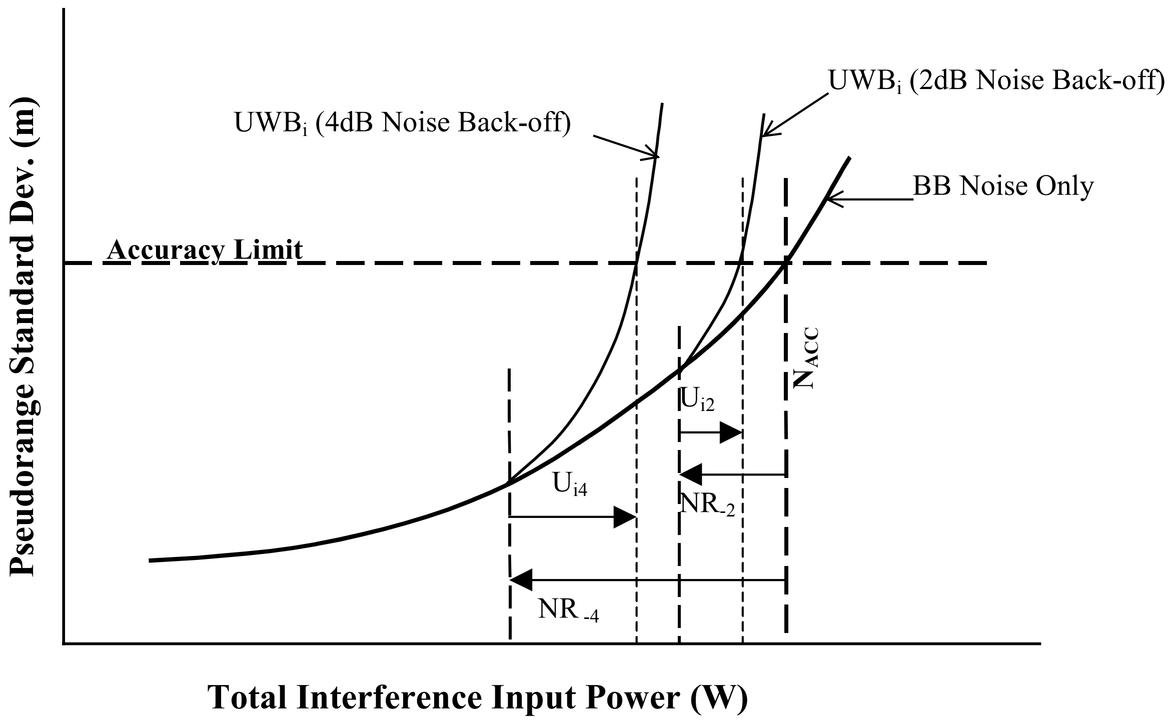

Figure 3.1. Broadband Noise Normalization and Partial UWB Substitution Illustration

The test method calls for making two additional sets of measurements for each UWB interference waveform where UWB RFI power replaces a known portion of the baseline broadband noise power. One set has broadband noise power reduced 4 dB below N_{ACC} (4 dB back-off curve) and the other uses broadband noise 2 dB below N_{ACC} (2 dB back-off curve). From the RFI effects standpoint, the noise equivalency of a UWB waveform comes from a comparison of the UWB power values added back (U_{i4} and U_{i2}) to give the same standard deviation with the known amount of broadband noise power they replaced (NR_{-4} and NR_{-2}). From the example UWB power values U_{i4} and U_{i2} are less than the broadband noise powers, NR_{-4} and NR_{-2}, they replaced to give equal RFI effect. Thus UWB waveform *i* has a greater RFI effect than broadband noise of equivalent power.

A noise equivalency factor numerical value for each UWB waveform is determined as shown in Figure 3.2. First, the values for added UWB power, U_{i4} and U_{i2}, are plotted against the associated broadband noise power removed values, NR_{-4} and NR_{-2}. A "best-fit" straight line is drawn from the origin (the baseline power N_{ACC} corresponds to the zero power reference) through the two UWB power points. The noise equivalency factor is the slope of the best fit line (noise equivalency in dB =10 $\log_{10}$[slope]).

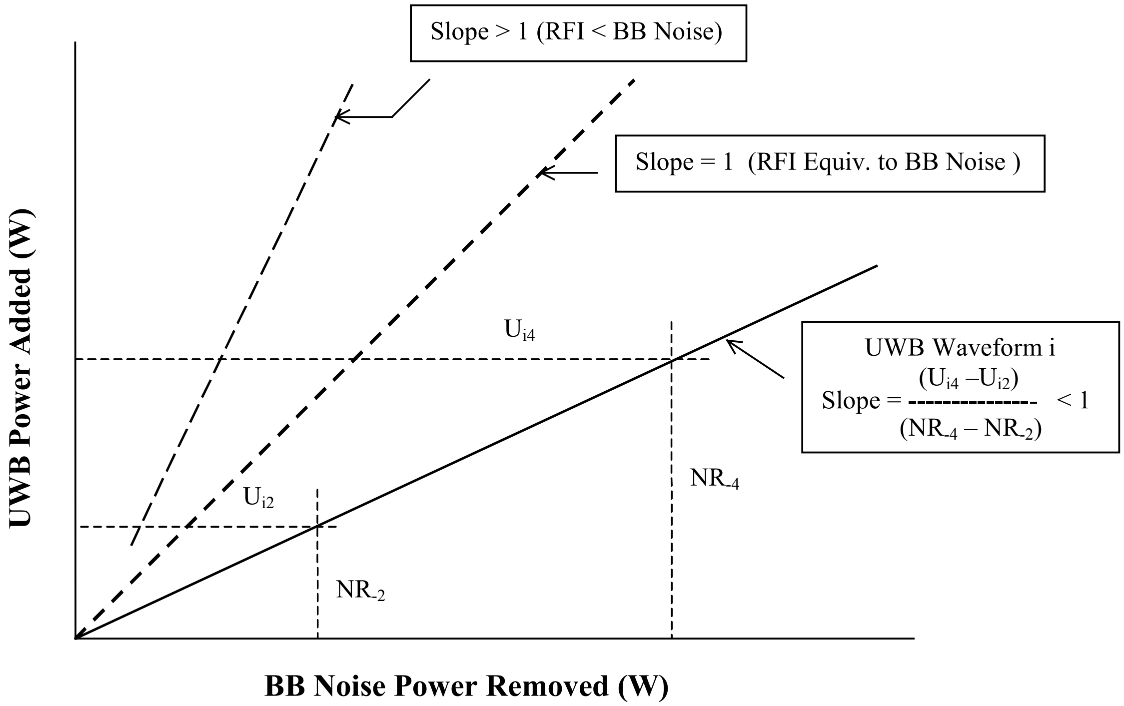

Figure 3.2. Broadband Noise Equivalency Factor Illustration

The curves in Figure 3.2 illustrate three possibilities for the noise equivalency. Namely, a slope less than 1 indicates the waveform has a more harmful RFI effect to GPS than the same amount of broadband noise. A unity slope indicates equivalent RFI effect to broadband noise, while a slope greater than 1 indicates less harmful RFI effect.

Another sort of outcome is also possible. If a line connecting the origin to the two UWB power points shows significant curvature (i.e.; greater than the measurement error for the points), it indicates that the UWB signal is not adding linearly to the noise power. The noise equivalency factor (slope) is still defined but it becomes a function of the amount of broadband RFI present in the particular scenario.

The equivalency factor (in dB) is used in an RFI link budget to correct the allotment for a noise-like RFI signal so the actual UWB emission gives the same RFI effect. That is, once an allocation for a particular amount of noise-like RFI is made to a UWB emitter, the noise equivalency factor (dB) is added to the noise power allotment to give the actual permitted UWB RFI power. If the noise equivalency factor for a particular UWB emitter waveform is –X dB, then the permitted UWB emission level is X dB less than the noise power RFI allotment to UWB.

3.1.2 Stanford University Phase II Test Results

This section contains a summary of the phase II testing of UWB RFI to GPS being conducted at Stanford University under the support of the DoT. A detailed background discussion and the results from phase I testing can be found in Attachment 1 of the October 30, 2000 DoT filing to the Federal Communications Commission (FCC) on the ET Docket 98-153. The first interim RTCA report[5] on UWB RFI also reviewed some of the preliminary results. Phase II testing included aviation receiver pseudorange error data taken for both 2- and 4 dB broadband noise back-off points. In addition, a preliminary investigation into the impact of UWB on GPS signal acquisition has been conducted.

3.1.2.1 Pseudorange Accuracy Testing:

The test configuration is depicted in Figure 3.3 and selected results are included in Figures 3.4, -3.6. Note the pseudorange accuracy threshold in the figures is 1.4 m (partially smoothed).

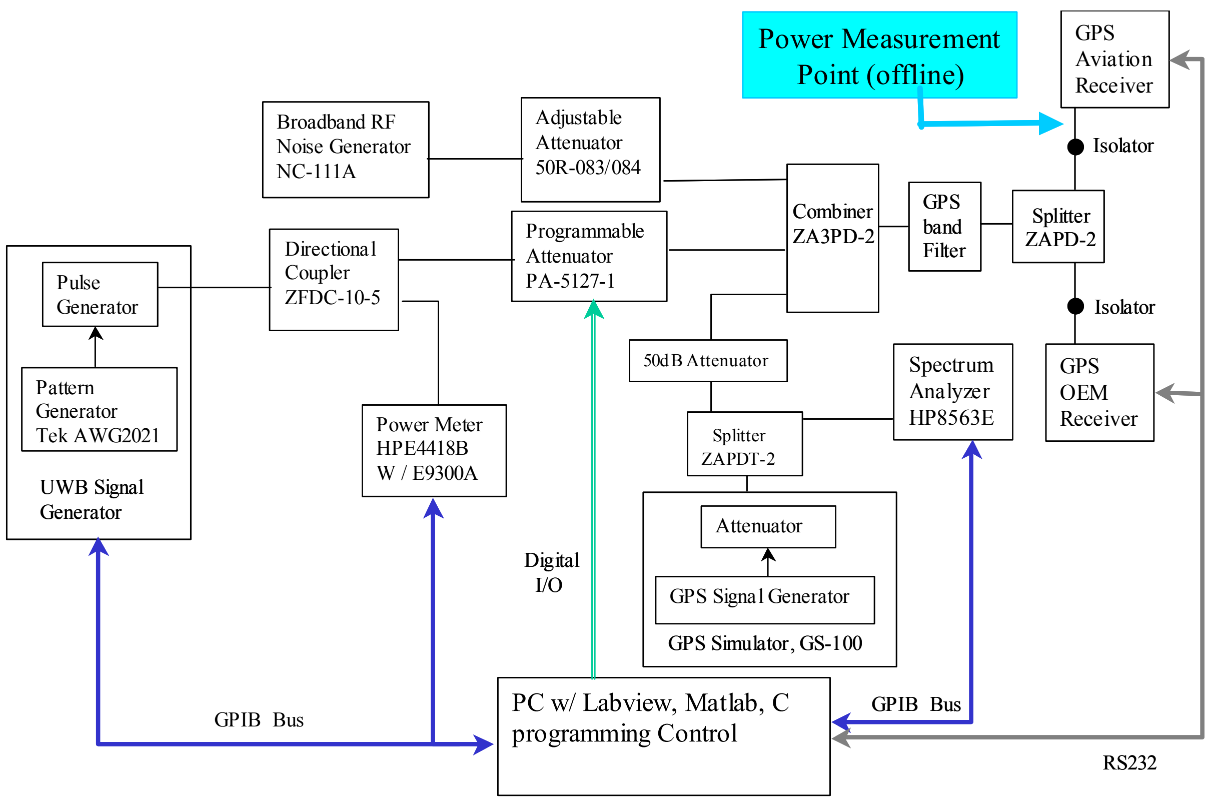

Figure 3.3. Test Set-up for Phase II Testing (Only GPS Aviation Results Reported)

5 See "RTCA First Interim Report"

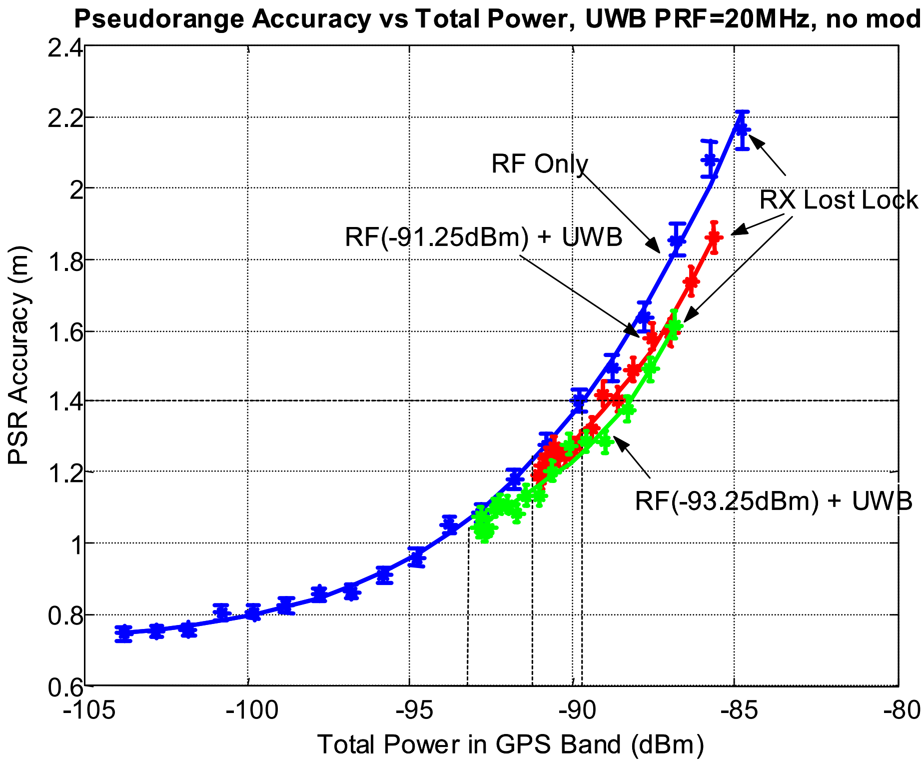

Figure 3.4. Test Results for 2 & 4 dB Back-offs for 20 MHz Constant PRF

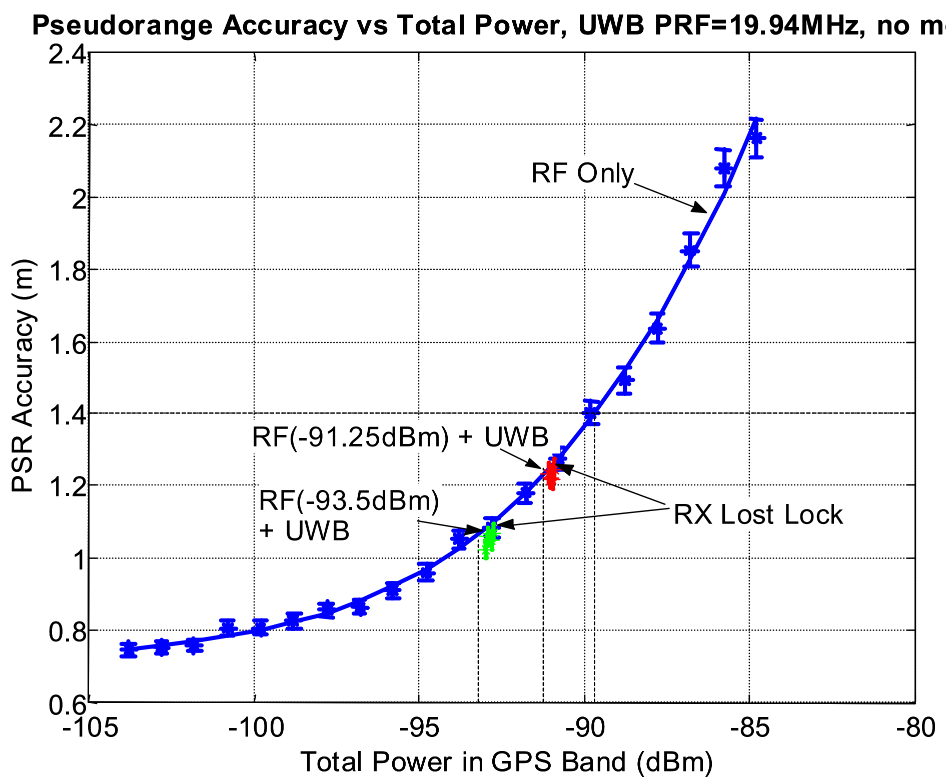

Figure 3.5. Test Results for 2 & 4 dB Back-offs for 19.94 MHz Constant PRF

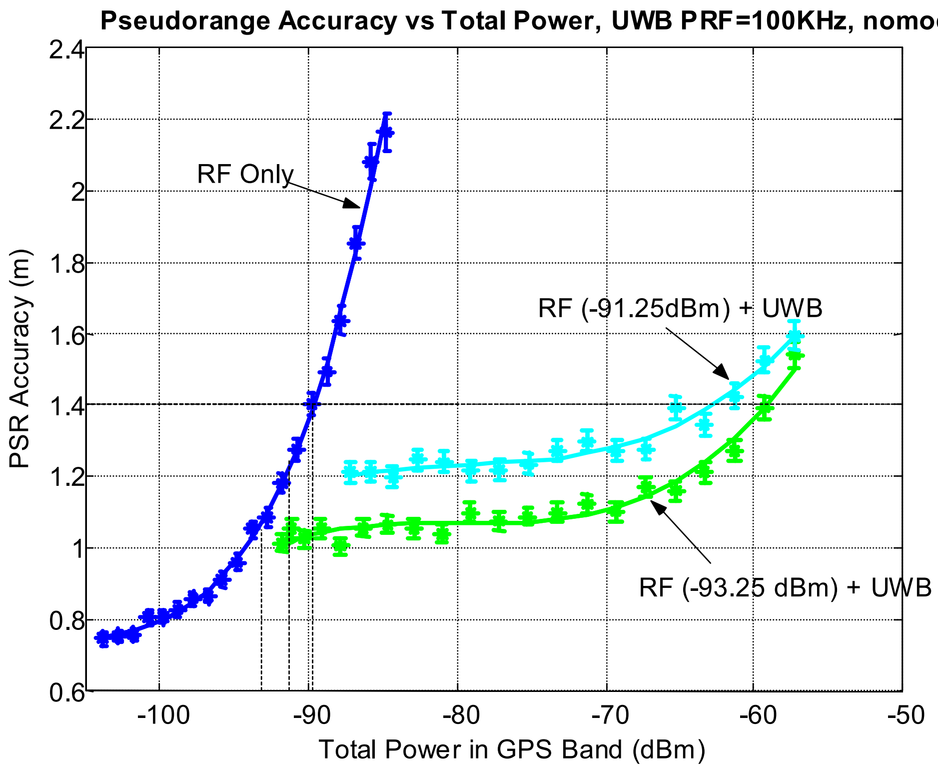

Figure 3.6. Test Results for 2 & 4 dB Back-offs for 100 kHz Constant PRF

In all of the above figures, the curve labeled "RF Only" traces out the pseudorange (PSR) accuracy as a function of broadband noise power in the GPS band. The curve labeled "RF [-93.25 dBm]+UWB" plots the result of the UWB introduction with a 4 dB back-off and the curve labeled "RF [-91.25 dBm]+UWB" is the 2 dB back-off trace.

As discussed in the phase I results, the slight shift in constant pulse repetition frequency (PRF) value from 20.0 MHz to 19.94 MHz introduces a distinct spectral line in the center of the GPS band. That causes a significant problem for the receiver and results in loss-of-lock of the GPS satellite signal with the addition of very little added UWB power. This is shown in Figures 3.4 and 3.5. However, Figure 3.6 shows a different result. For a low PRF, significantly more UWB power, relatively to broadband noise power, can be added for the same impact on accuracy. It is likely that this is a result of the reduced GPS susceptibility to pulsed interference.

For convenience, all testing utilized a GPS power level of –131.3 dBm. The broadband noise power in the GPS band at the 2 dB (or exactly 1.54 dB) and 4 dB (or exactly 3.54 dB) back-off points are –91.25 dBm and –93.25 dBm, respectively. Specific added UWB power levels for the threshold cross points are given in Table 3.1 for the UWB waveforms for which the accuracy degradation threshold was crossed before loss-of-lock. Table 3.2 compares the UWB added power levels at break-lock for selected high RFI impact waveforms with broadband-only break-lock power. Note in the cases listed, the UWB power values with backed-off broadband noise are more than 14 dB below the broadband noise-only break-lock value. The UWB values seem also to be rather insensitive to the amount of broadband noise back-off.

Table 3.1 Accuracy Threshold Levels of Added UWB Power and Removed Broadband Noise Power

Measurement Case		Power level at Pseudo-range error threshold dBm	mW	Noise Equiv Factor (dB)
Noise Power Removed (-2 dB)			3.192e-10	
Noise Power Removed (-4 dB)			5.959e-10	
No mod, PRF=100 kHz	UWB pwr added 2dB Back off	-61.82	6.5763e-7	33.0
	4dB Back off	-59.17	1.2093e-6	
No mod, PRF=20.0 MHz	UWB pwr added 2dB Back off	-92.81	5.2315e-10	5.02
	4dB Back off	-89.82	1.0418e-9	
2P PPM PRF=15.94MHz	UWB pwr added 2dB Back off	-95.64	2.732e-10	-0.5
	4dB Back off	-92.84	5.196e-10	
10P PPM PRF=2.0 MHz	UWB pwr added 2dB Back off	-93.43	4.536e-10	1.16
	4dB Back off	-90.89	8.1465e-10	
10P PPM PRF=1.994MHz	UWB pwr added 2dB Back off	-95.73	2.68e-10	4.5*
	4dB Back off	-89.32	1.1692e-9	

* Average slope - apparent non-linear combination.

Table 3.2 UWB Added Power for Break-lock versus Broadband Noise Break-lock

Measurement Case		Power level at the Rcvr break-lock point dBm	mW
Noise Only		-84.8	3.311e-9
No mod, PRF=19.94 MHz	2dB Back off (N=-91.25dBm)	-102.3	5.9e-11
	4dB Back off (N=-93.25dBm)	-102.3	5.9e-11
2P PPM PRF=15.91 MHz	2dB Back off (N=-91.25dBm)	-99.38	1.15e-10
	4dB Back off (N=-93.25dBm)	-98.38	1.45e-10

The break-lock test results must be translated to account for reference filter bandwidth and interference spectral line frequency before they can be compared with published RTCA receiver narrowband susceptibility and NTIA test results (sec. 3.4). Consider the case of the 19.94 MHz PRF UWB signal. (Fig. 3.5). The firsts step in the translation is to find the power per MHz at the set-up bandpass output for the broadband noise break-lock test. The break-lock noise power value (-84.8 dBm) when divided by the 3 dB bandwidth of the filter (30.5 MHz from Fig. 3.7) results in noise density of –99.64 dBm/MHz. The next step is to adjust downward the total UWB interference power to yield the power in the center frequency line. The two lines at ±19.94 MHz from center are rejected by about 15 dB each so they contribute 6.3 % of the total and the central line 93.7 %. Thus the actual power in the central line is –102.6 dBm (–102.3 – 10*log (0.937)). The ratio of the noise power density value to this corrected CW break-lock power to is -2.94 dB (-102.58 – (-99.64)). The final adjustment is to correct for the actual line frequency involved in the experiment compared to the worst case GPS C/A code line frequency. The following figures (Fig. 3.8 and 3.9) show the worst case lines for PRN 21 (the test satellite) is a ±55 and ±59 kHz from center, while the 19.94 MHz PRF harmonic occurs at –160 KHz from center. The 160 kHz code line height is 6.5 dB lower that the worst case line so the susceptibility is 6.5 dB better. If that adjustment was made in the measured –2.94 dB susceptibility ratio, then the worst case ratio value would be -9.44 dB (in good agreement with the -10 dB value from RTCA standards and NTIA tests).

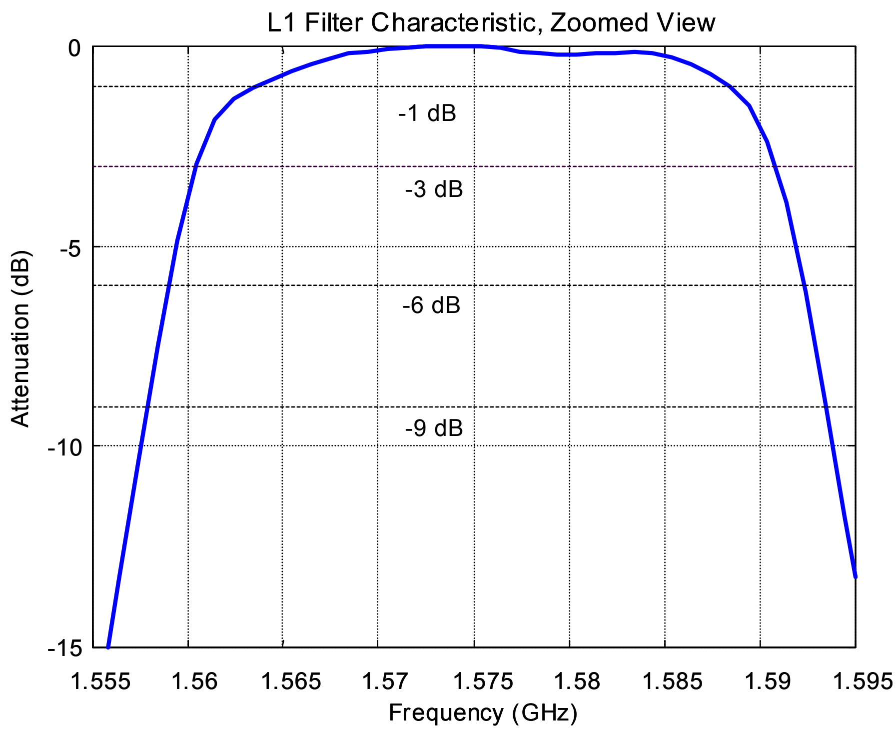

Figure 3.7. Reference Filter Frequency Reponse

1 dB BW: 24.9 MHz, 3 dB BW: 30.5 MHz
6 dB BW: 33.3 MHz, 9 dB BW: 35.6 MHz

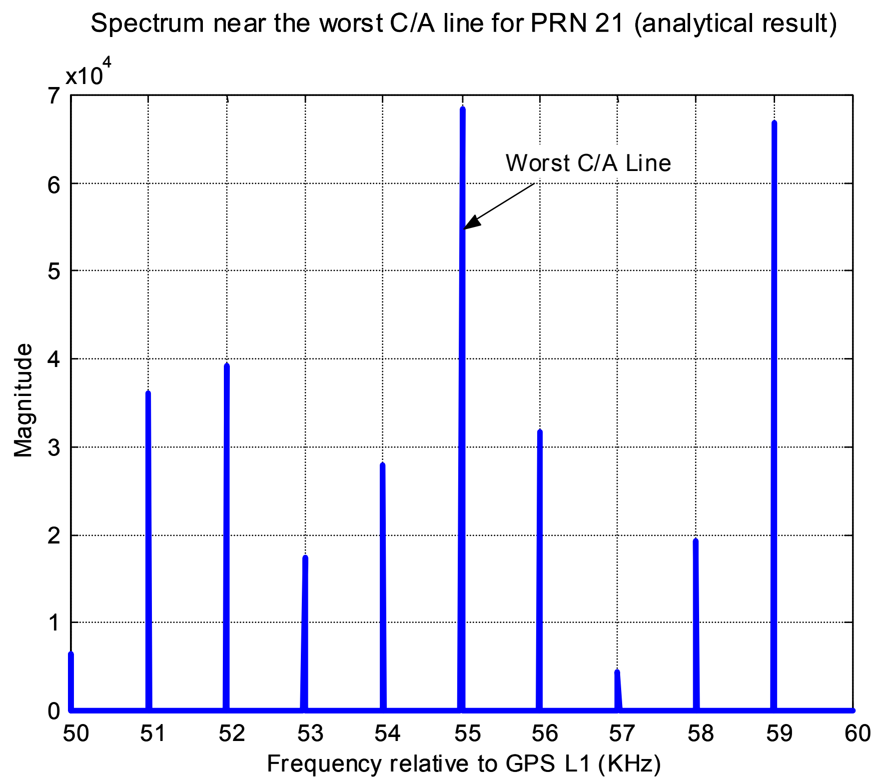

Figure 3.8. PRN 21 Spectrum Around the Most Sensitive Spectral Lines

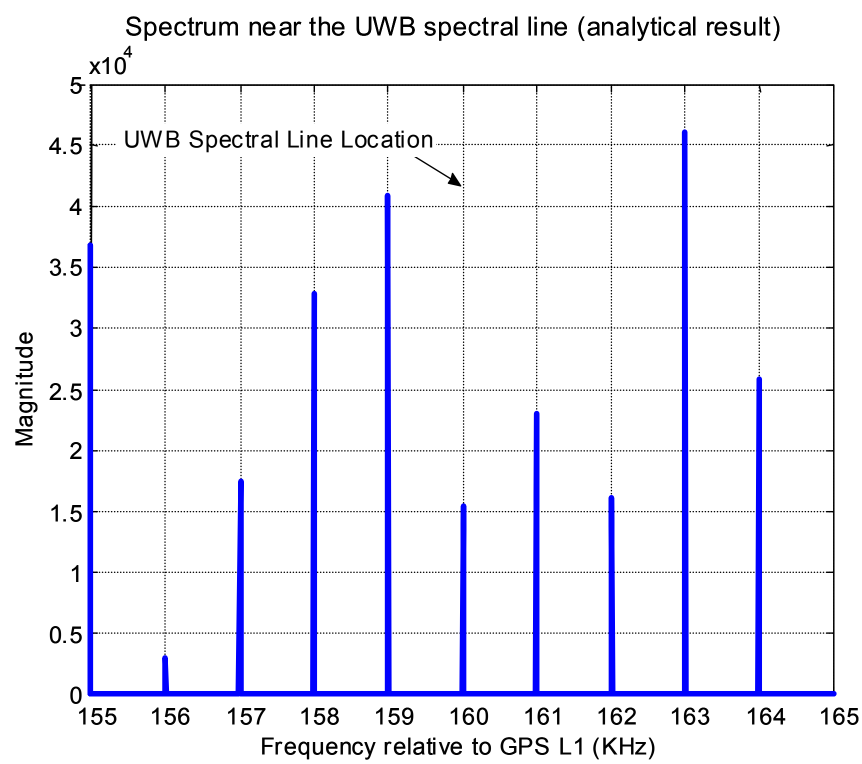

Figure 3.9. PRN 21 Spectrum At the Location of the Result UWB Spectral Line (19.94 MHz PRF)

3.1.2.2 Acquisition Testing:

In addition to the continued accuracy testing, Phase II covered initial GPS acquisition testing in the presence of UWB. Using the same test configuration from Figure 3.3, the GPS aviation receiver was replaced with a high-end, general-purpose GPS receiver. The test procedure was as follows: the GPS signal at a fixed power level of –131.3 dBm was introduced into the receiver with specific levels of noise and UWB; the receiver was given one minute to acquire the signal; if the signal was acquired, the C/No was recorded. This test was repeated five times at each combined noise/UWB power level to provide multiple trials for each power point. Based on this test procedure, a noise calibration curve was generated, similar to what was done for PR accuracy. The maximum noise power at which the receiver was able to acquire the signal in all five trials was determined to be a baseline level. From this point, the broadband noise power was reduced by 4 dB and UWB was introduced in the band of increasing power levels until GPS acquisition failed over all 5 trials. This testing allows characterization of GPS acquisition in the presence of UWB relative to broadband noise. Results of this testing are presented in Figure 3.10.

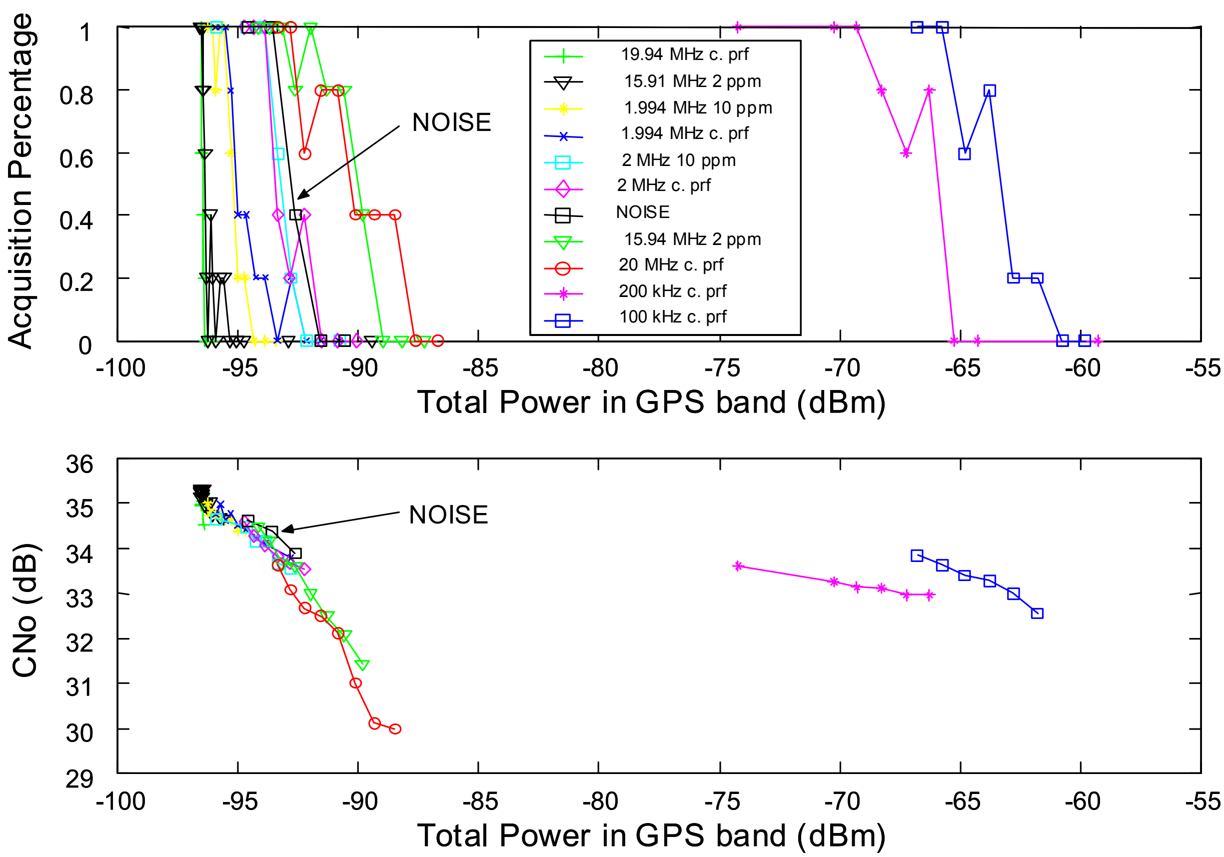

Figure 3.10. Result of GPS Acquisition Testing in the Presence of UWB/Noise

3.1.2.3 Stanford Results Summary:

Continued testing at Stanford University indicates that UWB has an adverse impact on the performance of GPS receivers and such performance is heavily dependent on UWB parameters. The most significant of such are the UWB pulse train modulation and resulting distinct spectrum lines.

The most problematic cases for accuracy testing (19.94 MHz constant PRF and 15.91 MHz 2 Position – Pulse Position Modulation (PPM)) are also the most problematic cases for GPS acquisition. The best case for GPS PR accuracy, that of UWB at a low PRF, was also the best case for the minimal impact of GPS acquisition performance.

Tabulated threshold-crossing power results at two specific broadband noise back-off points for a number of UWB waveforms of interest have been used to determine broadband noise equivalency factors for later use in RFI link budgets.

3.1.3 GPS Receiver UWB RFI Effects Model and Generalized RFI Analysis Equations

Appendix A provides some insight from an analytical perspective into how UWB RFI affects GPS receivers. This insight basically validates the test results obtained by Stanford University. It also validates the use of the large negative noise equivalency factor that is the difference between the application of discrete CW and random noise interference to the GPS receiver. Appendix B describes four general-purpose equations that cover the full range of RFI cases and demonstrate the sensitivity of GPS RFI response to UWB modulation format. Application of the Appendix B methodology makes it possible to extend the results for the tested receivers to other receiver cases with basic parameters in between the tested values.

3.2 Time Domain Corp.- Sponsored RFI Testing and Analysis

3.2.1 Applied Research Labs: University of Texas (ARL:UT) UWB RFI Data Collection Effort

As noted below, all conducted and radiated UWB RFI testing at ARL:UT has been completed and raw data have been posted on their web site. RTCA has received brief summaries of the actual procedures used and samples of the raw data collected. As noted in its first interim UWB RFI report, RTCA believes that, because of the inherent experimental problems in radiated RFI testing with live GPS signals, only the conducted RFI data is useful for further analysis. Also as noted in the first interim UWB report, however, no RFI analysis is possible without substantial data reduction. Johns Hopkins University Applied Physics Lab (JHU APL) has been contracted by Time Domain Corp. to perform that reduction (see 3.3.2 below). ARL:UT did not provide RTCA any detailed report text in suitable format that described their data collection campaign. They did, however, provide the following summary of their effort. The ARL:UT final report is available in part from their web site (noted below) and in total from the FCC electronic comment filing web site.[6]

The Applied Research Laboratories, The University of Texas at Austin (ARL:UT) has completed its measurement effort on the compatibility of Ultra Wideband (UWB) technologies and Global Positioning System (GPS) receivers. This measurement effort was not intended to produce an analytic result. Instead, it was intended to gather a data set that met the needs of the worldwide community and provide a public data set necessary for specific groups to make their own determination of impact. Over a four month period prior to testing, the test plan was presented to a large community that included members of public organizations such as the RTCA, academic organizations, and governmental organizations across the spectrum of governmental activity. Solicitations regarding improvements to the plan were sought and, where applicable and possible within the scope of the work effort, were implemented in order to acquire the most relevant data sets possible.

The test report describing the data collection effort has been produced and was submitted to the FCC on February 27, 2000 to be included as part of the comments on the FCC's NPRM. The data, and the test report, are public and available at the ARL:UT web site at http://sgl.arlut.utexas.edu/asd/Cure/testplan.html.

The testing involved a number of different GPS receivers (Novatel 3151; Ashtech Z12; Garmin International GPS 150 XL, Ashtech Z-Sensor; Novatel Millennium; and the Trimble 4700), several different UWB devices (Time Domain PAD, Time Domain signal generator, Sensors and Software Noggin 1000 GPR, Sensors and Software Noggin 250 GPR), as well as some existing digital devices (Motorola Radius SP10 Walkie-Talkie, and a Gateway Model GP7-450, Mini-Tower, Personal Computer) that have the potential to impact on GPS receivers. Over 10 Gigabytes of data has been acquired and, although the data set is large, the directory structure the data has been placed in lends itself readily to analysis by personnel familiar with the tools and methods necessary for analysis of GPS data. This fact has been proven by the numerous,

[6] FCC ECFS web site, proceeding number 98-153

worldwide requests for information which ARL:UT has fielded from personnel actively analyzing the data.

3.2.2 Johns Hopkins University Applied Physics Laboratory (JHU/APL) Data Reduction and Analysis

On March 13, 2001, JHU/APL presented the RTCA the executive summary of their final report[7] and some supporting material to explain their ARL:UT RFI data analysis. The following text from the JHU/APL report executive summary has added comments by RTCA as noted that reflect points of contention raised in the meeting.

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) has conducted a focused and independent assessment of the effects of ultra-wide band (UWB) emissions on GPS receiver performance. This assessment is based on a statistical evaluation of data collected by the Applied Research Laboratories University of Texas at Austin (ARL:UT) along with a strictly theoretical analysis. The ARL:UT data were gathered using six specific GPS receivers, two configurable UWB device types and four other devices currently regulated under FCC Part 15 rules.

The objective of this assessment was to quantify the relationship among key GPS performance parameters and UWB emissions parameters such that from this work policy makers can gauge the impact of potential UWB emissions. The results of this work are being provided to the FCC to assist them in making informed regulatory decisions with regard to UWB emissions under Part 15. Based on this assessment, JHU/APL has drawn the following conclusions.

1. UWB time coding or modulation implementation determines the nature of the resulting UWB signal. This nature in turn determines the impact on a particular GPS receiver implementation and its performance. The choices of time coding parameters can produce significant differences in the amount and type of performance effect experienced by GPS receivers.
2. The theoretical analysis and statistical data evaluation show that properly time coded UWB signals can be produced that have characteristics similar to white noise within the GPS frequency spectrum. White noise energy is uniformly distributed in frequency and will not excite any complex interactions in GPS receivers. The properties of white noise allow it to be characterized by average power when taken in the context of overall GPS receiver performance, and this performance is a well studied interaction. The UWB devices tested by ARL:UT produce signals that are white noise-like. The aggregate signal produced by more than one of these devices is also white noise-like.

RTCA disagrees with the characterization of “white noise-like” for the individual UWB devices tested. It appears from Joint Spectrum Center analysis of the same UT data set that these signals actually contain spectral lines spaced at PRF/1024 Hz. For example, a 5 MHz PRF yields a line spacing of 4.88 kHz. The effect on the receiver cycle slip rate appears to be associated with aligning of these 4.88 kHz lines with the C/A code spectral lines, thereby producing effects that are time varying and only weakly correlated with UWB interference power.

[7] JHU/APL Strategic Systems Department, “Final Report: UWB RFI Analysis Project,” 8 March, 2001, available at the FCC ECFS web site, proceeding number 98-153

3. There exist coding schemes that can produce non-white noise-like UWB signals that may have a greater impact on GPS performance than those effects shown herein.

RTCA notes that other testing efforts have shown coding schemes that actually do produce non-white-noise-like effects. (see, for example, Section 3.1.2 of this RTCA report.) The JHU/ APL theoretical analysis (JHU/APL report Ch. 5) does predict such effects.

4. For UWB devices with average powers that are compliant with the current FCC Part 15 regulations, the performance of GPS receivers exhibits severe degradation when the separation between the GPS receiver and UWB devices is less than about 3 meters. This distance is based solely on the GPS receivers and UWB devices tested by ARL:UT. As the separation decreases below 3 meters, all users of these GPS receivers will be severely impacted, and in the extreme, lose lock on all satellites. This phenomenon is exhibited across all relevant measures of performance analyzed. The single Part 15 device that was analyzed induced similar behavior in the GPS receivers.

RTCA disagrees with the arbitrary selection of 3 meter separation for the onset of “severe degradation” for several reasons. (1) Report data[8] contradict the conclusion that 3 meters is an appropriate distance separation for GPS effects analysis. (2) An emitter at the Part 15 average power limit (-71.3 dB W/MHz) produces a signal into an isotropic antenna 3 meters away which is over 200 times the internationally accepted standard for unacceptable interference to the GPS receiver.[9] This is equivalent to a noise density that is 24.3 dB above the thermal noise density for a typical GPS receiver. (3) Improper factors were used in the conversion from attenuator setting to equivalent range. Examination by RTCA of the basic ARL:UT measurements suggests that the performance degradation actually takes place at power levels (and associated distances) consistent with the international standards (see also Sec. 3.1 and 3.4 of this RTCA report) (4) The introduction of a range relation implies that a scenario-dependent link budget was employed when, in fact, it was not. (5) The criteria used to define “severe degradation” were somewhat arbitrary and not consistent with international standards, and did not include any safety-of-life margins.

5. For separations greater than 3 meters, GPS receiver performance converges to nominal levels. The minimum separation at which degradations are acceptable depends on individual user scenarios including performance thresholds, GPS receiver and UWB device(s).

RTCA notes that the 3 meter value is unrealistic (see RTCA comment above). Also, there is no explanation of “nominal levels.”

6. Variations in the measures of performance due to different GPS receivers are greater than those due to the operating modes of the UWB tested devices. The impact of UWB devices on all GPS receivers cannot be assessed using a single GPS receiver.

RTCA notes that the measures of performance are inadequate for many GPS applications. For example, cycle slip occurrence, not chosen as a MOP, is a critical measure for survey receiver performance, and for aviation precision approach.

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[8] See JHU/APL Final Report, Chapter 6, Figures 6-4, -5, -6, -9,-11

[9] ITU-R M.1477

The JHU-APL report summary concludes with the statement, “The reader is encouraged to use the results presented in the remainder of this report to draw additional appropriate conclusions. Based on this report and the inputs from other organizations, JHU/APL believes that sufficient information is available for the FCC to establish criteria for regulating UWB emissions. Methodologies such as those presented in this report can be used to help the FCC evaluate the application of these criteria.” RTCA believes that it is very inappropriate for JHU/APL to judge the sufficiency of the FCC record in the UWB proceeding. This final conclusion is inconsistent with and unsupported by the certain results in the body of their work as pointed out above. The conclusion is far too general and sweeping in relation to a study of only GPS L1 band RFI effects (See, for example, the discussion of the NTIA study in section 3.3 of this RTCA report).

3.3 NTIA Tests on Ultra-Wideband Devices and Compatibility with Non-GPS Federal Systems[10]

NTIA has conducted a series of measurements and analyses for characterizing and assessing the impact of UWB devices on selected Federal equipment operating between 400 and 6000 MHz, which includes 18 bands and a total of 2502.7 MHz of restricted spectrum.[11] The results include practical methods for characterizing UWB systems and providing the information needed to estimate or measure their potential to interfere with existing radio communications or sensing systems.[12]

NTIA calculated the maximum permissible, average Equivalent Isotropic Radiated Power (EIRP) density in a 1 MHz bandwidth (average EIRP, dBm/MHz (RMS)) that would allow a UWB device to transmit without exceeding the protection criterion determined for each of the systems analyzed after coordination with that system's users.[13] Throughout this section, the average power was calculated from the Root Mean Square (RMS) voltage of the UWB signal. For clarity and simplicity the average power has been written as average (RMS) power and the average spectral density expressed as dBm/MHz (RMS). In addition, NTIA calculated the minimum separation distance at which a UWB device with an average EIRP spectral density of -41.3 dBm/MHz (RMS), which is equivalent to the average field strength specified in Part 15 for devices operating above 1 GHz (a field strength of 500 µV/m at a 3 meter separation distance measured in a 1 MHz bandwidth), will ensure that the protection criteria are met in that receiver. Both the effects of one single UWB emitter on one receiver and of an aggregate of several UWB emitters on one receiver were analyzed. Throughout the assessment, the UWB devices analyzed were presumed to overlap the bands used by the equipment being assessed completely. The analytical results developed were been compared with the measurements made at NTIA's Institute for Telecommunication Sciences (ITS) in Boulder, Colorado and field measurements made at the Federal Aviation Administration facilities at Oklahoma City, Oklahoma.

The power levels of the UWB devices are expressed here as RMS spectral power densities, as noted above, rather than the average of the logarithms of the peak power densities measured with

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[10] Section 3.3 is an excerpt of the Executive Summary of NTIA Special Publication 01-43, "Assessment of Compatibility between Ultra-Wideband Devices and Selected Federal Systems," Jan., 2001.

[11] In addition, because of widespread concern, both the Interagency Government Executive Board, which oversees the development of the Global Positioning System (GPS), and the Federal Aviation Administration (FAA), have funded NTIA to conduct a related series of studies assessing UWB impact on GPS receivers. The measurements involving GPS receivers will be reported separately in a later document. See National Telecommunications and Information Administration, *Notice, Request for Comments on Global Positioning System/Ultrawideband Measurement Plan, 65 Fed. Reg. 49544 (Aug. 14, 2000).*

[12] NTIA and the Institute for Telecommunication Sciences with the support of the National Institute of Science and Technology verified the accuracy of the measurements made using readily available commercial test equipment in three separate ways. The first was by very accurately measuring the temporal (time domain) characteristics of the several devices and comparing the Fourier transformations of the signals in various bandwidths with measurements of the actual spectrums received in those bandwidths. The second was by theoretical analyses of the waveforms and their spectrums. The third way was through numerical simulations of the waveforms.

[13] The protection criteria, which are presented in Appendix A, are based on ITU-R Recommendations, ICAO Standards, and RTCA Minimum Operational Performance Criteria and were provided by the agencies operating the affected systems. NTIA's model is not generally accurate at ranges less than 200 meters due to uncertainties of near field, propagation and antenna gain.

the video averaging technique used by the FCC for measuring narrow band Part 15 devices. Although NTIA recognizes that no single average detector function adequately describes the interference effects of UWB signals, the RMS detector function better represents the interference effects of UWB signals than averages of the logarithms of the peak detector output of the video filtered response used by the FCC for Part 15 measurements.

3.3.1 Results: Single Emitter

TABLES 1 and 2 provide the results of NTIA's analyses of the effect of single UWB emitters on selected devices. TABLE 1 shows the results for all the systems analyzed, assuming that receiver performance degradation is a function of the UWB signal average power, while TABLE 2 shows the results of the analyses for digitally modulated Earth stations in which receiver performance degradation may be a function of the UWB signal peak power. In TABLE 2 the lower PRF rows are shaded to reflect a possible restriction of the ratio of permissible peak power in a 50 MHz band to the RMS power in a 1 MHz band to less than 30 dB.[14]

To better understand TABLE 1 please look at the results for the Terminal Doppler Weather Radar (TDWR), which shows that a UWB device with an EIRP in the 5600-5650 MHz band of -41.3 dBm/MHz (RMS) could operate out-of-doors without exceeding the TDWR's protection criteria at heights of 2 meters or less with no geographic restriction. Moreover, a UWB device at 2 meters would require an in-band EIRP of -35 dBm/MHz (RMS) or greater to exceed the TDWR's protection criteria. The entry for the Air Route Surveillance Radar (ARSR-4), however, shows that a UWB device at a height of 2 meters with an EIRP of -41.3 dBm/MHz (RMS) in the 1240-1370 MHz band would have to stay about 6 km away to meet the radar's protection criterion or reduce its in-band EIRP to about -61 dBm/MHz (RMS). Please note also that TABLE 1 shows also that if UWB devices were to operate in the same horizontal plane as the TDWR or ARSR-4 antennas (see the columns labeled UWB Ht = 30 m), then the separation distance would have to increase to 6 km for the TDWR and over 15 km for the ARSR-4, or the in-band EIRPs would have to decrease to -63 dBm/MHz (RMS) for the TDWR and -82 dBm/MHz (RMS) for the ARSR-4.

TABLE 1
Summary of Assessment of Effects of UWB Devices on Federal Systems
For Average Power Interactions[Note]

SYSTEM	Freq. (MHz)	UWB PRF (MHz)	UWB Height 2 Meters				UWB Height 30 Meters			
			Non-Dithered		Dithered		Non-Dithered		Dithered	
			Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria

[14] The 30 dB value was chosen for illustrative purposes and does not suggest an NTIA policy position. This 30 dB value would limit the PRF of UWB non-dithered devices to values greater than 3.5 MHz, and of UWB dithered devices to values greater than 12.5 MHz as shown in Appendix D.

TABLE 1
Summary of Assessment of Effects of UWB Devices on Federal Systems For Average Power Interactions[Note]

SYSTEM	Freq. (MHz)	UWB PRF (MHz)	UWB Height 2 Meters				UWB Height 30 Meters			
			Non-Dithered		Dithered		Non-Dithered		Dithered	
			Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/M-Hz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/M-Hz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/M-Hz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/M-Hz (RMS) EIRP to Meet Protect. Criteria
Distance Measuring Equipment (DME) Interrogator Airborne Rcvr	960-1215	□0.1 □1	-46 -47	0.08 0.09	-46 -46	0.08 0.08				
DME Ground Transponder Rcvr	1025-1150	□0.1 □1	-63 -64	0.26 0.29	-63 -63	0.26 0.26	-56 -57	0.26 0.29	-56 -56	0.26 0.26
Air Traffic Control Radio Beacon Sys (ATCRBS) Air Transponder Rcvr	1030	□1 □10	-44 -37	0.02 NA	-44 -44	0.02 0.02				
ATCRBS Gnd Interrogator Rcvr	1090	□1 □10	-31 -21	NA NA	-31 -31	NA NA	-45 -36	0.27 NA	-45 -45	0.27 0.27
Air Route Surveil. Radar (ARSR-4)	1240-1370	□0.1 □0.1	-60 -61	5.5 6.1	-60 -60	5.5 5.5	-80 -82	>15 >15	-80 -80	>15 >15
Search & Rescue Sat. (SARSAT) Ground Station Land User Terminal (LUT)	1544-1545	□0.1 □1	-68 -69	2.9 3.1	-68 -68	2.9 2.9	-65 -66	5.5 6.1	-65 -65	5.5 5.5
Airport Surveillance Radar (ASR-9)	2700-2900	□0.1 □1	-44 -46	0.8 1.1	-44 -44	0.8 0.8	-64 -66	1.3 1.5	-65 -65	1.3 1.3
Next Gen Weather Radar (NEXRAD)	2700-2900	□0.1 □1	-39 -42	NA 1.4	-39 -39	NA NA	-73 -76	5.8 7.9	-73 -73	5.8 5.8
Maritime Radars	2900-3100	□1 □10	-56 -50	1.2 0.6	-56 -56	1.2 1.2	-57 -51	1.2 0.6	-57 -57	1.2 1.2
FSS Earth Station (20□ Elevation)	3700-4200	□1 10 □100	-36 -26 -20	NA NA NA	-36 -36 -36	NA NA NA	-42 -32 -26	.20 NA NA	-42 -42 -42	.20 .20 .20
FSS Earth Station (5□ Elevation)	3700-4200	□1 10 □100	-51 -41 -35	0.60 NA NA	-51 -51 -51	0.60 0.63 0.63	-77 -67 -61	1.0 0.6 0.4	-77 -77 -77	1.0 1.0 1.0

TABLE 1
Summary of Assessment of Effects of UWB Devices on Federal Systems For Average Power Interactions[Note]

SYSTEM	Freq. (MHz)	UWB□PRF□(MHz)	UWB Height 2 Meters				UWB Height 30 Meters			
			Non-Dithered		Dithered		Non-Dithered		Dithered	
			Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/M-Hz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/M-Hz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/M-Hz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/M-Hz (RMS) EIRP to Meet Protect. Criteria
CW Radar Altimeters at minimum altitude	4200-4400	□0.1 □1	25 14	NA NA	25 14	NA NA				
Pulsed Radar Altimeters at Minimum Altitude	4200-4400	□1 10 □10	14 14 14	NA NA NA	14 14 14	NA NA NA				
Microwave Landing System	5030-5091	□0.1 □1	-45 -54	0.07 0.16	-45 -45	0.07 0.07				
Terminal Doppler Wx Radar (TDWR)	5600-5650	□1 □10	-35 -35	NA NA	-35 -35	NA NA	-63 -63	6.0 6.0	-63 -63	6.0 6.0

Note: (1) The calculations were made at UWB PRF Values of, 0.001, 0.01, 0.1, 1, 10, 100, and 500 MHz. When the distance values and Maximum EIRP values were the same for a range, they were grouped together to save space in the table. Thus, for the first row, the calculations for PRF values of 0.001, 0.01, and, 0.1 MHz were the same and are shown in the row labeled □0.1 MHz, while the calculations for 1, 10, 100, and 500 MHz were the same and are shown in the row labeled □1 MHz. (2) The shaded areas represent implausible scenarios where the UWB and aircraft would be at the same altitude (i.e., a collision course). (3) The symbol NA indicates that the maximum calculated EIRP never exceeded -41.3 dBm/MHz (RMS).

TABLE 2 shows that if the receiver performance degradation to digital Earth terminals is related to the peak power rather than the average power, separation distances or additional losses would have to increase to meet the protection criteria established for those receivers.

TABLE 2
Summary of Assessment of Effects of UWB Devices on Federal Systems For Peak Power Interactions with Digitally Modulated Systems[Note]

SYSTEM	Freq. (MHz)	UWB PRF (MHz)	UWB Height 2 Meters				UWB Height 30 Meters			
			Non-Dithered		Dithered		Non-Dithered		Dithered	
			Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria
Search & Rescue Sat. (SARSAT) Ground Station Land User Terminal	1544-1545	0.001	-104	>15	-104	>15	-101	>15	-101	>15
		0.01	-94	12.0	-94	12.0	-91	>15	-91	>15
		0.1	-84	7.3	-84	7.3	-81	>15	-81	>15
		1	-74	4.2	-74	4.2	-71	11.3	-71	11.4

TABLE 2
Summary of Assessment of Effects of UWB Devices on Federal Systems For Peak Power Interactions with Digitally Modulated Systems[Note]

SYSTEM	Freq. (MHz)	UWB PRF (MHz)	UWB Height 2 Meters: Non-Dithered: Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	UWB Height 2 Meters: Non-Dithered: MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	UWB Height 2 Meters: Dithered: Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	UWB Height 2 Meters: Dithered: MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	UWB Height 30 Meters: Non-Dithered: Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	UWB Height 30 Meters: Non-Dithered: MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria	UWB Height 30 Meters: Dithered: Max. EIRP to Meet Protect. Criteria (dBm/MHz (RMS))	UWB Height 30 Meters: Dithered: MinSep.(km) for -41.3 dBm/MHz (RMS) EIRP to Meet Protect. Criteria
(LUT)		□10	-69	3.1	-68	2.9	-66	6.1	-65	5.4
FSS Earth Station (20□ Elevation)	3700-4200	0.001	-89	6.6	-89	6.6	-95	>15	-95	>15
		0.01	-79	3.9	-79	3.9	-85	>15	-85	>15
		0.1	-69	2.2	-69	2.2	-75	5.3	-75	5.3
		1	-59	1.2	-59	1.2	-65	1.7	-65	1.7
		10	-39	NA	-50	0.5	-45	0.25	-55	0.6
		100	-20	NA	-40	NA	-26	NA	-45	0.25
		500	-20	NA	-36	NA	-26	NA	-42	.20
FSS Earth Station (5□ Elevation)	3700-4200	0.001	-104	12.3	-104	13.2	-130	>15	-130	>15
		0.01	-94	8.4	-94	8.4	-120	>15	-120	>15
		0.1	-84	5.1	-84	5.1	-110	>15	-110	>15
		1	-74	3.0	-74	3.0	-100	10.1	-100	10.2
		10	-54	1.0	-64	1.7	-80	1.3	-90	3.3
		100	-35	NA	-54	1.0	-61	0.44	-80	1.3
		500	-35	NA	-51	0.6	-61	0.44	-77	1.0

Note: (1) The calculations were made at UWB PRF Values of, 0.001, 0.01, 0.1, 1, 10, 100, and 500 MHz. When the distance values and Maximum EIRP values were the same for a range, they were grouped together to save space in the table. Thus, for the LUT the calculations for 10, 100, and 500 MHz were the same and are shown in the row labeled □10 MHz. (2) The shaded areas are for PRF values that would result in peak-to-average power levels greater than 30 dB.

3.3.2 Results: Aggregate Emitters

NTIA examined the implications of possible aggregate interference from UWB devices and developed a number of findings, both general and specific. NTIA developed the UWBRings computer model for this study to calculate effectively aggregate interference levels in a given receiver under a variety of conditions. The model is based upon two fundamental assumptions – that the UWB emitters are uniformly distributed geographically and that the average power received from each emitter adds linearly.

NTIA validated both the aggregate interference assumptions and the methodology through two steps. First, from a limited number of measurements using UWB simulators, NTIA found that the received average (RMS) power from two identical UWB emitters is approximately twice that from a single UWB emitter, in agreement with the linear addition assumption. These results logically extend to an arbitrarily large number of UWB emitters. Second, NTIA examined four other aggregate interference methodologies described in the literature and found that all yielded results quite similar (within 2 dB) to those derived from the NTIA UWBRings model for a variety of hypothetical UWB scenarios. The UWBRings model, however, is unique in its ability to effectively consider various modes of radio propagation and three-dimensional receiver antenna patterns, both being key factors for aggregate studies.

Results of these studies show that received aggregate average (RMS) power from a uniform distribution of identical UWB emitters varies directly with the UWB EIRP, UWB emitter density, and number of active transmitters (transmitter activity factor). These results show that under ideal radio propagation conditions, *i.e.*, with no man-made or natural obstructions, aggregate interference levels from UWB devices can exceed that from a single emitter at densities as low as a few emitters per square kilometer or more than 1000 emitters per square kilometer, depending on the specific receiver.

While some studies of aggregate effects filed in response to the FCC's UWB NPRM used a comparable analytic methodology to that used by NTIA, the studies typically compared the aggregate interference levels to that from a single UWB emitter situated at an unrealistically close distance to the receiving antenna. As a result, conclusions from these studies are misleading.

NTIA also examined additional factors that tend to mitigate aggregate interference as an issue, including higher propagation losses associated with irregular terrain, urban and suburban environments, and building penetration, or antenna directivity. A possible methodology is described for applying these factors.

3.3.3 Interpretation of Results

This NTIA study shows that operation of UWB devices is feasible in portions of the spectrum between about 3.1 and 5.650 GHz at heights of about 2 meters with some operating constraints.[15] Operations of UWB devices below 3.1 GHz will be quite challenging and any policy developed will need to consider the results of the analyses of interactions of GPS and UWB systems underway at NTIA and other facilities. RTCA notes that the NTIA analysis shows UWB compatibility problems exist under certain circumstances with FSS earth stations, MLS and Terminal Doppler Weather Radar which all operate between 3.1 and 5.65 GHz.

While the study showed that aggregate UWB interference can be a significant factor to receiving systems under ideal propagation conditions, a number of mitigating factors must also be taken into account that may reduce or eliminate these aggregate affects. There are also numerous mitigating factors that could relax restrictions on operation of UWB devices below 3.1 GHz. Although these are discussed in the report, the development of suitable policy restrictions and guidance for both aggregate and single emitter interference is beyond the scope of this report and must await the results of the ongoing UWB measurement programs, including those of the GPS.

[15] UWB operations at greater heights between 3.1 and 5.650 GHz and near low elevation angle 4 GHz FSS earth stations may have to be constrained with respect to such factors as spectral output power, amount of operating time, and quantity of units operating in any area.

3.4 NTIA GPS RFI Susceptibility Tests and Analysis

The study described in this section was undertaken by the NTIA to assess the electromagnetic compatibility (EMC) of the proposed UWB transmitting devices with GPS receivers. The primary objective of the NTIA study was to define maximum allowable UWB effective isotropic radiated power (EIRP)[16] levels that can be tolerated by GPS receivers, when used within various operational applications, without causing degradation to GPS operations.

3.4.1 Measurement Approach

A two-part approach consisting of both a measurement and an analysis component was adopted for this assessment. NTIA's Institute for Telecommunication Sciences (ITS) measured the interference susceptibility of various GPS receiver architectures to a set of UWB waveforms.[17] Utilizing the measured GPS receiver interference susceptibility levels, analyses were performed by the NTIA Office of Spectrum Management (OSM) for various operational scenarios to determine the maximum allowable UWB EIRP level that can be tolerated by GPS receivers before performance degradation is realized.

3.4.1.1 GPS Receivers Selected for Testing

The NTIA study attempted to measure across the space of GPS receiver architectures. One receiver from each of three basic GPS receiver architectures was identified for inclusion in the measurements. The receiver architectures represented are: C/A-code tracking receivers (which make up a significant share of the civil GPS receivers in use today), semi-codeless receivers (used in low-dynamic applications requiring high precision), and C/A-code tracking receivers employing multiple, narrowly-spaced correlators to enhance accuracy and mitigate the effects of multipath. In addition to these three technologies, a TSO-C129a compliant receiver is to be tested.

3.4.1.2 UWB Signals Examined

NTIA identified 32 UWB signal permutations for examination with respect to their interference potential to GPS receivers. For each of four pulse repetition frequencies (PRFs);100 kHz, 1 MHz, 5 MHz, and 20 MHz, eight distinct UWB waveforms were generated by combining four modulation types (constant PRF, On-Off Keying (OOK), 2% relative dither, and 50% absolute dither) and two states of gating (100% and 20%). For the measurements performed in this study, the gated UWB signal utilized a scheme where a burst of pulses lasting 4 milliseconds (ms) was followed by a 16 ms period when no pulses were transmitted. UWB pulse width of 0.5ns was used for all single-entry measurements. A combination of 0.5 and 0.245 ns pulse widths was used in the aggregate testing. All UWB waveforms were characterized by measured average power in the GPS band. NTIA has stated that the data collected from these measurements are applicable only to the UWB signal permutations that were considered in this assessment, and that no attempt should be made to extrapolate this data beyond these particular UWB parameters.

[16] The computation of EIRP is in terms of the average power of the UWB signal for all cases considered in this section. This average power is based on root-mean-square (RMS) voltage.
[17] NTIA 01-384

3.4.1.3 Performance Criteria Used

The two performance criteria examined were the "break-lock" and "reacquisition" thresholds. Break-lock threshold refers to the UWB power level causing loss of signal lock between the GPS receiver and a GPS satellite. The reacquisition threshold is defined as the UWB power level that results in an abrupt increase in reacquisition time.

3.4.1.4 Measurements Performed

ITS performed closed system (conducted) measurements to assess the potential impact to each of the GPS receivers from both a single UWB transmitter (single entry) interaction and from a multiple UWB transmitter (aggregate) interaction. To examine the applicability of the conducted measurements, the effects of the GPS antenna on the radiated signals within the frequency band of interest were measured. Measurements were performed wherein the UWB signal was radiated and received within an anechoic chamber to prevent outside interference sources from affecting the results. Amplitude probability distribution (APD) measurements were also performed for each of the UWB signal permutations considered in this effort, to aid in classifying the UWB signals. APD gives a measure of the signal characteristics within the GPS receiver bandwidth.

The data collected from the measurements were used to calculate the maximum allowable EIRP that can be emitted from a UWB transmitter without exceeding the measured interference susceptibility level. A source-path-receiver analysis was performed to calculate these maximum allowable EIRP levels for both a single UWB transmitter-to-GPS receiver interaction and for the case of an aggregate of UWB transmitters-to-GPS receiver interaction. The operational scenarios considered in the NTIA study are discussed in Section 3.4.3 below.

3.4.2 Analysis Approach

The measurements performed by the ITS define the interference threshold of a UWB transmission system as a function of the UWB signal parameters (e.g., power, PRF, gating, modulation). The interference threshold is measured at the input of the GPS receiver and is used in the analysis for each specific GPS/UWB operational scenario to calculate the maximum allowable emission level at the output of the UWB device antenna. The following paragraphs describe the analysis method used.

3.4.2.1 Link Analysis Equation

The maximum allowable emission level from the UWB device is based on an EIRP limit. The EIRP is the power supplied to the antenna of the UWB device multiplied by the relative antenna gain of the UWB device in the direction of the GPS receiver. The maximum allowable EIRP is computed using the following equation:

$$EIRP_{max} = I_T - G_r + L_p - L_{mult} - L_{allot} - L_{man} + L_{AF} + L_{BA} - L_{safety} \tag{1}$$

where:

$EIRP_{max}$ is the maximum allowable EIRP of the UWB device (dBW or dBW/MHz);
I_T is the interference threshold of the UWB signal at the input of the GPS receiver (dBW or dBW/MHz);

G_r is the gain of the GPS antenna in the direction of the UWB device (dBi);
L_p is the radiowave propagation loss (dB);
L_{mult} is the factor to account for multiple UWB devices (dB);
L_{allot} is the factor for interference allotment (dB);
L_{man} is the factor to account for manufacturer variations in GPS receivers (dB);
L_{AF} is the activity factor of the UWB device (dB);
L_{BA} is the building attenuation loss (dB);
L_{safety} is the aviation safety margin (dB).

The following paragraphs explain each of the technical factors used in the analysis.

3.4.2.2 Link Equation Factors

UWB Interference Threshold (I_T)

The UWB interference threshold referenced to the input of the GPS receiver is obtained from the single source interference susceptibility measurements performed by ITS as discussed in the NTIA OSM Report Section 2.1.1 (Tables 2-1 and 2-2)[18]. Adjustments are made to the measured interference susceptibility levels to compute the UWB interference threshold. As discussed in OSM Report Section 3.3 (Tables 3-13 and 3-14)[19], the adjustments made to the measured interference susceptibility levels are based on the individual UWB signal structure.

GPS Receiver Antenna Gain (G_r)

The GPS antenna gain model used in this analysis is provided in Table 3.3. The antenna gain used is based on the position of the UWB device with respect to the GPS antenna and is determined from the GPS/UWB operational scenario under consideration.

Table 3.3. GPS Antenna Gain Based on UWB Device Position With Respect to GPS Antenna

Off-axis Angle (Measured with Respect to the Horizon)	GPS Antenna Gain (dBi)
-90 degrees to -10 degrees	-4.5
-10 degrees to 10 degrees	0
10 degrees to 90 degrees	3

The off-axis angle measured with respect to the horizon is computed by:

$$\alpha = \tan^{-1} [(h_{UWB} - h_{GPS})/D] \qquad (2)$$

where

α is the angle measured with respect to the horizon (degrees);
h_{UWB} is the UWB device antenna height (m);
h_{GPS} is the GPS receiver antenna height (m);

[18] NTIA 01-45, Sec. 2.1.1
[19] NTIA 01-45, Sec. 3.3, pp. 3-26, -27

D is the horizontal separation between the GPS receiver and UWB device antennas (m).

RTCA notes that this antenna gain model may not be applicable for applications involving ground-plane mounted antennas such as in aviation.

Radiowave Propagation Model (L_p)

The radiowave propagation loss is computed using the minimum distance separation between the GPS receiver and the UWB device as defined by the GPS/UWB operational scenario. The radiowave propagation model used also depends on the GPS/UWB operational scenario. By definition, "free-space" assumes that there is a line-of-sight (LOS) path between the UWB device and the GPS receiver. The radiowave propagation model described by the free-space loss equation is :

$$L_p = 20 \text{ Log } F + 20 \text{ Log } D_{min} - 27.55 \qquad (3)$$

where:

L_p is the free-space propagation loss (dB);
F is the frequency (MHz);
D_{min} is the minimum distance separation between the GPS receiver and UWB device (m).

As a result of antenna heights and terrain conditions, free-space conditions may not exist. There is a phenomenon referred to as the propagation loss breakpoint, which consists of a change in the slope of the propagation loss with distance at a radial distance from the transmitter. It is caused by the reflection of the transmitted signal. This multipath signal interferes with the direct path signal and usually occurs only in areas with clear LOS and ground reflection paths.

For the frequency range of interest, the propagation loss changes by 20 dB/decade (i.e., free-space loss) close to the transmitter, and by 40 dB/decade after the propagation loss breakpoint occurs. The propagation loss breakpoint radius from the transmitter, R_b, is calculated using the formula [20]:

$$R_b = 2.3 \times 10^{-6} F (h_t h_r) \qquad (4)$$

where:

R_b is the propagation loss breakpoint radius (mi);
F is the frequency (MHz);
h_t is the UWB device antenna height (ft);
h_r is the GPS receiver antenna height (ft).

When the minimum distance separation between the UWB device and the GPS receiver is less than R_b, the free-space propagation model should be used. When the minimum distance separation between the UWB device and the GPS receiver is greater than R_b, a propagation model that takes into account non-LOS conditions should be used.

Multiple UWB Devices (L_{mult})

The GPS/UWB operational scenario determines whether single or multiple UWB devices should be considered. The factor for multiple UWB devices was obtained from the multiple source

[20] E. N. Singer, *Land Mobile Radio Systems* (Second Edition) at 194.

(aggregate) measurements performed by ITS. OSM Report Section 2.1.2[21] discusses the multiple UWB devices measurement results. Based on the multiple source measurements, the factor to be included in the analysis for multiple UWB devices will depend on whether the interference effect has been characterized as being pulse-like, CW-like, or noise-like. The exception is the en-route navigation operational scenario, where it is assumed that there are a large enough number of UWB devices, such that independent of the individual UWB signal parameters, the aggregate effect causes noise-like interference.

As discussed in OSM Report Section 2.2.3, signals that were characterized as being pulse-like for single UWB device interactions were characterized as being noise-like when multiple UWB devices are considered. The occurrence of the transition from pulse-like to noise-like interference was verified in Measurement Case V[22]. The number of UWB devices required for this transition to occur depends on the PRF. For the 1 MHz PRF signals, the measurements show that three signals are required for the transition to occur. In the case of the 100 kHz PRF signals, the number of UWB devices necessary for the transition to occur will be much larger than the number of UWB devices under consideration in the operational scenarios. Based on the measurement results, a factor for multiple UWB devices is not included in this analysis for signal permutations that have been characterized as causing pulse-like interference with a PRF of 100 kHz.

[The interference effect for UWB signals that have been characterized as being CW-like is attributed by NTIA to the single interfering CW line that is coincident with a dominant C/A code line.] This was discussed in Section [2.2.3], and confirmed in Measurement Cases III and IV. Multiple UWB signals that are characterized as causing CW-like interference, do not add to determine the effective interfering signal power. RTCA notes that this conclusion is based solely on the break-lock threshold measurements. A large number of UWB devices producing spectral lines would be necessary before there is a transition to a noise-like interference effect. This transition from CW-like to noise-like will not occur with the number of UWB devices under consideration in the operational scenarios. Based on the measurement results, a factor for multiple UWB devices is not included in this analysis for UWB signal permutations that have been characterized as causing CW-like interference.

UWB signals permutations with PRFs of 1 MHz, 5 MHz, and 20 MHz that have been characterized as being pulse-like, will transition to noise-like interference as the number of UWB devices is increased. This is discussed in Section [2.2.3] and verified in Measurement Case V. For these UWB signals permutations, a factor of 10 Log (number of UWB devices) is included in the analysis.

As discussed in Section [2.2.3], and verified in Measurement Case I and II, if the individual signals cause an interference effect that is noise-like, the interference effect of the multiple noise-like signals is noise-like. Based on the measurement results, for UWB signal permutations that have been characterized as causing noise-like interference, a factor of 10 Log (number of UWB devices) is included in the analysis.

[21] NTIA 01-45, Sec. 2.1.2, pg. 2-5
[22] NTIA 01-45, Table 2-3, pg. 2-5.

Interference Allotment (L_{allot})

Several potential sources of interference to GPS L1 receivers have been identified. These include but are not limited to: 1) adjacent band interference from mobile satellite service (MSS) handsets; 2) harmonics from television transmitters; 3) adjacent band interference from super geostationary (super GEO) satellite transmitters[23]; 4) spurious emissions from 700 MHz public safety base, mobile, and portable transmitters; and 5) spurious emissions including harmonics from 700 MHz commercial base, mobile, and portable transmitters. Multiple sources of interference, which might individually be tolerated by a GPS receiver, may combine to create an aggregate interference level (e.g., noise and emissions) that could prevent the reliable reception of the GPS signal. In the GPS/UWB operational scenario, a percentage of the total allotment for all interfering sources will be attributed specifically to UWB devices.

In this analysis the percentage of the total interference allotment that is attributed to UWB devices is dependent on the minimum distance separation between the GPS receiver and the UWB device. The minimum distance separation is established by each operational scenario. For operational scenarios where the minimum distance separation is small (e.g., on the order of several meters), the UWB device is expected to be the dominant source of interference, and 100% of the total interference is allotted to UWB devices. For operational scenarios where a larger distance separation exists, there is a greater likelihood that other interfering sources will contribute to the total interference level at the GPS receiver. In these operational scenarios, 50% of the total interference is allotted to UWB devices. That is, one half of the total allowable interference is allotted to UWB and the other half is allotted to all other interfering sources combined. For the aviation operational scenarios, larger geographic areas are visible to a GPS receiver onboard an aircraft. This larger field of view will increase the number of interfering sources that can contribute to the total interference level at the receiver. In the aviation operational scenarios, 10% of the total interference is allotted to UWB devices. The factor for UWB device interference allotment is computed from 10 Log(UWB interference allotment ratio). For example, if the UWB device interference allotment is 50% (a ratio of 0.5), a 3 dB factor is included in the analysis.

GPS Receiver Variation (L_{man})

The ITS measurement effort did not consider multiple samples of each model of GPS receiver. Therefore, it is not possible to determine if there is a statistical variation in the performance of GPS receivers. As an estimate, a 3 dB factor has been included to take into account likely variations among GPS receivers of the same model as well as variations in GPS receivers from different manufacturers.

UWB Device Activity Factor (L_{AF})

The activity factor represents the percentage of time that the UWB device is actually transmitting. For example, a UWB device that is transmitting continuously will have an activity factor of 100%, no matter what PRF, modulation, or gating percentage is employed. The activity factor is only applicable when multiple UWB devices are considered in the GPS/UWB operational scenario. Some UWB devices are expected to have inherently low activity factors such as those that are manually activated with a trigger or "deadman" switch. Others will likely

[23] Super GEOs are geostationary earth orbiting satellites that are designed to employ a high transmit power to communicate with mobile handsets.

have high activity factors such as a UWB local area network. Since it was not possible to estimate practical values of activity factors for each potential UWB application, an activity factor of 100% (a ratio of 1) was used in all of the operational scenarios considered in this analysis. Thus, the activity factor used is set equal to 0 dB (i.e., 10 Log (1)).

Building Attenuation (L_{BA})

For GPS/UWB operational scenarios that consider the use of UWB devices operating indoors a building attenuation factor is included. ITS has conducted building attenuation loss measurements at 912, 1920, and 5990 MHz.[24] The measurements were performed for different buildings representing typical residential and high rise office construction. Based on the results of these measurements, whenever the UWB device is considered to be operating indoors an average building attenuation of 9 dB is used.

Aviation Safety Margin (L_{safety})

When the GPS/UWB operational scenario involves aviation applications using GPS (e.g., en-route navigation and non-precision approach landing) a safety margin is appropriate. The aviation safety margin takes into account sources of radio-frequency interference that are real but not quantifiable (e.g., multipath). A safety margin of 6 dB is included for GPS receivers used in aviation applications.[25] RTCA notes that material has been presented indicating that a safety margin is appropriate for non-aviation, safety-related scenarios.

[GPS Receiver Architecture] Use Material

Interference susceptibility measurements were performed on the C/A code and semi-codeless GPS receiver architectures. The GPS receiver architecture examined in the analysis are different depending upon the operational scenario under consideration. In those where the GPS receivers are used in moving [vehicles] (terrestrial, maritime, and railway), the C/A code architecture was used. In the surveying operational scenario, where the GPS receiver is not moving (or moving very slowly), the semi-codeless receiver architecture was used. For the en-route navigation and non-precision approach landing operational scenarios, a TSO-C129a compliant GPS receiver will be used.[26]

3.4.3 Development of the GPS/UWB Operational Scenarios

As discussed in the previous section, the measurements of the maximum tolerable interference threshold at the input to the GPS receiver is used in this analysis to compute the maximum allowable EIRP of the UWB device. The operational scenario is necessary to relate the interference level at the input of the GPS receiver to the output of the UWB device. The GPS/UWB operational scenarios establish: the minimum distance separation between the GPS receiver and the UWB device; the appropriate antenna coupling; the applicable radio wave

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[24] National Telecommunications and Information Administration, Institute for Telecommunication Sciences, NTIA Report 95-325, Building Penetration Measurements From Low-height Base Stations at 912, 1920, and 5990 MHz, at 43.

[25] ITU-R M.1477 at Annex 5.

[26] The measurement results of the C/A code TSO-C129a receiver are not available at this time. The analysis results that are presented are based on the measurements for the non-aviation C/A code receiver. Although not aviation certified, it is representative of the architecture used by aviation in these applications. When data on the TSO-C-129a receiver is available, the results of the analysis may be revised.

propagation model; whether single or multiple UWB devices should be considered; and any other scenario specific factors (e.g., building attenuation and aviation safety margin).

Five categories of GPS applications are considered in the development of the GPS/UWB operational scenarios: terrestrial, maritime, railway, surveying, and aviation (en route and nonprecision approach). The operational scenario proposals also considered several UWB device applications. The UWB device applications include: embedded functions in a mobile phone, wireless local area networks, and short-range communication systems. The specific operational scenarios included GPS receivers used in the following applications[27]:

- Public Safety (E-911 embedded in a cellular phone);
- Public Safety (emergency response vehicles);
- Geographic Information Systems;
- Precision Machine Control;
- Maritime (constricted waterway navigation, harbor navigation, docking and lock operations;)
- Railway (positive train control);
- Surveying;
- Aviation (en-route navigation and non-precision approach landings).

In addition to these specific GPS/UWB operational scenarios, NTIA proposed a general operational scenario for GPS receivers used for terrestrial applications that considered multiple UWB device interactions. None of the scenarios investigated considered devices containing both UWB and GPS. Also, UWB and GPS both operating indoors was not considered by NTIA, but is discussed elsewhere in this report.[28]

3.4.4 NTIA Measurement and Analysis Results

3.4.3.1 Measurement Results Discussion

The single entry measurement results indicate that both the C/A-code tracking GPS receiver and the semi-codeless GPS receiver demonstrate a degree of tolerance to all of the UWB 100 kHz PRF signal permutations examined. For the thirteen scenarios considered in this assessment, aggregate effects were deemed by NTIA not to be a concern with respect to those UWB waveforms with a PRF of 100 kHz. {RTCA notes that above a certain UWB device density for the enroute aviation scenario even 100 kHz PRF UWB emitters can cause noise-like interference at an unacceptable level when operating at Part 15 limits. [Ed. note: Fig. 3-37, 3-38 are both for indoor UWB devices. The calculation in the report appendix apparently used proper factors]. RTCA also notes the en route scenario only considered off-aircraft ground sources with a minimum separation distance of 1,000 feet, and did not consider potential on-board RFI sources.} When the PRF was increased to 1 MHz, the C/A-code receiver began to show continuous wave (CW)-like interference susceptibility to the unmodulated UWB signal permutations at low power levels. When the PRF was increased to 5 MHz and then to 20 MHz, CW-like interference effects to the C/A-code receiver were observed to be more prevalent.

[27] All of the documents from the public meetings are available upon request from the NTIA Office of Spectrum Management or from the NTIA website.

[28] RTCA Second Interim Report, Section 4.3.1

The measurements also show that dithering of the UWB pulses in the time domain, using the techniques considered in the NTIA assessment, can be effective in spreading the spectral lines in the frequency domain, making the effect of the signal appear more noise-like. {RTCA notes that the effectiveness of spectral line-spreading is quite complex[[29]].} The GPS C/A-code receiver showed approximately 10 dB less susceptibility to these noise-like UWB signals as compared to those UWB signals deemed to have a CW-like effect. For PRFs of 1 MHz, 5 MHz, and 20 MHz, some of the UWB waveforms caused an effect similar to low duty cycle pulsed interference, to which the GPS C/A-code receiver is relatively tolerant. However, the multiple-entry (aggregate) measurements indicate that this advantage is lost when a multiple of as few as three of these UWB signals with equivalent power levels at the GPS receiver input are considered in aggregation. The aggregate measurements also verify that when multiple noise-like UWB signals are considered with equivalent power levels at the GPS receiver input, the effective aggregate signal level in the receiver intermediate frequency (IF) bandwidth is determined by adding the average power of each of the UWB signals.

For all of the UWB signal permutations employing PRFs of 1, 5, and 20 MHz, the semi-codeless GPS receiver measured in the NTIA assessment showed susceptibility similar to what was measured in the broadband noise interference baseline. RTCA notes that this is because the semi-codeless technique spreads the interference using the P-code, rather than the C/A code. The semi-codeless GPS receiver was more susceptible than the C/A-code receiver to noise-like interference.

3.4.3.2 Analysis Results

In the analysis component of the study, NTIA determined the maximum allowable EIRP level for the different UWB signal permutations using the operational scenarios. The results of the analysis are summarized in Tables 3.4 through 3.7.[30] Each table corresponds to a UWB PRF examined in the analysis. Tables 3.4 through 3.7 also include a comparison of the computed maximum allowable EIRP level with the current Part 15 level of -71.3 dBW/MHz. When the interference effects are classified as pulse-like or noise-like, the maximum allowable EIRP spectral density can be directly compared to the current Part 15 level. When the interference effect is classified as CW-like, the maximum allowable EIRP level can be directly compared to the Part 15 level, only if it is assumed that there is a single spectral line in the measurement bandwidth. As shown in Tables 3.4 through 3.7, the results of the analysis indicates that the maximum allowable EIRP necessary to satisfy the measured performance thresholds of the GPS receivers considered in this study is very dependent on the UWB signal structure.

3.4.5 NTIA Conclusions

The following general conclusions were drawn by NTIA based on the findings of the study:[31]

1) The GPS receiver performance thresholds measured within this study are consistent with the interference protection limits developed within national and international GPS study groups.

[29] See NTIA report 01-384, Appendix C, page C-3.
[30] NTIA 01-45 at Executive Summary.
[31] NTIA 01-45 at pg. 4-27.

2) When multiple noise-like UWB signals with equivalent power levels at the GPS receiver input are considered, the effective aggregate signal level in the receiver IF bandwidth is determined by adding the average power of each of the UWB signals.

3) Within the limitations of this study (i.e., the available number of UWB signal generators), it was found that when multiple CW-like UWB signals are considered, the effective aggregate interference effect to a C/A-code GPS receiver is the same as that of a single CW-like signal. The interference mechanism is a result of the alignment of a UWB spectral line with a GPS C/A-code line. [ref. Previous RTCA comment]

4) The CW-like interference effect is not applicable to the semi-codeless receiver examined when operating in the dual frequency mode. RTCA notes that this finding is not consistent with the need for C/A tracking to aid the P(Y) tracking, and that further examination is desired.

5) A GPS antenna does not offer any additional attenuation to that portion of a UWB signal within the GPS frequency band.

6) For those UWB signals examined with a PRF of 100 kHz, maximum permissible EIRP levels between -73.2 and -26.5 dBW/MHz are necessary to ensure EMC with the GPS applications defined by the operational scenarios considered within this study. [ref. Previous RTCA comment].

7) For those UWB signals examined with a PRF of 1 MHz, the maximum allowable EIRP levels necessary to achieve EMC with the GPS receiver applications considered in this study range from -70.2 to -104.3 dBW for the CW-like (unmodulated) UWB waveforms, and -57.6 to -91.6 dBW/MHz for the noise-like (modulated and/or dithered) UWB waveforms.

8) For those UWB signals examined with a PRF of 5 MHz, the maximum allowable EIRP levels necessary to ensure EMC with the GPS receiver applications considered in this study range from -70.7 to -106.1 dBW for the CW-like (non-dithered) UWB waveforms, and from -49.6 to -97.6 dBW/MHz for the noise-like (dithered) UWB waveforms.

9) For those UWB signals examined with a PRF of 20 MHz, the maximum allowable EIRP levels required to ensure EMC with all of the GPS receiver applications considered in this study range from -71.0 to -106.9 dBW for the CW-like (non-dithered) UWB waveforms, and from -60.0 to -98.6 dBW/MHz for the noise-like (dithered) UWB waveforms.

Table 3.4. Summary of Analysis Results (PRF = 100 kHz)

Operational Scenario Description					UWB Signal Characteristics			GPS Receiver Architecture	Classification of Interfering Signal	Maximum Interference Threshold (dBW/MHz)	Maximum Allowable EIRP (dBW/MHz)	Comparison with the Current Part 15 Level (dB)
GPS Application	UWB Single	UWB Multiple	UWB Indoor	UWB Outdoor	PRF (MHz)	Gating %	Mod.					
Terrestrial	X			X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-73.2	1.9
Terrestrial		X	X		0.1	100	None	C/A-code	Pulse-Like	-112.6	-57.6	-13.7
Terrestrial		X		X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-62.3	-9
Maritime		X	X		0.1	100	None	C/A-code	Pulse-Like	-112.6	-41.7	-29.6
Maritime		X		X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-48.1	-23.2
Railway		X	X		0.1	100	None	C/A-code	Pulse-Like	-112.6	-56.3	-15
Railway		X		X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-57.8	-13.5
Surveying	X			X	0.1	20	2% Rel.	Semi-Codeless	Noise-Like	-138	-81.1	9.8
Surveying		X		X	0.1	20	2% Rel.	Semi-Codeless	Noise-Like	-138	-81.2	9.9
Aviation-NPA		X		X	0.1	100	None	C/A-code	Pulse-Like	-112.6	-52.9	-18.4
Aviation-ER		X	X		Note 1	Note 1	Note 1	C/A-code	Noise-Like	-134.8	-76.6[2]	5.3
Aviation-ER		X		X	Note 1	Note 1	Note 1	C/A-code	Noise-Like	-134.8	-85.6[2]	14.3

Notes: En-Route Navigation (ER), Non-Precision Approach (NPA)
1. In this operational scenario, it is assumed that there is a large enough number of UWB devices such that independent of the individual UWB signal parameters, the aggregate effect causes noise-like interference.
2. This maximum allowable EIRP is based on an assumed density of 200 UWB devices per square kilometer transmitting simultaneously .

Table 3.5. Summary of Analysis Results (PRF = 1 MHz)

Operational Scenario Description					UWB Signal Characteristics			GPS Receiver Architecture	Classification of Interfering Signal	Maximum Interference Threshold[1]	Maximum Allowable EIRP[1]	Comparison with the Current Part 15 Level (dB)
GPS Application	UWB Single	UWB Multiple	UWB Indoor	UWB Outdoor	PRF (MHz)	Gating %	Mod.					
Terrestrial	X			X	1	100	None	C/A-code	CW-Like	-143.7	–104.3	33
Terrestrial	X			X	1	100	2% Rel.	C/A-code	Pulse-Like	-131	-91.6	20.3
Terrestrial		X	X		1	100	None	C/A-code	CW-Like	-143.7	-88.7	17.4
Terrestrial		X	X		1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-85.5	14.2
Terrestrial		X		X	1	100	None	C/A-code	CW-Like	-143.7	-93.4	22.1
Terrestrial		X		X	1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-90.2	18.9
Maritime		X	X		1	100	None	C/A-code	CW-Like	-143.7	-72.8	1.5
Maritime		X	X		1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-69.6	-1.7
Maritime		X		X	1	100	None	C/A-code	CW-Like	-143.7	-79.2	7.9
Maritime		X		X	1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-76	4.7
Railway		X	X		1	100	None	C/A-code	CW-Like	-143.7	-87.4	16.1
Railway		X	X		1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-83.0	11.7
Railway		X		X	1	100	None	C/A-code	CW-Like	-143.7	-88.9	17.6
Railway		X		X	1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-84.5	13.2
Surveying	X			X	1	100	50% Abs.	Semi-Codeless	Noise-Like	-151	-94.1	22.8
Surveying		X		X	1	100	50% Abs.	Semi-Codeless	Noise-Like	-151	-94.2	22.9
Aviation-NPA		X		X	1	100	None	C/A-code	CW-Like	-143.7	-84	12.7
Aviation-NPA		X		X	1	20 & 100	Multiple	C/A-code	Noise-Like	-134.5	-80.8	9.5
Aviation-ER		X	X		Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-76.6[3]	5.3
Aviation-ER		X		X	Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-85.6[3]	14.3

Notes: En-Route Navigation (ER), Non-Precision Approach (NPA)
1. When the interference effect has been classified as pulse-like or noise-like, the value is expressed in units of dBW/MHz. The value is expressed in units of dBW when the interference effect has been classified as CW-like.
2. In this operational scenario, it is assumed that there is a large enough number of UWB devices, such that independent of the individual UWB signal parameters the aggregate effect causes noise-like interference.
3. This maximum allowable EIRP is based on an assumed density of 200 UWB devices per square kilometer transmitting simultaneously.

Table 3.6. Summary of Analysis Results (PRF = 5 MHz)

Operational Scenario Description					UWB Signal Characteristics			GPS Receiver Architecture	Classification of Interfering Signal	Maximum Interference Threshold[1]	Maximum Allowable EIRP[1]	Comparison with the Current Part 15 Level (dB)
GPS Application	UWB Single	UWB Multiple	UWB Indoor	UWB Outdoor	PRF (MHz)	Gating %	Mod.					
Terrestrial	X			X	5	100	None	C/A-code	CW-Like	-145.5	–106.1	34.8
Terrestrial	X			X	5	20	50% Abs.	C/A-code	Pulse-Like	-105	-65.6	-5.7
Terrestrial	X			X	5	100	50% Abs.	C/A-code	Noise-Like	-137	–97.6	26.3
Terrestrial		X	X		5	100	None	C/A-code	CW-Like	-145.5	-90.5	19.2
Terrestrial		X	X		5	100	50% Abs.	C/A-code	Noise-Like	-137	-88	16.7
Terrestrial		X		X	5	100	None	C/A-code	CW-Like	-145.5	-95.2	23.9
Terrestrial		X		X	5	100	50% Abs.	C/A-code	Noise-Like	-137	-92.7	21.4
Maritime		X	X		5	100	None	C/A-code	CW-Like	-145.5	-74.6	3.3
Maritime		X	X		5	100	50% Abs.	C/A-code	Noise-Like	-137	-72.1	0.8
Maritime		X		X	5	100	None	C/A-code	CW-Like	-145.5	-81	9.7
Maritime		X		X	5	100	50% Abs.	C/A-code	Noise-Like	-137	-78.5	7.2
Railway		X	X		5	100	None	C/A-code	CW-Like	-145.5	-89.2	17.9
Railway		X	X		5	100	50% Abs.	C/A-code	Noise-Like	-137	-85.5	14.2
Railway		X		X	5	100	None	C/A-code	CW-Like	-145.5	-90.7	19.4
Railway		X		X	5	100	50% Abs.	C/A-code	Noise-Like	-137	-87.0	15.7
Surveying	X			X	5	20 & 100	50% Abs.	Semi-Codeless	Noise-Like	-151	-94.1	22.8
Surveying		X		X	5	20 & 100	50% Abs.	Semi-Codeless	Noise-Like	-151	-94.2	22.9
Aviation-NPA		X		X	5	100	None	C/A-code	CW-Like	-145.5	-85.8	14.5
Aviation-NPA		X		X	5	100	50% Abs.	C/A-code	Noise-Like	-137	-83.3	12
Aviation-ER		X	X		Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-76.6[3]	5.3
Aviation-ER		X		X	Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-85.6[3]	14.3

Notes: En-Route Navigation (ER), Non-Precision Approach (NPA)
1. When the interference effect has been classified as pulse-like or noise-like, the value is expressed in units of dBW/MHz. The value is expressed in units of dBW when the interference effect has been classified as CW-like.
2. In this operational scenario, it is assumed that there is a large enough number of UWB devices, such that independent of the individual UWB signal parameters the aggregate effect causes noise-like interference.
3. This maximum allowable EIRP is based on an assumed density of 200 UWB devices per square kilometer transmitting simultaneously.

Table 3.7. Summary of Analysis Results (PRF = 20 MHz)

Operational Scenario Description					UWB Signal Characteristics			GPS Receiver Architecture	Classification of Interfering Signal	Maximum Interference Threshold[1]	Maximum Allowable EIRP[1]	Comparison with the Current Part 15 Level (dB)
GPS Application	UWB Single	UWB Multiple	UWB Indoor	UWB Outdoor	PRF (MHz)	Gating %	Mod.					
Terrestrial	X			X	20	20	OOK	C/A-code	CW-Like	-146.3	–106.9	35.6
Terrestrial	X			X	20	20	50% Abs.	C/A-code	Pulse-Like	-135	-95.6	24.3
Terrestrial	X			X	20	100	50% Abs.	C/A-code	Noise-Like	-138	–98.6	27.3
Terrestrial		X	X		20	20	OOK	C/A-code	CW-Like	-146.3	-91.3	20
Terrestrial		X	X		20	100	50% Abs.	C/A-code	Noise-Like	-138	-89	17.7
Terrestrial		X		X	20	20	OOK	C/A-code	CW-Like	-146.3	-96	24.7
Terrestrial		X		X	20	100	50% Abs.	C/A-code	Noise-Like	-138	-93.7	22.4
Maritime		X	X		20	20	OOK	C/A-code	CW-Like	-145	-75.4	4.1
Maritime		X	X		5	100	50% Abs.	C/A-code	Noise-Like	-138	-73.1	1.8
Maritime		X		X	20	20	OOK	C/A-code	CW-Like	-145	-81.8	10.5
Maritime		X		X	20	100	50% Abs.	C/A-code	Noise-Like	-138	-79.5	8.2
Railway		X	X		20	20	OOK	C/A-code	CW-Like	-145	-90	18.7
Railway		X	X		20	100	50% Abs.	C/A-code	Noise-Like	-138	-86.5	15.2
Railway		X		X	20	20	OOK	C/A-code	CW-Like	-145	-91.5	20.2
Railway		X		X	20	100	50% Abs.	C/A-code	Noise-Like	-138	-88.0	16.7
Surveying	X			X	20	100	50% Abs. & 2% Rel	Semi-Codeless	Noise-Like	-149.5	-92.6	21.3
Surveying		X		X	20	100	50% Abs. & 2% Rel.	Semi-Codeless	Noise-Like	-149.5	-92.7	21.4
Aviation-NPA		X		X	20	20	OOK	C/A-code	CW-Like	-145	-86.6	15.3
Aviation-NPA		X		X	20	100	50% Abs.	C/A-code	Noise-Like	-138	-84.3	13
Aviation-ER		X	X		Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-76.6[3]	5.3
Aviation-ER		X		X	Note 2	Note 2	Note 2	C/A-code	Noise-Like	-134.8	-85.6[3]	14.3

Notes: En-Route Navigation (ER), Non-Precision Approach (NPA)
1. When the interference effect has been classified as pulse-like or noise-like, the value is expressed in units of dBW/MHz. The value is expressed in units of dBW when the interference effect has been classified as CW-like.
2. In this operational scenario, it is assumed that there is a large enough number of UWB devices, such that independent of the individual UWB signal parameters the aggregate effect causes noise-like interference.
3. This maximum allowable EIRP is based on an assumed density of 200 UWB devices per square kilometer transmitting simultaneously.

RTCA notes that as indicated in section 3.4.3.1, the interference effects upon the GPS receivers were classified as pulse-like, noise-like and CW like transmissions. The classification of a given UWB device is determined by the PRF, gating, and the modulation discipline. The modulation disciplines used in the NTIA program were no modulation, constant PRF with random on-off keying, or random dithering. The shape of the transmitted pulse determines the RFI spectrum. In practical UWB applications the spectrum is primarily determined by the pulse width which typically has width ≅ 0.5 to 1 ns. The data collection and analysis portion of the NTIA test program summarized the results in a three dimensional matrix where each point in the matrix is the <u>measured receiver susceptibility level</u> for that group of transmission parameters. The dimensions of this matrix were intended to cover the range of pulse-like, noise-like and CW like RFI transmissions.

Appendix B gives equations that allows the <u>measured receiver susceptibility level</u> to be estimated between the data points of the NTIA three dimensional measurement matrix. Three of the four cases treated in the appendix cover the transmission classifications measured in the NTIA test program. Case I in Appendix B represents CW-like transmissions, Case II represents noise-like transmissions, and Case IV represents pulse-like transmissions.

As an example extension of the measurement results, consider the Case II noise-like transmissions for C/A code receivers with UWB parameters 100% gating, 50% dither and 5 MHz PRF. The measured receiver susceptibility level for the reacquisition point under these conditions was -94 dBm/20MHz (Table 2.1 of NTIA special publication 01-45) . The corresponding interference threshold is -137dBW/MHz when the 20MHz measurement bandwidth was reduced to 1 MHz (-13dB) and the conversion from dBm to dBW (30dB) was made. This case is given for the non-precision scenario in Table 3.6 (third line from the bottom). Assume one wants the interference threshold when the PRF = 15MHz. Using equation (2) from Appendix B, and letting $\overline{R}_P = \overline{R}_5 = 5\text{MHz}$ and B_h = 1MHz , we have

$$P_{RFI} = \Phi(f_0)B_h\overline{R}_5 = -137\text{dBW in 1MHz bandwidth} \qquad (1)$$

Solving (1) for the energy spectral density per pulse, we have $\Phi(f_0)$ = -264 joules/Hz per pulse. For 1 ns pulse width, Φ is constant over ± 10MHz about f_0. For $\overline{R}_P = \overline{R}_{15} = 15\text{MHz}$, the interference power is

$$P_{RFI} = \Phi(f_0)B_h\overline{R}_{15} = -132.2 \text{ dBW in 1MHz bandwidth} \qquad (2)$$

Since the reacquisition point remains the same, the energy per pulse must be reduced by 4.77dB so that P_{RFI} = -137 dBW/MHz or energy spectral density must be reduced to $\Phi(f_0)$ = -259.2 joules/Hz per pulse. This result is confirmed in Table 3.6 third line from the bottom where the non-precision scenario RFI has PRF = 20MHz and the interference threshold = -138 dBW/MHz which corresponds to the -137 dBW/MHz for 5MHz. Note that (1) in Appendix B becomes more accurate as the average PRF relative to B_h is increased.

4.0 RFI ENCOUNTER SCENARIO DEVELOPMENT

An RFI encounter scenario is defined by knowledge of the victim receiver, the propagation path and the RFI source. Key aspects of the receiver are its necessary performance characteristics in the presence of interference (RFI susceptibility) and the receiver antenna gain. The main characteristics of the propagation path are the source-receiver separation distance (constant or time-varying) and the type of propagation. The main RFI source characteristics are its emission parameters (power, modulation, etc.) and its antenna gain. RFI scenario development involves determination of these several parameters. With the parameter values, analysis using a radio interference link budget is possible. One form of RFI link budget analysis involves computing the product (i.e.; the logarithmic sum) of the RFI source power, the propagation loss (determined by separation distance and propagation type) and the receiver antenna gain in the direction of the RFI. The result is the incident interference at the victim receiver.

For aviation and maritime applications government regulatory agencies establish RFI protection limits for receivers against which they compare the offending interference. If the interference is less than the protection limit then the RFI is compatible for that scenario. If on the other hand, the RFI is greater than the protection limit, it is not compatible. Radio regulations establish the emissions requirements for transmitters or unintentional emitters to manage interference at the source.

Table 4.1 contains the link budget template to be applied to UWB RFI for the protection of GPS when used for safety of life service.

Table 4.1 GPS RFI Link Budget Template

1	Receiver Susceptibility Mask (for broadband noise)	Standard based on broadband noise receiver performance characteristics (RTCA DO 235)
2	Aeronautical or Public Safety Margin	Protects against unknown errors in link budget estimates
3	Total Allowed Broadband RFI (at receiver input)	Subtract logarithms 2) from 1)
4	Broadband Noise Equivalent Correction Factor	Determined using standardized test/analysis procedures (e.g. Stanford test or NTIA BWCF)
5	Multiple System Allotment (excluding MSS)	Used for composite of all UWB and all future RFI sources
6	Single Emitter Allotment	Allotment for each individual emitter of each system which makes up the composite.
7	RFI level at Victim Receiver	Add logarithms of 3), 4), 5), and 6)
8	Antenna Gain in Direction of RFI	Determined by operational scenario
9	Maximum RFI Propagation Loss	Based on separation distance determined by operational scenario (positive value)
10	Source RFI Emission Limit	RFI Emission Limit =(7) – (8) + (9) logarithms

As described above, Aeronautical Margin is an estimate of unknown errors that may exist in the RFI link budget. This margin is not available to non-aeronautical RFI sources. The intent of the multiple system and single emitter allotments is to recognize the current situation with the existing out-of-band emissions from MSS mobile terminals and accommodate UWB and future RFI sources.

Note that the structure of Table 4.1 implies a linear model. This is so because the intensity of the RFI is typically maintained at a low level (< -160 dBW/MHz). Nonlinear effects such as might be caused by the UWB spike-like waveforms are not a consideration.

4.1. Aviation Approach Scenarios

For the approach scenarios considered thus far in this study, the principal interference is thought to be from mobile terrestrial sources. Future work, especially for the GPS L5 frequency, will treat other cases such as fixed terrestrial sources (DME ground transponders) and on-board aircraft equipment. To the extent that material becomes available, on-board passenger electronic interference sources may be studied as well.

RFI link budget analysis based on the interference mask requirements show that the loss of continuity would occur with unacceptable probability when the interfering power exceeds the receiver susceptibility mask. Loss of continuity due to RFI may occur in the vicinity of the precision approach decision height if the aircraft flight path deviations decrease the distance between the aircraft and the RFI source below the minimum separation distance. The aircraft total system error (TSE) is defined as the aircraft's deviation from its nominal decent path (e.g., 3^o glideslope). The TSE probability distribution can be determined by convolving the flight technical error (FTE) distribution and the navigation system error (NSE) distribution as described Appendix D.

The risk of loss of continuity due to failures of the GPS signal-in-space is about one in 3.5 million approaches (~5σ) over a 15-second exposure interval. The risk of continuity due to an RFI event is not strictly defined anywhere in the requirements. It is obviously important to keep this risk very low as loss of continuity may result in a go-around which is potentially disruptive to air traffic management and costly to airplane operators. Because the RFI continuity risk is influenced by factors that are not strictly part of the signal in space (i.e. the airplane FTE) it is inappropriate to apply the signal-in-space continuity requirement to this continuity risk. More will be said about a reasonable level of continuity risk for this potential source in Appendix D.

RF-induced loss-of-continuity events are a statistical problem. If the separation distance falls below the minimum, it is assumed that the RFI at the receiver exceeds its susceptibility limit and that with probability 1 that there will be a cycle slip in a 10 second interval. Therefore it is important to determine the probability that an aircraft on a Category II approach can get closer than the minimum separation distance to an interference source. It is assumed that an emitting RFI source can be anywhere within the obstacle clearance surface.

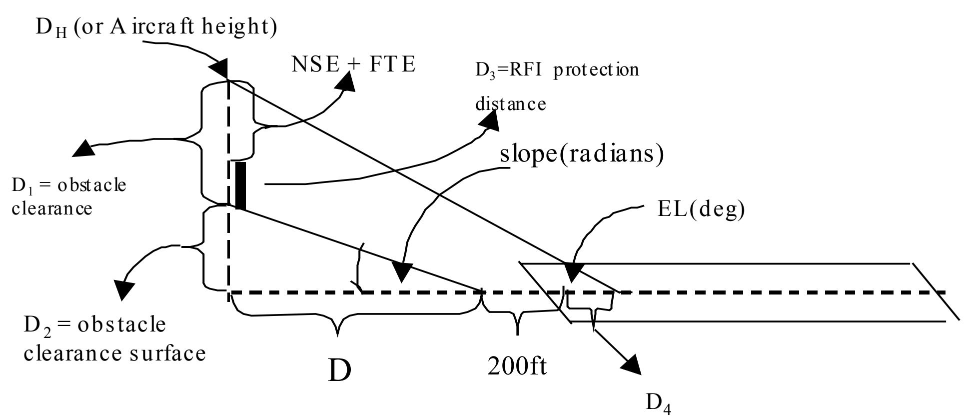
4.1.1 Minimum RFI Separation Distance and Link Budget for Category II/III Approaches

4.1.1.1 Category II/III Minimum Separation Distance:

The geometry between the interference source and an airplane on a Category II approach is illustrated in Figure 4.1. For the scenario it is assumed that there is one MSS mobile earth terminal and a collection of other mobile RFI sources such as UWB transmitters operating in the vicinity of the ground point under the Category II decision point. When airplane is at the 100 foot decision height point, it is assumed the RFI source(s) can be at the extreme of the obstacle clearance surface that is 15.1 feet above the ground. Hence the nominal 3° path is 100-15.1=84.9 ft above the RFI source. The GPS antenna is assumed to be top to the airplane so an additional 7 feet of altitude is included. If the airplane is to maintain a minimum separation of 70 ft, then the maximum allowable TSE is:

TSE = 84.9+7-70 = **21.9 ft**.

Further analysis (Appendix D) shows this is a reasonable distance with appropriate statistical significance.



Aircraft antenna height above control point = 7ft

EL = 3 deg

D_H = 100 ft CAT II

D_4 = 50/tan(EL) ft

D = D_H/tan(EL) - D_4 - 200 = 754.1 ft for CAT II

slope = 1/50 for CAT II/III

D_2 = D*slope = 15.1 ft

Obstacle Clearance = D_1 = D_H - D_2 = 84.9 ft

aircraft antenna-to-obstacle surface = 84.9 + 7 = 91.9 ft

Figure 4.1 Category II/III Approach Geometry

The Category III vertical encounter geometry is the same as Category II up to the Category II decision point. Calculations for a lateral RFI encounter geometry suggest that lateral RFI on taxiway at threshold has a separation distance of 184ft which results in a 76.4 dB path loss given a –5dbi antenna gain. Comparison with the link values in Table 4.2 shows that the Category II vertical encounter is the more stringent case.

4.1.1.2 Precision Approach RFI Link Budgets:

Table 4.2 lists the parameters of the Category II/III scenario developed by SC-159 as described above. Previously developed Category I scenario values are adapted to the new situation of multiple mobile UWB and other RFI sources by same method.

Table 4.2. GPS Precision Approach RFI Link Budgets

	GPS WAAS/LAAS Category I	**GPS LAAS Category II/III**
Frequency	1575 MHz	1575 MHz
Receiver Susceptibility Mask (broadband noise)	-140.5 dBW/MHz	-140.5 dBW/MHz
Aeronautical Margin	-5.6 dB	-5.6 dB
Total Allowed Broadband RFI (at receiver input)	-146.1 dBW/MHz	-146.1 dBW/MHz
Worst-Case UWB Noise Equivalent Correction Factor (note 1)	-10 dB	-10 dB
Multiple System Allotment (excluding MSS)	-10 dB	-10 dB
Single Emitter Allotment (note 2)	-10 dB (strawman value until data available)	-10dB (strawman value until data available)
UWB RFI @GPS receiver	-174.1 dBW/MHz	-174.1dBW/MHz
Antenna gain toward RFI source	10 dB	13.1dB
Propagation Loss (separation distance)	66.1 dB (100ft)	63.0 dB (70ft)
RFI Emission Limit	-100 dBW/MHz	- 100 dBW/MHz

Notes: 1) Testing to date has shown that some UWB test waveforms can produce interference that is 10 dB worse than broadband noise. While this worst case must be accounted for, current data shows that the correction factor is highly modulation specific. Some test modulations (high dithering, low duty cycle) may result in a less negative correction factor. See section 3.1.

2) Discussion in Appendix C shows the need for a factor to handle the aggregate (cumulative) effect of RFI from multiple mobile sources such as UWB sources. The value of that factor should allow for at least the density of vehicle-mounted interference sources on a heavily traveled roadway. That value should be at least 10 dB (i.e.; the effect of 10 UWB units transmitting non-concurrently, with power combining linearly).

There have been several significant interference issues that necessitated the development of international standards. Examples include ILS (FM-broadcast RFI), MLS (MSS FLES RFI), and

GPS (MSS MET RFI). These aviation safety-of-life systems had to accommodate the indicated RFI. With the exception of GPS, each aeronautical navigation system adopted the informal frequency management procedure that the RFI must be 8[32] to 12 dB below the victim receiver's noise floor. This RFI practice is common in the national civil aviation agencies of ICAO and the industry /government committees of RTCA and EUROCAE. The procedure is invoked whenever a safety-of-life system does not have margin in its link budget to absorb RFI. This is the case for GPS since the MSS mobile terminal received essentially all of Total Allowed RFI. Therefore the Multiple System Allotment to additional system must be small. The chosen value, consistent with past practice, is –10 dB. The worst-case noise equivalency factor value (–10 dB) is based at present on the known ratio of the receiver susceptibility for CW RFI to that for broadband noise power in a 1 MHz bandwidth.

Compared to Category I, Category II operations must makeup a potential 3 dB deficit in link margin from to smaller 70 ft. by reducing the antenna gain toward the RFI from –10 dB to -13.1dB. This reduction is justified because of the sizes and types of aircraft certified for Category II have lower installed GPS antenna gain in the lower hemisphere. Note also that the required UWB RFI emission level (–100 dBW/MHz) is 28.7 dB below the proposed Part 15 limit of –71.3 dBW/MHz

4.1.2 Non-precision Approaches

Regulatory agencies define enroute airways and terminal area approach paths by a series of waypoints connected by straight-line segments. Each waypoint is assigned a name and a location such as initial approach point, final approach point and missed approach point. About each waypoint is a rectangular protected displacement area. For the TSO-129 GPS the dimensions of the displacement area at the missed approach point are ± 0.5 nautical miles by ± 0.3 nautical miles; its center is at the runway threshold for straight-in approaches (Figure 4.1). By contrast Category I precision approaches have an "effective" lateral displacement of ± 350ft (full-scale deviation of the ADI display) at the runway threshold.

The FAA distinguishes a precision approach from a non-precision approach by requiring a precision approach to have combined lateral and vertical (glide slope) guidance. The term non-precision approach refers to facilities without the vertical guidance of a glide slope. This however does not imply an unacceptable quality of guidance. The FAA maintains the same level of flight safety for non-precision approaches as it does for precision approaches. They achieve this by requiring a much larger protected displacement area at the missed approach point and a higher minimum descent altitude (MDA) for non-precision approaches than they do for the precision approach. The MDA is the lowest altitude to which descent shall be authorized prior to seeing the airport for procedures not using a glide slope. For precision approaches, the term used for this corresponding altitude is decision height (DH), the height above the runway threshold. Note: for ILS, the Category I DH is 200ft. During a non-precision approach, the pilot can manage his descent using any vertical profile he chooses subject to the constraints of his aircraft and navigation equipment. He may for example descend to the MDA and then fly a constant altitude flight path to the runway. He also must determine the time in advance that he will arrive

[32] Recommendation ITU-R IS.1009-1, "Compatibility between the Sound-Broadcasting Service in the band of about 87-108 MHz and the Aeronautical Services in the band 108-137 MHz.

at the missed approach point, which is usually prior to the runway threshold. If he cannot see the runway environment at that time he must perform a missed approach.

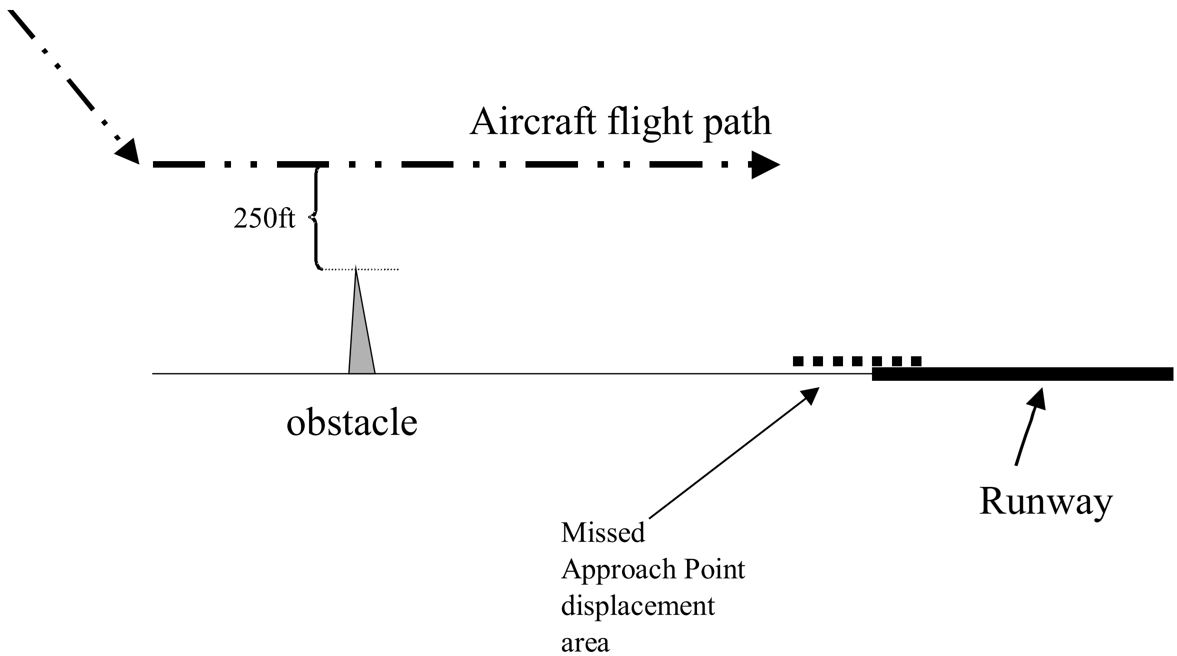


Figure 4.2 Non-Precision Approach Geometry

Associated with each non-precision final approach segment (Fig. 4.2) there is an MDA. In general, the MDA = 250 feet above the airport + (obstacle height). If there are no obstructions, then the MDA = 250 feet above ground. The RFI separation distance calculations will use the 250 foot value for two reasons. An RFI source can be on top of the obstacle or it can be an obstacle free zone and MDA = 250feet above the highest point. An additional 7 feet is added to account for the aircraft antenna displacement from the aircraft control point. Thus the calculation to determine the RFI separation distance is expressed as:

Separation distance = 257 ft – TSE (Eq 1);

where the total system error, TSE, is the root-sum-square of the flight technical error, FTE, and the navigation system error, NSE. The separation distance will be calculated corresponding to a 95 % probability. Table 1-1 of RTCA/DO-208 gives the vertical FTE = 100 ft (95%) while the vertical NSE for the vertical guidance component is given in Table 2-3 of RTCA/DO-208 as 68 ft (95%). This means that the 2 σ vertical position error is:

$$TSE = \sqrt{100^2 + 68^2} = 121\text{ft}.$$

Therefore from (Eq. 1) separation distance = 257 – 121 = 136ft.

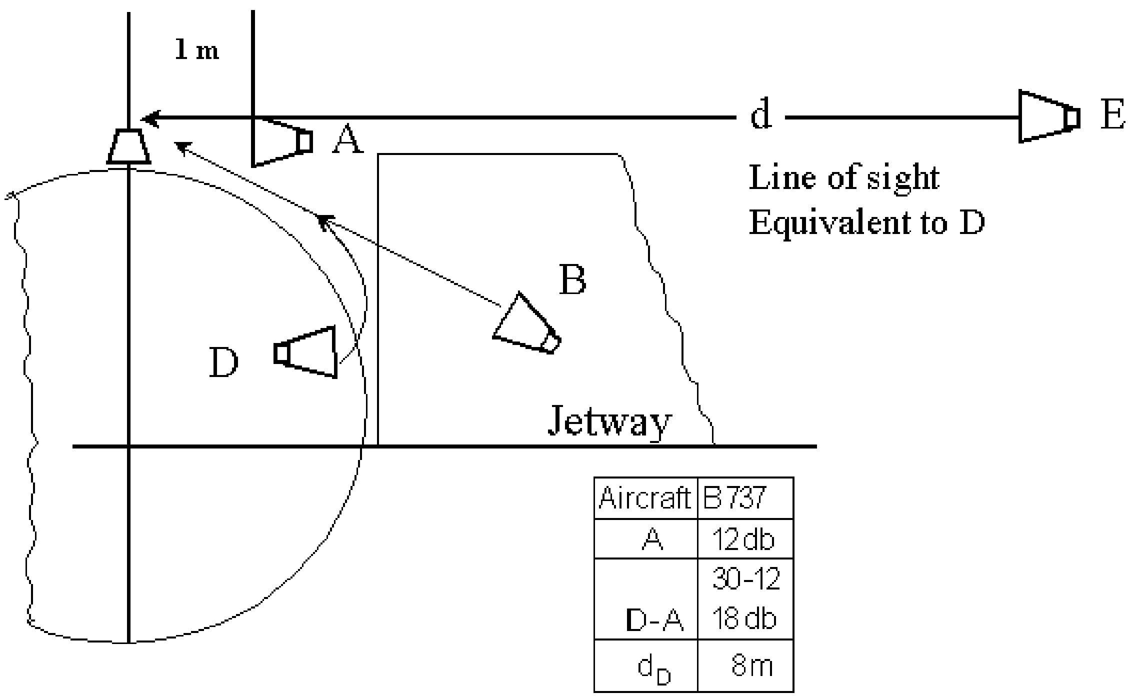
4.2 Other Aviation Scenarios

4.2.1 Aircraft Surface Movement Scenario

Work on this scenario is incomplete as of the time of this second interim report. Further development is planned and the analysis is to be inserted in the RTCA final report.

4.2.2 Aircraft Enroute Navigation with On-board Personal Electronic Device RFI

Based on the proliferation of wireless products and services, including the potential of UWB devices operating in safety-of-life bands, the aviation industry is providing the following data relating to critical operational scenarios. The need for such data is based on the fact that numerous unlicensed intentional and unintentional radiating devices are appearing onboard commercial aircraft. Extensive studies have been done to quantify the likelihood that any of these devices may cause harmful interference to aircraft communications and navigation systems. For the purpose of identifying the risks to Global Navigation Satellite Systems, particularly GPS, there have been over 2,160 measurements made from numerous points within many aircraft to identify path losses between GPS antennas and radiators inside the passenger cabin.



Aircraft	B737
A	12db
D-A	30-12 18db
d_D	8m

Figure 4.3 Aircraft Path Loss Determination

In Figure 4.3 above, the reference antenna placed at distance of one free space meter from the onboard GPS antenna yielded a total system path loss of 12 dB. Testing from within the aircraft yielded a worst case excessive path loss (D-A) of 18 dB. This represents a free space equivalent distance of 8 meters.

4.2.3 Aeronautical Mobile Satellite (Route) Service (AMS(R)S) Scenario Development and RFI Impact Assessment

The following text was supplied by RTCA Special Committee 165.

4.2.3.1. AMS(R)S Operational Scenario

The operational scenario is presently under development but will likely be similar to that for GPS enroute.

4.2.3.2. AMS(R)S Receiver Susceptibility and Interference Emission Limits

The interference criteria for AMS(R)S (Aeronautical SATCOM safety-of-life service) were established in RTCA DO-215 in terms based on system-level interference criteria as used in the ITU-R. The quantitative aspects of those criteria, slightly modified, were incorporated in ITU-R Recommendation M.1234, and were subsequently updated in RTCA DO-215A Change No. 1.

The AMS(R)S MASPS, scheduled for completion by July 2001, will repeat the DO-215A criteria. The specific criteria are predicated on observing the apparent increase of a "victim" system's noise floor temperature caused by interference and expressed as ΔT/T. For single-entry interference (that due to any interfering system or "network"), ΔT/T shall be not greater than 6 %; and shall be not greater than 25 % for all sources of interference. "All sources" includes both inter- and intra-system interference.

RTCA DO-210D (MOPS for AMSS avionics) defines the minimum requirements for Aeronautical Earth Stations (AESs), including the maximum avionics system noise temperature and the consequent susceptibility of the AES receiver system based on the DO-215A Change No. 1 requirements. The maximum single-entry interference level is -163.2 dBm in the band 1529 - 1560 MHz, with increasing levels defined outside that band. It is noted that this level may impose more severe requirements on other interfering system than do some other aviation applications. SC-165 is currently investigating the specific effects of UWB-type interference.

Table 4.3. DO-210D AMSRS Receiver Susceptibility vs. Frequency

Frequency Range	Maximum Interference Level
470 to 1450 MHz	+3 dBm
1450 to 1529 MHz	Decreases linearly in decibels from +3 dBm at 1450 MHz to –72 dBm at 1529 MHz
1529 to 1560 MHz	-163.2 dBm
1560 to 1626.5 MHz	Increases linearly in decibels from –72 dBm at 1560 MHz to +3 dBm at 1626.5 MHz
1626.5 to 1660.5 MHz	+47.8 dBm
1660.5 to 18000 MHz	+3dBm

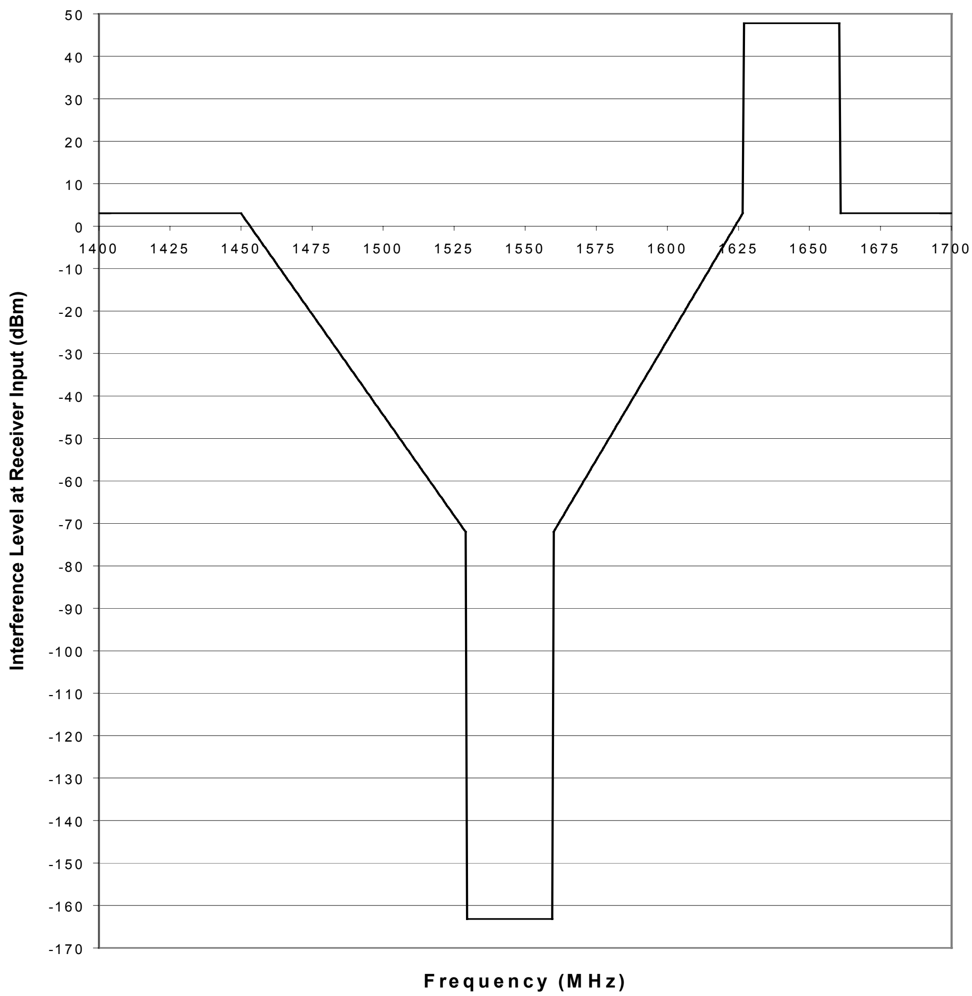


Figure 4.4. AMS(R)S Receiver Susceptibility for Single Entry Narrowband RFI

4.3 Non-Aviation Scenarios

When DOT tasked RTCA to study the GPS L5 and later the L1 interference environments, aviation-related issues were acknowledged to be of primary importance. The group was, however, encouraged to seek significant involvement and input from non-aviation GPS uses, especially public safety applications (e.g., maritime, E-911, police, fire fighting). The following section is the result of that input. More information is expected from maritime and other applications

4.3.1 Enhanced 911

The following material was presented to the RTCA study group at the most recent meeting.

4.3.1.1 E-911 Background

One very important Public Safety scenario is that of the Enhanced 911 (E911) Emergency Calling Systems. CC Docket No. 94-102, *Third Report and Orde*r, dated October 6, 1999, stated, "To improve public safety and extend ALI to wireless callers, the Federal Communications Commission has established a schedule, subject to certain conditions, for deployment of E911 features by wireless carriers." The following are excerpts from that Report and Order:

"In Phase I, which began on April 1, 1998, Public Safety Answering Points (PSAPs) were to receive a rough estimate of a caller's location and a dialable call-back number. In Phase II, scheduled for October 1, 2001, or six months after the service is requested, whichever is later, PSAPs are to receive a much more precise location identification, within 125 meters or about 410 feet of the caller's location."

"Wireless carriers who employ a Phase II location technology that requires new, modified or upgraded handsets (such as Global Positioning Systems (GPS)-based technologies) may phase-in deployment of Phase II subject to the following requirements:

Without respect to any PSAP request for Phase II deployment, the carrier shall:

1. Begin selling and activating ALI-capable handsets no later than March 1, 2001;
2. Ensure that at least 50 percent of all new handsets activated are ALI-capable no later than October 1, 2001; and
3. In addition to the 50 percent requirement, ensure that at least 95 percent of all new digital handsets activated are ALI-capable no later than October 1, 2002.

Once a PSAP request is received, the carrier shall, in the area served by the PSAP:

1. Within six months or by October 1, 2001, whichever is later:
    a. Ensure that 100 percent of all new handsets activated are ALI-capable;
    b. Implement any network upgrades or other steps necessary to locate handsets; and
    c. Begin delivering to the PSAP location information that satisfies Phase II requirements.

2. Within two years or by December 31, 2004, whichever is later, undertake reasonable efforts to achieve 100 percent penetration of ALI-capable handsets in its total subscriber base.

To be allowable under our rules, an ALI technology that requires new, modified, or upgraded handsets shall conform to general standards and be interoperable, allowing roaming among different carriers employing handset-based location technologies."

The FCC adopted the following revised standards for Phase II location accuracy and reliability: For handset-based solutions: 50 meters for 67 percent of calls, 150 meters for 95 percent of calls.

Later, in the 4th Memorandum Opinion and Order, dated September 8, 2000, the above schedules were modified as follows:

"We modify the rules for carriers employing handset-based ALI solutions in the following respects:

- Extend from March 1, 2001 to October 1, 2001, the date for carriers to begin selling and activating ALI-capable handsets.
- New Activations:
    - We eliminate the separate phase-in schedule that is triggered by a PSAP request.
    - We adopt the following revised phase-in schedule:
        - December 31, 2001: at least 25 percent of all new handsets activated are to be ALI-capable;
        - June 30, 2002: 50 percent of all new handsets activated are to be ALI-capable;
        - December 31, 2002 and thereafter: 100 percent of all new digital handsets activated are to be ALI-capable.
- Penetration:
    - Extend from December 31, 2004, to December 31, 2005, the date for carriers to reach full penetration of ALI-capable handsets in their total subscriber bases.
    - Modify the operational definition of full penetration from "reasonable efforts" to achieve 100 percent penetration of ALI-capable handsets to a requirement that 95 percent of all handsets in a carrier's total subscriber base be ALI-capable."

In that memorandum, some manufacturers raised questions on the feasibility of the schedule. Others, using GPS or a hybrid approach for the capability, agreed that it was feasible. Sprint stated "the only way to ensure compliance with the phase-in rule would be to sell only Global Positioning System (GPS) handsets effective October 1, 2001, which would limit consumer choice and potentially force consumers to pay high prices for first generation handsets." However, in the discussions part of the memorandum, it was pointed out by the Commission "At the time of the adoption of our current rules, substantial evidence existed establishing that ALI solutions had been tested successfully in field trials." Most of these solutions used GPS. Some were network-based CDMA solutions. The increased availability of GPS chips for the handset solution was also stated.

To meet the FCC mandate for E911 ALI services within schedule, GPS will be an integral part of the E911 services. This includes the use of GPS anywhere – inside of buildings, under trees, in urban canyons. This is not to say that GPS will be the only sensor. Some of the proposed solutions are "hybrid" solutions that use both GPS and network-based CDMA measurements, but GPS is still an integral part of this safety-critical service.

4.3.1.2 E911 GPS Indoors

For the E911 handset application, GPS must be used indoors. That technology has been developed. QUALCOMM now owns the technology originally developed by SnapTrack, now owned by QUALCOMM. QUALCOMM developed an enhanced GPS sensor gps*One*™ to support E911 Phase II services using a handset-based technology mandated by the FCC. The technology takes advantage of the communication link between the wireless device and the infrastructure and has many modes of operation. In one mode of operation, the wireless device collects measurements from the GPS constellation and the terrestrial network and sends the information back to a location server in the network. The server also receives terrestrial measurements made by the base stations. The location server fuses the measurements together to produce an accurate position. Alternatively, the wireless device may compute the location itself instead of sending the measurements to a location server. Because of the enhanced sensitivity, gps*One*™ based sensors are able to work indoor and under severe shadowing conditions. This is an important life saving feature as far as E911 is concerned, and was developed in time to meet the FCC mandated schedules.

The specification for the GPS signal level under clear view of the sky is –130 dBm. Building penetration, shadowing, and foliage could degrade the signal by more than 20 dB. These weaker signals require more processing gain (longer integration) for successful acquisition. Knowing "true" GPS time at the wireless device and the approximate range to the satellite enables the wireless device to integrate the GPS signal coherently over much more than 20 milliseconds (one GPS navigation bit period. This is because the base station can predict the bit sequence for some parts of the navigation message, and the bit polarity can be sent to the wireless device to help with integrating coherently over multiple bits. QUALCOMM states that its bit prediction algorithm achieves an accuracy of about 99.5% and further states that gps*One*™ based GPS sensors are able to acquire and track GPS signals as weak as –150 dBm. Doppler and timing information used for signal acquisition are also established via CDMA communication with the base station. At such a low signal level however, even a small amount of interference can have adverse effects.

4.3.1.3 E911 GPS Outdoors

The E911 GPS scenario outdoors can be similar scenario as for indoors due to operation in urban canyons, under trees, etc. There can also be severe multipath fading because of structures, and the wireless device will be more susceptible to other interference.

4.3.1.4 E911 UWB Environment

The interference with the most serious potential for the indoor environment is that from UWB Wireless Local Area Networks (WLANs). These WLAN devices can be very close to an E911 user, and are expected to be very high PRF devices.

Since these types of WLANs can be collocated with E911 GPS devices, there is a potential for GPS reception degradation and more work is needed to further develop the scenario.

4.3.1.5 Summary and Conclusions

In conclusion, E-911 relies heavily on GPS for position reporting. Furthermore, indoor, urban canyon and foliage make certain GPS operations much more sensitive to interference. UWB Wireless Local Area Networks have already been announced, using very high PRFs and may be used widely. The Part 15 EIRP limit of –71.3 dBW/MHz results in a received level at 3 meter separation 24.3 dB above the GPS receiver noise floor. Unless UWB device EIRP values are reduced below that level, excessive interference to GPS-based E-911 operations may result. Further work is needed to quantify the scenario.

APPENDIX A GPS RECEIVER UWB RFI EFFECTS MODEL – BASIS FOR INTERFERENCE LINK BUDGET

This section provides some insight into how UWB affects GPS Receivers by looking into it with an analytical perspective. This insight validates the test results obtained by Stanford University. It also validates the use of the 10 dB correction factor that is the difference between the application of CW and noise interference.

A.1 UWB Pulse Characteristics

UWB implies the transmission of narrow pulses with fast rise times. If they were not narrow with fast rise times, they would not be UWB. How narrow and how fast defines the UWB spectrum. Figures A.1 and A.2 illustrate example UWB pulses – the first having a 1 ns pulse width, while the second has a 0.25 ns width.

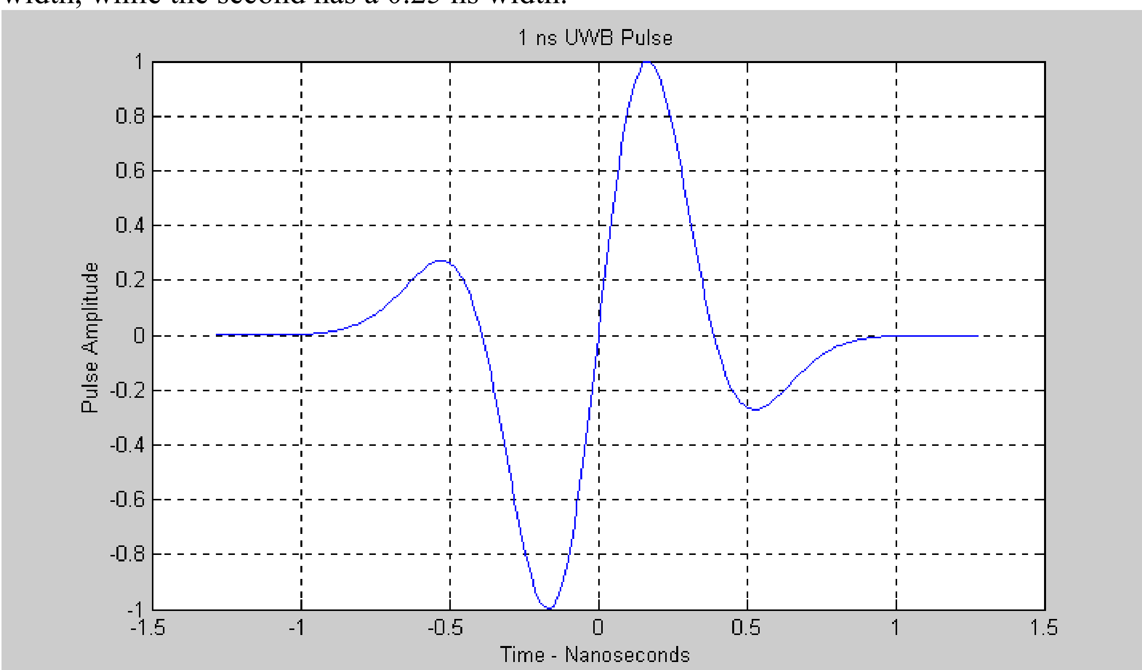


Figure A.1 One-Nanosecond UWB Pulse

The width of the pulse affects its spectral content significantly. For example, the spectral densities of the pulses shown in Figures A.1 and A.2 are shown in Figures A.3 and A.4. Note that the power spectral density (PSD) of the narrow pulse (Figure A.4) is centered at about 4.5 GHz, while the PSD of the wider pulse (Figure A.3) is centered at about 1.25 MHz, which is very close to the GPS band.

The difference between these two pulse-widths is significant, but so is the difference in their PSDs. This emphasizes that the any pulse stretching can significantly alter the PSD of a transmitted pulse that is intercepted by a GPS receiver. This pulse stretching could be caused by transmit-antenna non-linearities, transmission through walls or windows or collision with other pulses or multipath pulses.

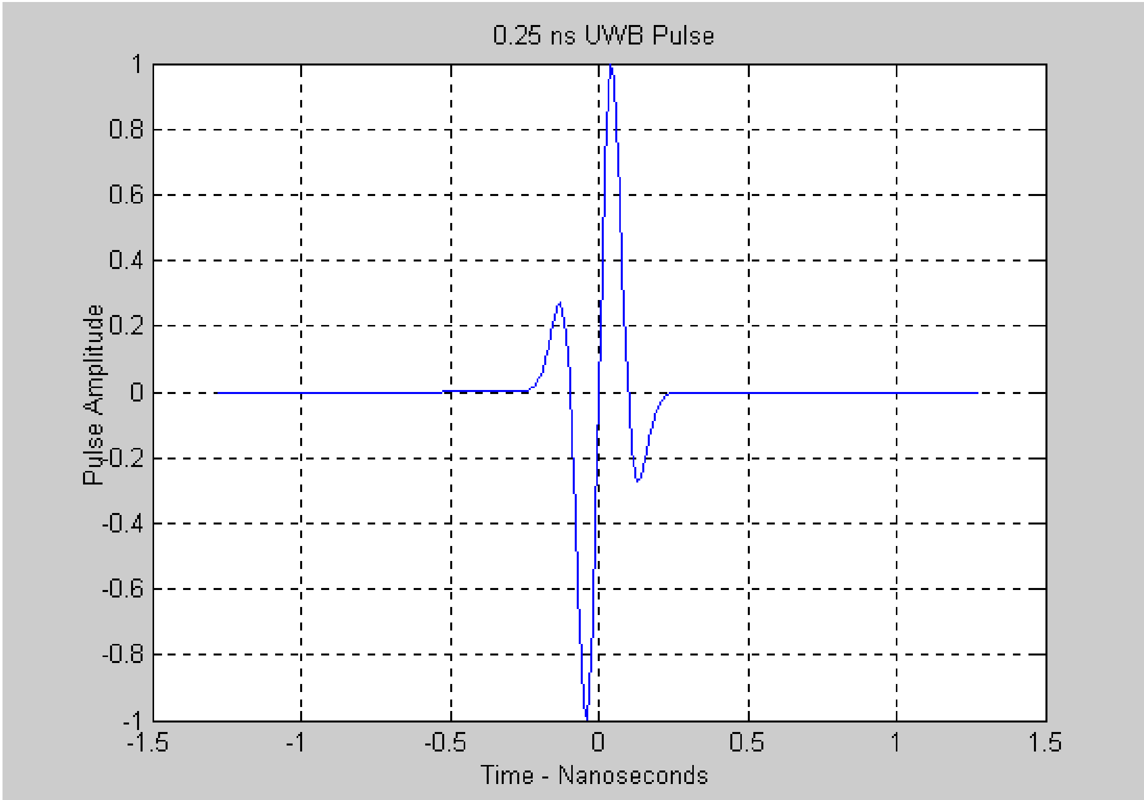


Figure A.2 0.25-Nanosecond UWB Pulse

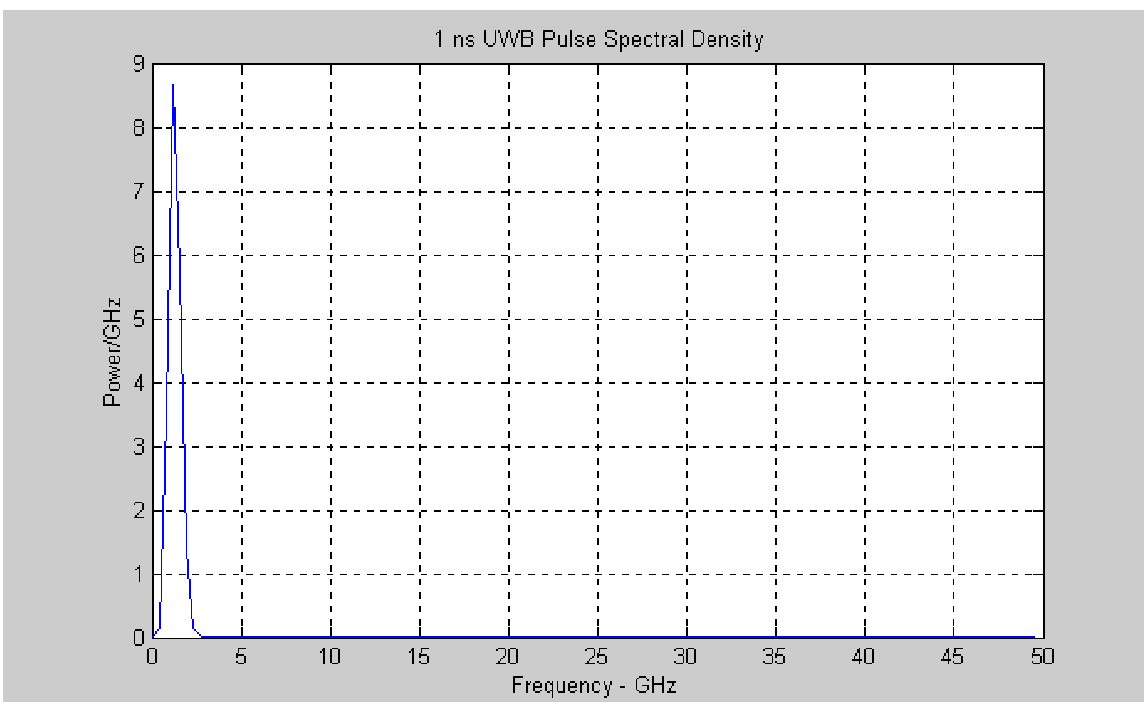


Figure A.3 One-Nanosecond UWB Pulse Power Spectral Density

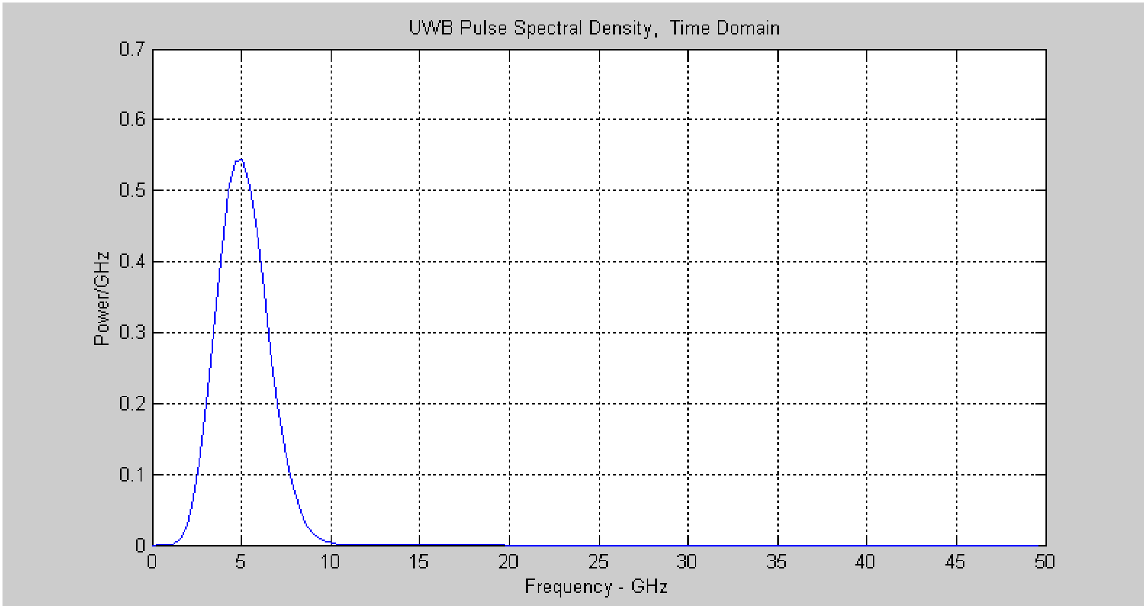


Figure A.4 0.25-Nanosecond UWB Pulse Power Spectral Density

A.2 Sequences of UWB Pulses

If one generates a sequence of UWB pulses, the PSDs change somewhat. Figure A.5 is a sequence of 6555 pulses occurring at uniformly random times with uniformly random amplitudes covering about 1311 microseconds. The pulses were added so that overlapping pulses were added together. This sequence simulates the reception of pulses from multiple sources at multiple distances, including pulses caused by multipath. The PSD for this sequence is shown in Figure A.6. Note that there is a slight shift compared to the single-pulse PSD of Figure A.4, probably caused by pulse collisions that can change the shape of the PSD. The probable reason for this is discussed below

Figure A.7 shows the PSD result of a similar sequence of one-nanosecond pulses. In this case, the reshaping of the PSD is somewhat more pronounced, probably because, with the wider pulse, the probability of pulse collision is higher.

Figure A.8 is a sequence of pulses at a constant PRF of 19.6875 MHz (1.575 GHz/80). Figure A.9 shows the PSD of this sequence, close-in near 1575 MHz. Note that there is a spectral line right at 1575 MHz.

A.2.1 What the GPS Receiver (Correlator) Sees

The pulse sequences described above were applied to a 20 MHz 6th-order Butterworth filter centered at 1575 MHz. A typical output of that filter for the random sequence of 0.25-nanosecond pulses is shown in Figure A.10. Very little can be discovered from that figure because of the presence of the 1575 MHz carrier. The effect of the filtering can be better observed at baseband. Thus, the filter output was mixed with a 1575 MHz carrier to convert the output to in-phase (I) and quadraphase (Q) components.

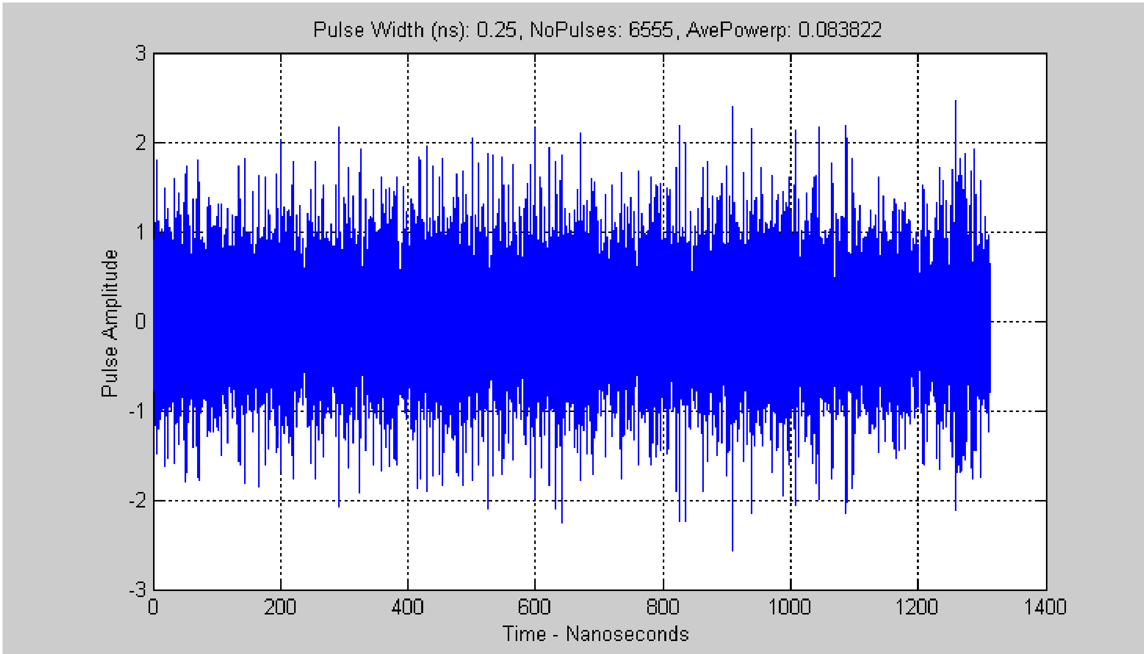


Figure A.5 Sequence of Uniformly Random Amplitude 0.25-Nanosecond UWB Pulses Occurring at Uniformly Random Times

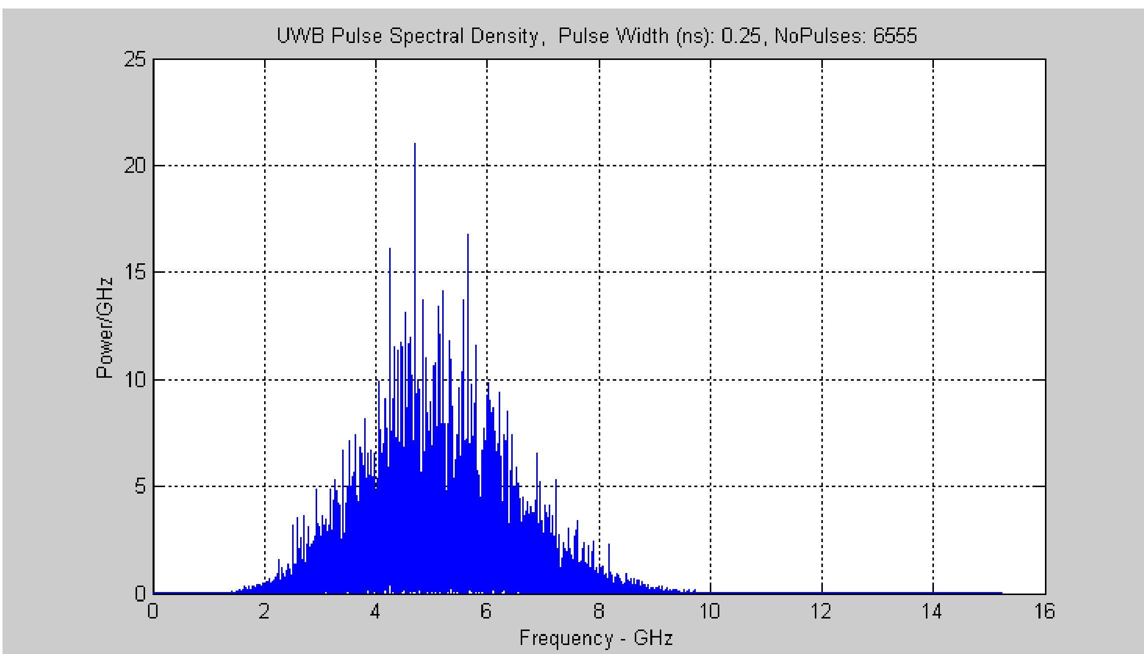


Figure A.6 PSD for Random Sequence of 0.25-Nanosecond Pulses

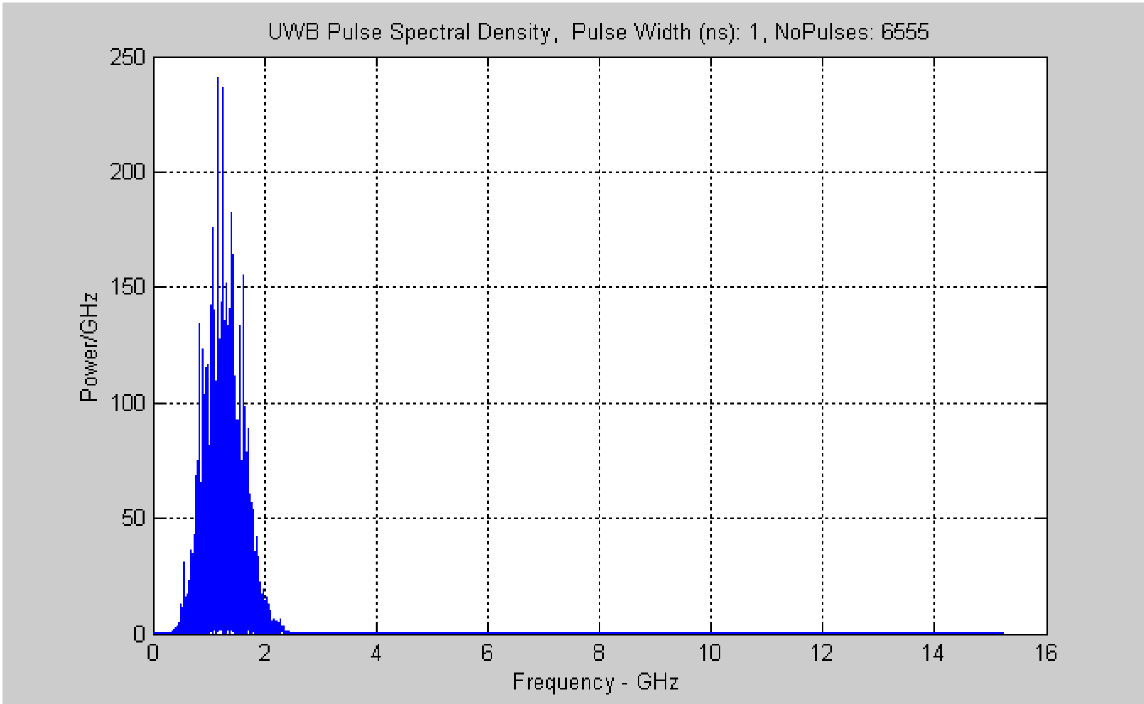


Figure A.7 PSD of Random Sequence of One-Nanosecond Pulses

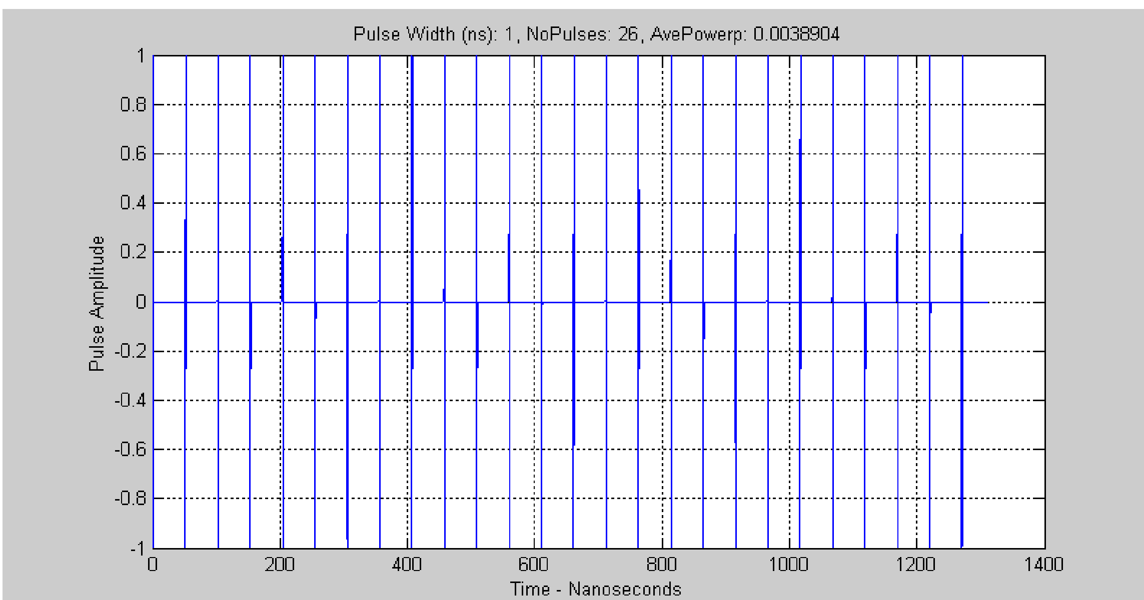


Figure A.8 Sequence of One-Nanosecond Pulses at Constant PRF of 19.6875 MHz

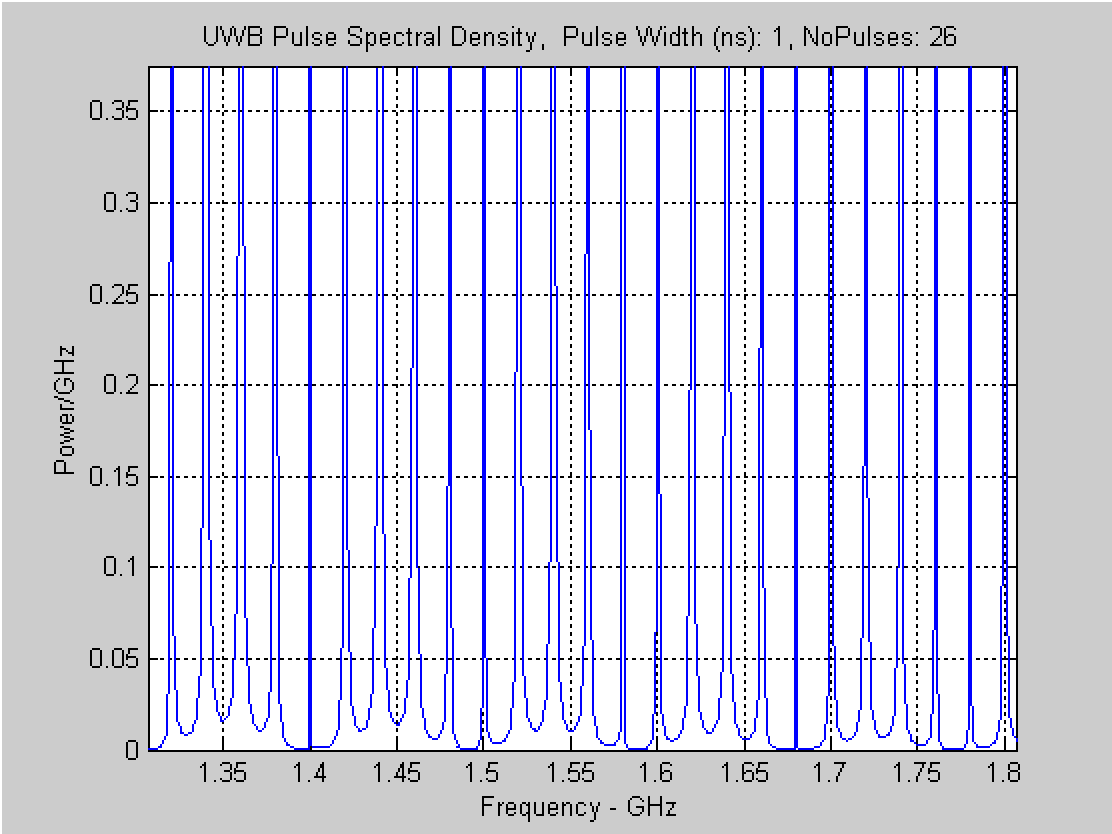


Figure A.9 Close-in PSD of Constant 19.6875 MHz PRF Sequence of Pulses

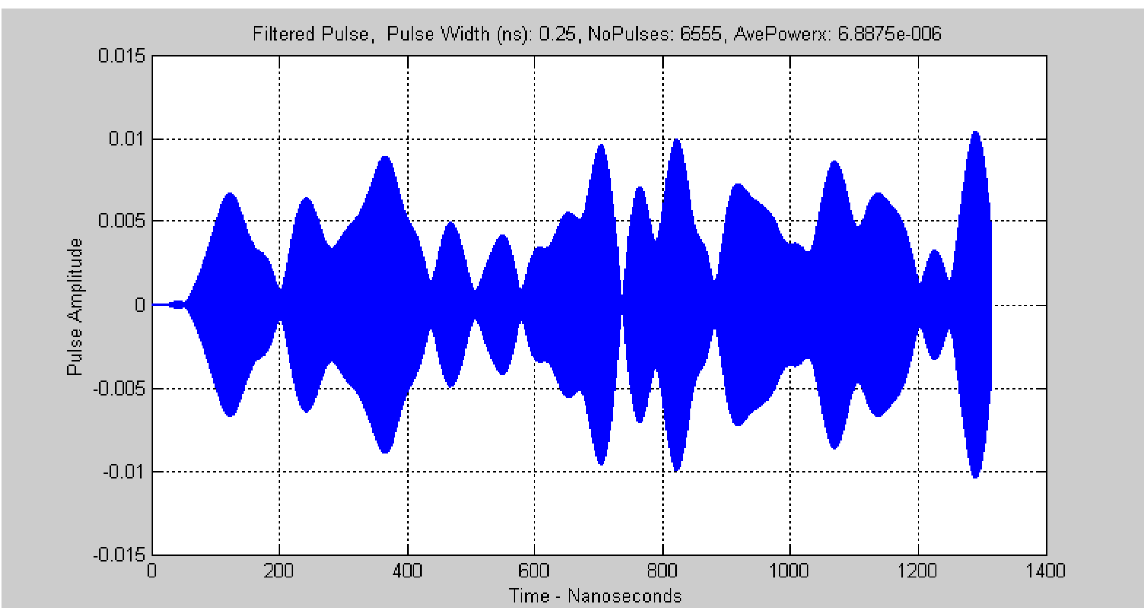


Figure A.10 Filtered Random Sequence of 0.25-Nanosecond Pulses

The I and Q components corresponding to the RF filter response shown in Figure A.10 are illustrated in Figures A.11 and A.12. Note that the average power was reduced by 37.84 dB, primarily because the pulse PSD was mostly above the GPS band.

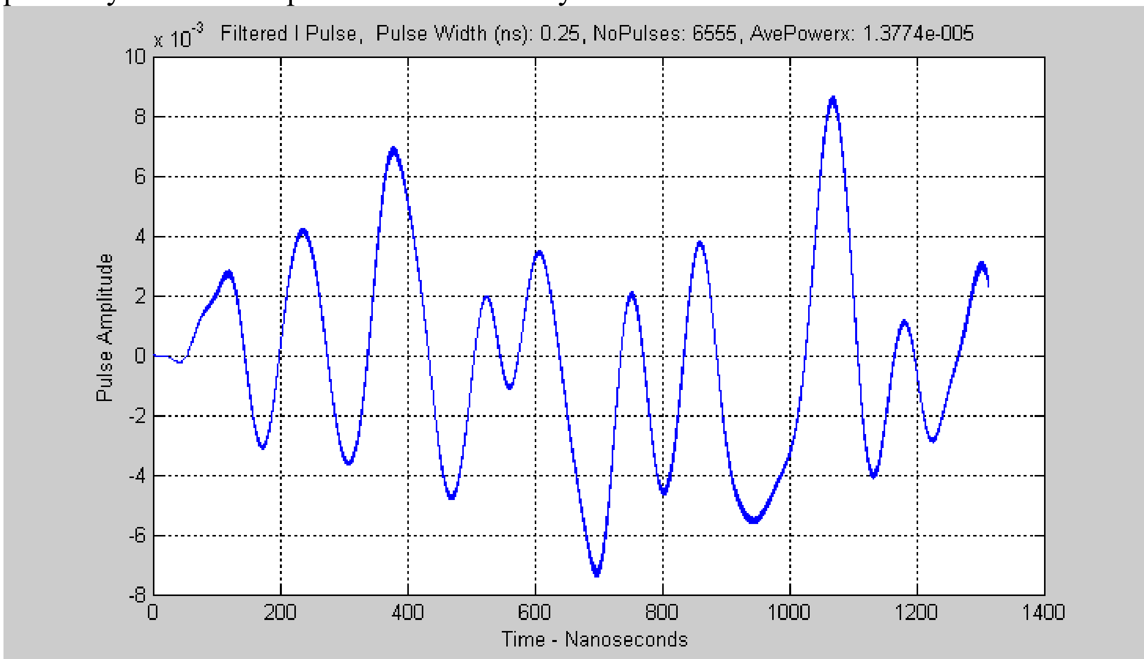


Figure A.11 In-Phase Component of Filtered Random 0.25-Nanosecond Pulse Sequence

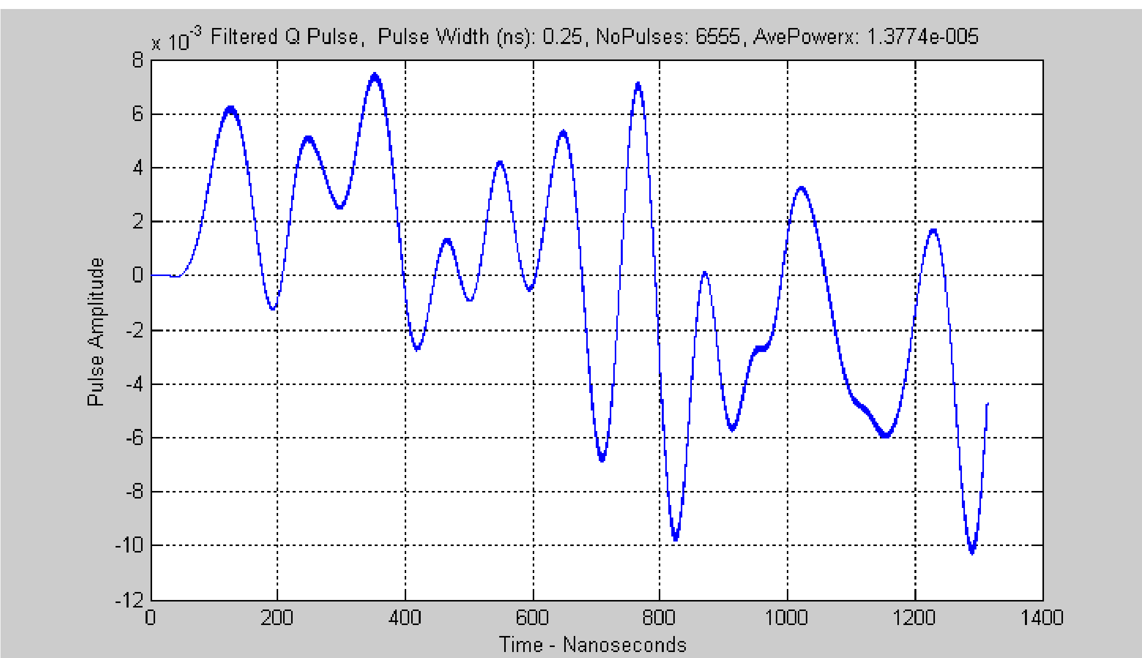


Figure A.12 Quadraphase Component of Filtered Random 0.25-Nanosecond Pulse Sequence

It is truly observable in Figures A.11 and A.12 is that the filtered output is essentially random with respect to the time-scale of the C/A code chips and subsequent correlation and smoothing in the receiver (1 millisecond or more). Thus, the effect of random UWB pulses on a GPS receiver is truly that of wideband noise.

The filtered response to the one-nanosecond pulses is very similar, except that the power reduction is much less. This is because much of the unfiltered pulse power is in the GPS band.

The filtered response to the constant PRF sequence resembles CW interference. The filtered response at RF is illustrated in Figure A.13. Again the figure is interesting, but it does not convey much detail. As before, conversion to baseband provides a much clearer picture of the filtered response. The converted In-Phase and Quadraphase responses are shown in Figures A.14 and A.15. Note that these responses truly do represent CW interference. In fact, the PSDs of these responses are that of spectral lines as is shown in Figures A.16 and A.17. These spectral lines could very well interact with the spectral lines of the C/A code.

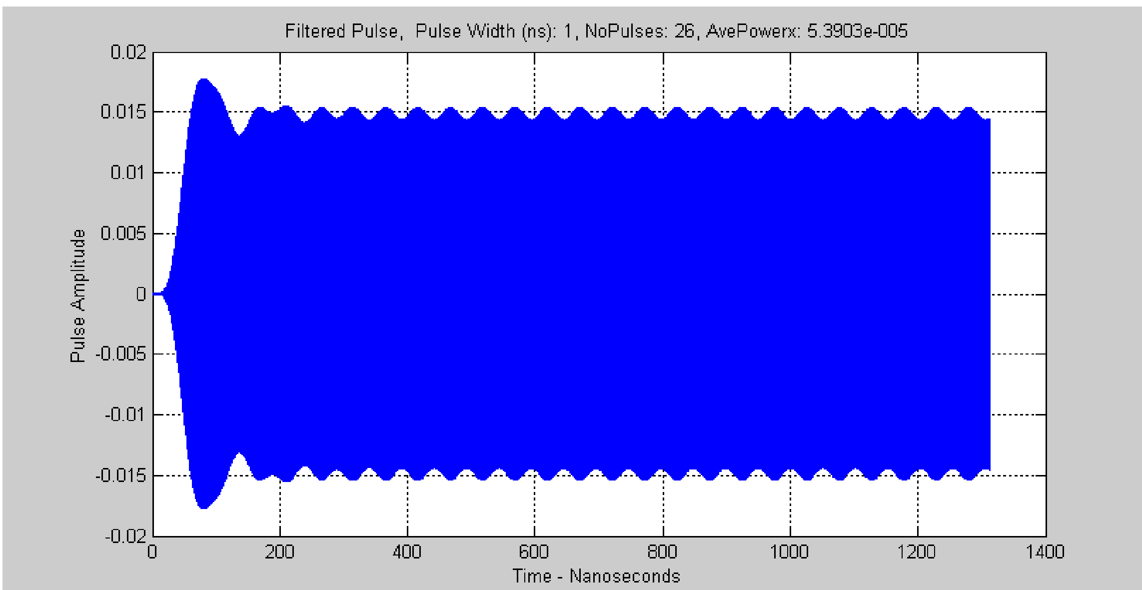


Figure A.13 Filtered Response to Constant PRF at RF

A.3 Pulse Collisions

As indicated above, the shape of the PSD of the transmitted pulses can change if pulses from different sources (or pulses due to multipath) collide and overlap in time. This is because the overlapping pulses correlate, or, in other words, generate a combined pulse that has a different shape. There is a mathematical basis for this that will be described here.

Consider two pulses that have identical shape, $x(t)$, except that one is delayed with respect to the other by Δt seconds, where Δt is less than the pulse width. The collision generates a new pulse $y(t)$, where

$$y(t) = ax(t) + bx(t + \Delta t) \qquad \text{A.1)}$$

where *a* and *b* represent different pulse attenuation. The autocorrelation function of the new pulse, in terms of the autocorrelation function of the original pulses, is then

$$\begin{aligned} R_y(\tau) &= \mathrm{E}\left[y(t)y(t+\tau)\right] \\ &= a^2\,\mathrm{E}\left[x(t)x(t+\tau)\right] + b^2\,\mathrm{E}\left[x(t+\Delta t)x(t+\Delta t+\tau)\right] \\ &\quad + ab\left\{\mathrm{E}\left[x(t)x(t+\Delta t+\tau)\right] + \mathrm{E}\left[x(t+\tau)x(t+\Delta t)\right]\right\} \\ &= \left(a^2+b^2\right)R_x(\tau) + ab\left[R_x(\tau+\Delta t) + R_x(\tau-\Delta t)\right] \end{aligned} \quad \text{A.2)}$$

The PSD is defined as the Fourier Transform of the autocorrelation function, resulting in

$$S_y(\omega) = \left(a^2+b^2+2ab\cos\omega\Delta t\right)S_x(\omega) \quad \text{A.3)}$$

The term in parenthesis reshapes the original PSD. To make this more clear, set $a = b = 1$. Then

$$S_y(\omega) = \left(2+2\cos\omega\Delta t\right)S_x(\omega) \quad \text{A.4)}$$

If there is more than one pulse collision, the shaping coefficient simply becomes the some of the total number of pulse collision shaping coefficients.

Pulse collisions within the GPS receiver are much more probable because the filtering stretches the pulses and Δt can be much larger. Of course, this is accounted for in the graphs shown above. This is also true for the 19.6875 MHz PRF case, where the time between pulses is 50.8 nanoseconds. Due to filtering, the pulses are stretched much more than that. This is shown in Figure A.18 for one one-nanosecond UWB pulse. Thus, PSD shape within the receiver can change considerably and explains why the responses and PSDs in Figures A.14 through A.17 show a significant offset in frequency (about 5 MHz) when the input spectral line was right on the center of the filter.

A.4 Conclusions

From the responses shown above, it is very clear that the effect of UWB pulse sequences on a GPS receiver is much like random wideband noise, CW interference, and anything in-between, depending upon the pulse sequence (random, constant PRF or mixture of the two). Thus, the response to UWB emissions can be treated like any other GPS interference. That is, the random sequences can be treated like white noise and the constant PRF sequence can be treated like CW interference – treated as though it were 10 times worse than white noise. Any semi-random sequence would fit somewhere in-between. Thus, because the signal structure of UWB devices are unknown, the must be treated as the worst case CW interference at a 10 dB penalty with respect to white noise interference.

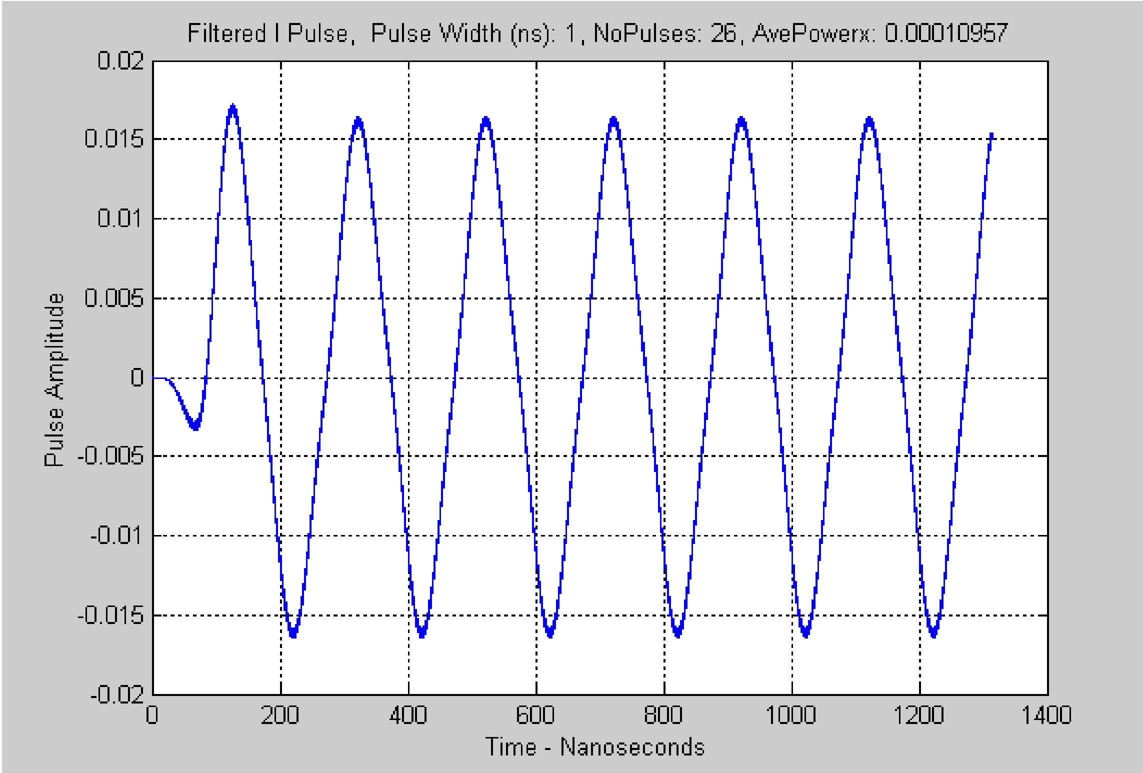


Figure A.14 Filtered In-Phase Response to Constant PRF Sequence

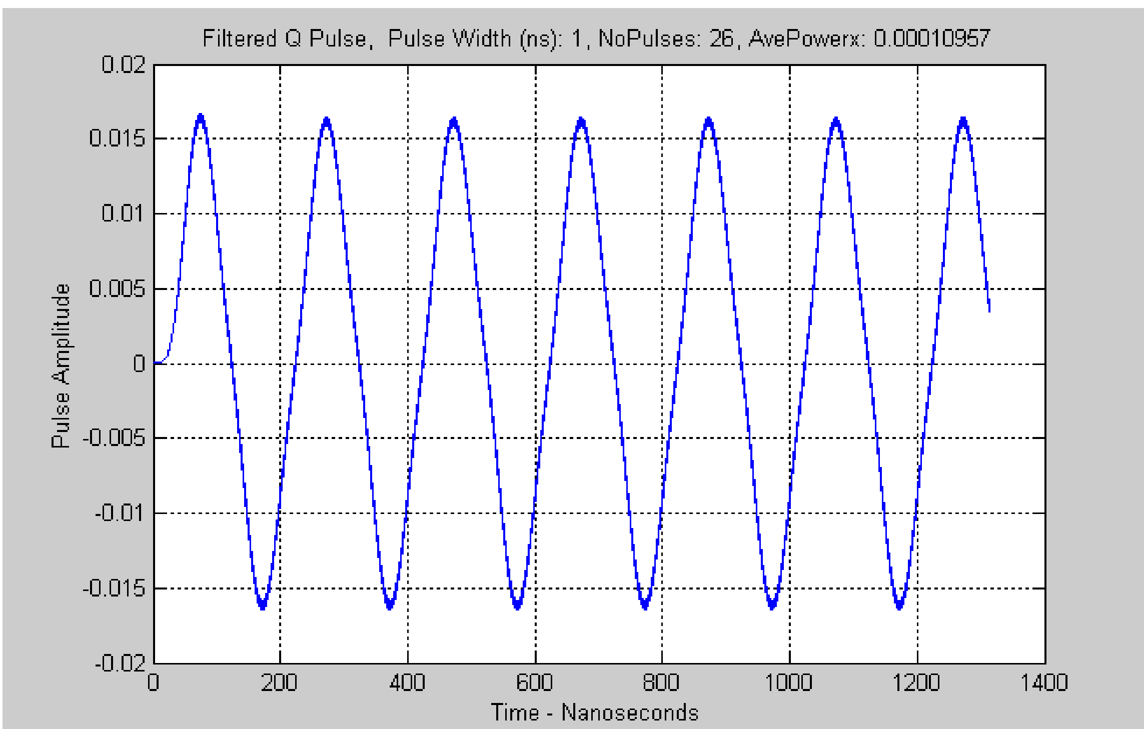


Figure A.15 Filtered Quadraphase Response to Constant PRF Sequence

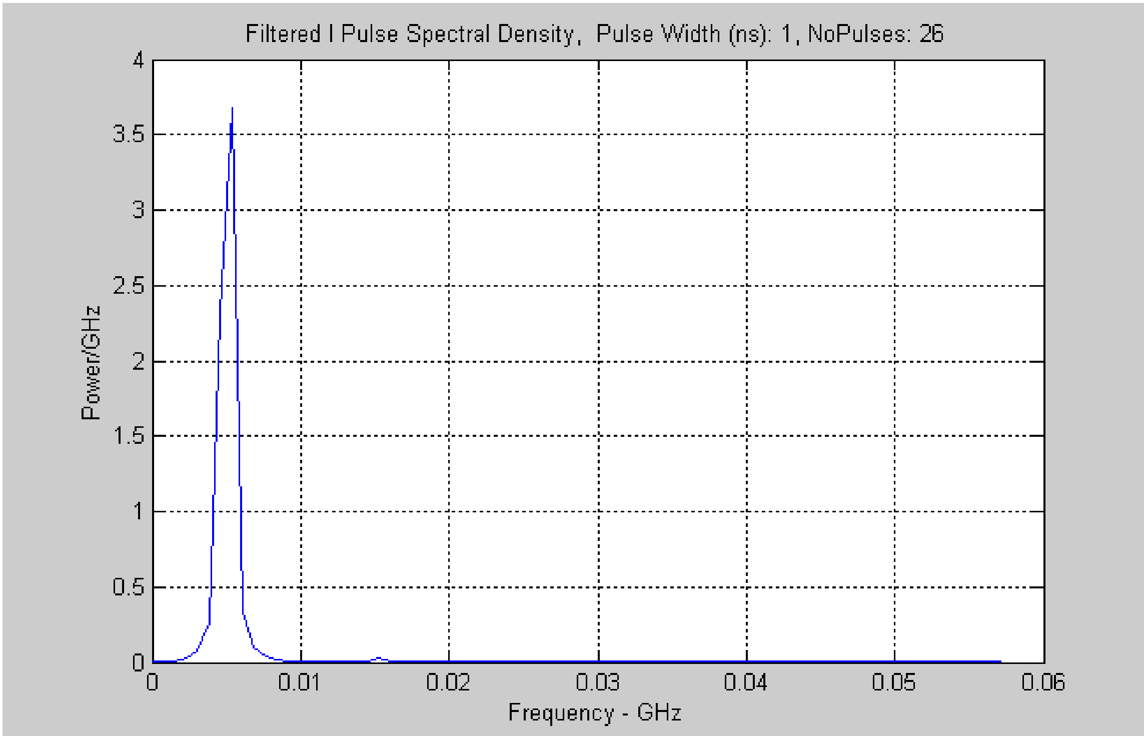


Figure A.16 PSD of Filtered In-Phase Component for Constant PRF Sequence

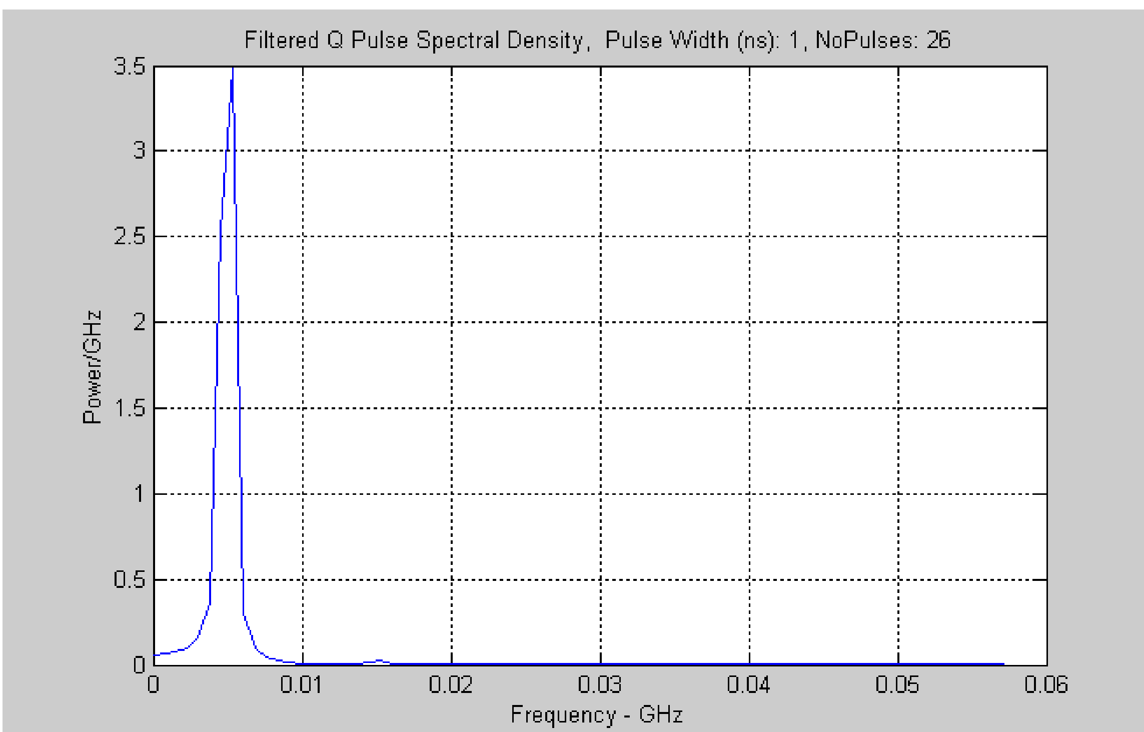


Figure A.17 PSD of Filtered Quadraphase Component for Constant PRF Sequence

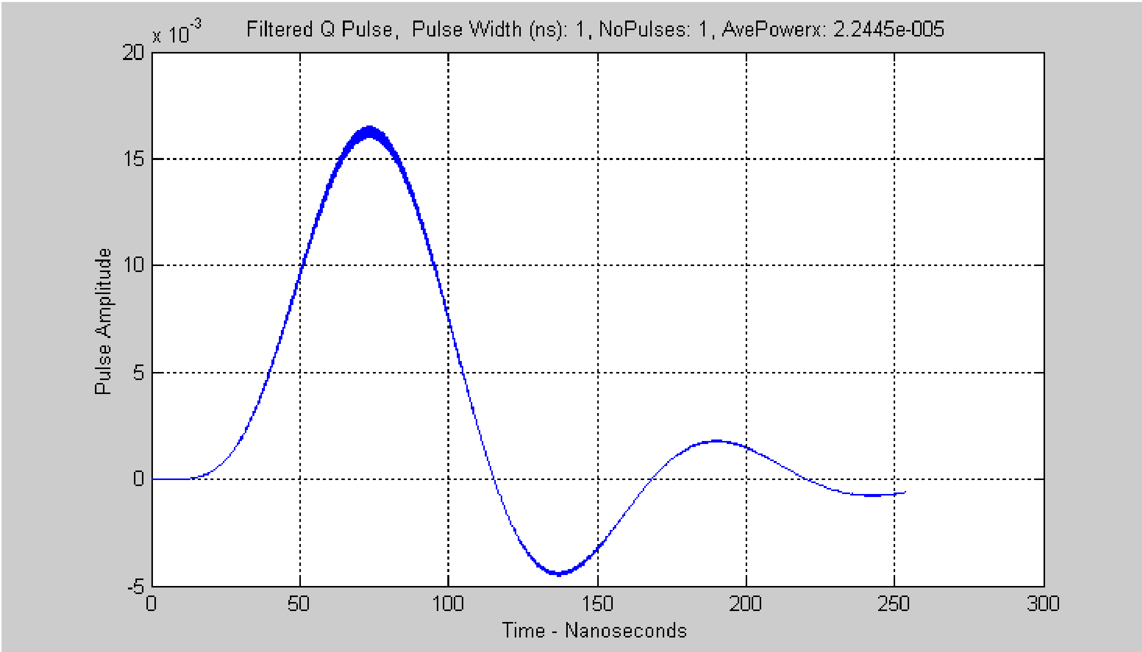


Figure A.18 Receiver Filter Output Response to a Single One-Nanosecond UWB Pulse

APPENDIX B GENERALIZED RFI EFFECTS COMPUTATION METHOD

The modulation formats of UWB transmissions can be characterized so that their RFI power can be simply estimated[33]. UWB signals are modeled as nanosecond and sub-nanosecond duration pulses that repeat with a pulse repetition frequency R_p. The victim receiver has bandwidth B_h whose center frequency is f_o. The effective duration of the receiver IF filter is ~ $1/B_h$. Each pulse has an energy spectral density, $\Phi(f_o)$. The output power of the filter due to input pulse sequence is P_{RFI}. There are 4 cases:

B.1 Case I: $B_{IF} < R_P$

Let R_P have constant intervals so that the Fourier transformation of the time sequence has a simple line spectra whose frequencies are multiples of R_P. The power in the spectral line $f_0 = jR_P$ is:

$$P_{RFI} = \Phi(jR_P)\, R_P^2. \qquad (1)$$

When $B_{IF} < R_P$, only one line component will lie in the pass band of the output filter. Thus the spectral lines are resolved and the output of the filter is a single line with power given by (1). In the time domain, the filter response time interval $1/R_h$ exceeds the pulse repetition time $1/R_P$. This is the worst case RFI modulation format for GPS receivers. Its broadband noise correction factor is –10 dB. Note: the RFI power increases as $20\log(R_P)$.

B.2 Case II: B_h << Average R_p

Let the pulse repetition rate be dithered (pulse position modulation) with average repetition rate of $\overline{R}_P$ and let $B_h \ll \overline{R}_P$. Then the output filter responses will overlap and the output time waveform will be a continuous random waveform whose probability distribution approaches Gaussian noise. UWB devices having this modulation format satisfied the broadband noise criteria and is the recommended RFI modulation format. Its broadband noise correction factor is zero. The output filter RFI power is:

$$P_{RFI} = \Phi(f_0) B_h \overline{R}_P \qquad (2)$$

Note: The RFI power increases as $10\log(\overline{R}_P)$.

B.3 Case III: B_h < Average R_p

Let the pulse repetition rate be dithered (pulse position modulation) with average repetition rate of $\overline{R}_P$ and let $B_h < \overline{R}_P$. There will be both continuous spectra and line spectra of varying strength at integer multiples of $\overline{R}_P$. The strongest lines will have power of:

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[33] Pagett, J., "WINForum Response to FCC 98-208 NOI, Review of of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems," Attachment 1 'Analysis Ultra-Wideband Transmissions' Dec. 7, 1998

$P_{RFI} = \Phi(f_0)\,\overline{R}_P^2$ (3)

The position and intensities depend upon the pulse-position deviation relative to the average pulse rate deviation $1/\overline{R}_P$. Because of the presence of line spectra, Case III can have a broad band noise correction factor approaching –10 dB.

Note: The RFI power increases as $20\log(\overline{R}_P^2)$.

B.4 Case 4: $R_P << B_h$

When the filter bandwidth B_h is much greater than the pulse repetition frequency R_P, the pulses can be resolved in the time domain. In the frequency domain, the filter bandwidth spans many multiple spectral lines and cannot resolve them. This fact holds regardless of whether the pulse repetition frequency is dithered or not. This follows because the pulses are completely resolved in time. The filter output RFI power is:

$P_{RFI} = \Phi(f_0)\,B_h^2$ (4)

Note: The P_{RFI} varies as $20\log(B_h)$. Case 4 causes symbol interference in the victim receiver.

The four cases described above are the theoretical basis of the Stanford University and NTIA test results. In particular, they are the models that NTIA used to obtain their bandwidth correction factor methodology. Clearly these equations show why the UWB devices must be specified in terms of their modulation format. This is the reason why the broadband noise correction factor is necessary in the RFI link budget.

APPENDIX C LINE-OF-SIGHT PROPAGATION FROM MULTIPLE RFI SOURCES

An aircraft flying over ground-based RFI sources can have a relatively short line-of-sight distance and nearly equal path loss to a number of those sources. An RFI link budget factor that accounts for cumulative RFI effects from multiple RFI sources can be derived from consideration of the geometry below.

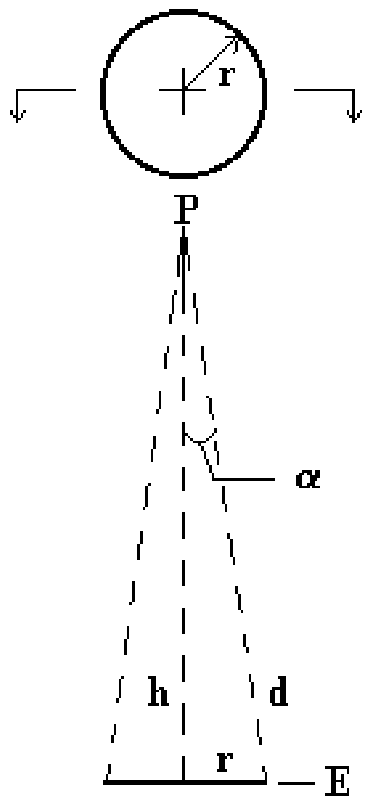

Figure C1. Geometry for Aircraft Overhead Pass of RFI Sources

In Figure C1, Point P represents the airborne GPS receive antenna and Surface E represents a planar surface containing RFI sources. Definitions for the geometric factors in the figure are:

- h = minimum distance from P to plane E;
- d = distance from points on E whose free-space propagation path spreading loss differs from the loss at distance h by a fixed ratio *LR* (loss is proportional to distance squared);
- r = the radius of the circle containing the points of the fixed path loss ratio *LR* related to the length d; and
- α = the angle between lines h and d, a GPS antenna pattern angle.

Since the propagation path spreading loss ratio between the paths of lengths d and h is given by

$$LR = d^2 / h^2 ,$$

and since the line segments *h*, *d*, and *r* form a right triangle so

$$r^2 = d^2 - h^2 ,$$

then simple substitution and algebraic manipulation yields the result:

$$\mathbf{r = h \bullet \sqrt{(LR - 1)}},$$

where $LR = \text{antilog}_{10}(LR_{dB} / 10)$.

The antenna pattern angle (α) is defined as $\cos^{-1}(h/d)$; thus

$$\boldsymbol{\alpha = \cos^{-1}(1/\sqrt{(LR)})}.$$

Use of the equations for circle radius, *r*, and antenna pattern angle, α, is illustrated by Category I aviation precision approach numerical examples where the closest antenna separation distance (*h*) is 100'. Consider loss ratio values (LR_{dB}) of 0.5, 1 and 3 dB. For the 0.5 dB ratio value:

$r = 100 \bullet \sqrt{(1.1220 - 1)} = 34.93$ feet (**69.9** feet diam.), and

$\alpha = \cos^{-1}(1/\sqrt{(1.1220)}) = 19.25$ degrees.

For a 1 dB loss ratio:

$r = 100 \bullet \sqrt{(1.2589 - 1)} = 50.9$ feet (**101.8** feet diam.), and

$\alpha = \cos^{-1}(1/\sqrt{(1.2589)}) = 26.97$ degrees.

For a 3 dB ratio:

$r = 100 \bullet \sqrt{(1.9953 - 1)} = 99.8$ feet (**199.5** feet diam.), and

$\alpha = \cos^{-1}(1/\sqrt{(1.9953)}) = 44.93$ degrees.

For the Category II precision approach minimum separation distance (h = 70'), the circle size for a given loss ratio scales down as *h* and antenna pattern angle remains constant.

These numerical examples illustrate several concepts. First, path loss increases rather slowly for fairly large horizontal separations from closest point below the airborne antenna. Second, antenna angles associated with small path loss ratios are small enough to neglect antenna gain variation. For larger path loss ratios, the antenna gain may actually increase for sources near the edge of the area and thus partially offset the effect on overall propagation path loss of the increased distance to those sources. Neglecting antenna gain variation is probably unwarranted for cases with larger than 3 dB loss ratio. Finally and most importantly, circular spaces around the closest RFI location associated with small path loss differences are large enough to contain several mobile sources. A common case where multiple sources might be visible is that of multiple vehicle-mounted UWB emitters in heavy traffic on a roadway below a runway approach.

APPENDIX D TOTAL SYSTEM ERROR STATISTICS

This appendix gives further analysis which justifies the minimum separation distance between a UWB emitter and an airplane performing a CAT II/III operation. Specifically, the statistical characteristics of the TSE are analyzed to show that the 21.9 ft of deviation below the glidepath assumed in the analysis in section 4.1.1 is reasonable.

D.1 Flight Technical Error

Requirements for flight technical error (FTE) in the vicinity of the category II decision height are defined in the FAA regulations for category II approval given in FAA AC 120-29A. These regulations require the airplane to be able to track the path to within +/- 35µA or +/-12 ft, whichever is larger. At 100 ft HAT, +/-12 ft is larger. AC 120-29A also recommends that excessive vertical deviation indications be implemented. On many modern airplanes, excessive vertical deviation indications are implemented such that some annunciation is given when the deviations exceed one half of full scale. At 100 ft HAT, this also corresponds to +/-12 ft. Even where special annunciation of excessive vertical deviations are not provided, it is common for standard operational procedures to specify that a go-around should be performed when the vertical deviations exceed 1 dot (on a 5 dot scale) or approximately one half full scale. This effectively creates a +/-12 ft window, which acts as a FTE probability distribution tail-cutter. Therefore, it is assumed pilots will maintain vertical course deviation within the Category II window which is half the full-scale deflection and where 0.7^o is full-scale deflection. The conversion from degrees to feet for ILS is given by the following equation: $[0.7^o\pi/180]$ $100/\mathrm{Tan}(3^o) = 23.3$ ft. The category II indicated window is ½ full scale or 23.3/2 = 11.65 ft ≈ 12ft. Typically, a pilot will do a go-around if he exceeds 1 dot deviation for a 5-dot display (2 dots above the glide path and 2 dots below the glide path). For an 11- dot display there would be 5 dots above the glide path and 5 dots below the glide path so the pilot would do a go-around if the deviation exceeds 2.5 dots.

The Advisory Circular requirements for a minimum system allow 5% of the approaches to exceed the +/-12 ft window. Thus a worst case FTE distribution would be represented by a normal distribution with a 1 sigma value of 6 ft. As a matter of practicality, the rate of missed approach is known to be much lower than 5%. Consequently, this analysis will also consider a nominal vertical FTE distribution such that 99.9% of the approaches remain within the +/- 12 ft window. This would result from a normal distribution with a 1 sigma value of 3.65 ft.

D.2 Navigation System Error

Navigation System Error (NSE) requirements for GBAS to support CAT II/III are not yet finalized and accepted internationally. Recent work indicates those previously proposed values for the Vertical Alert Limit (VAL) for CAT II/III may be unnecessarily stringent.[34] Nominal accuracy for GBAS is driven by the VAL. Typically, VPL_{H0} dominates and service is available if VPL_{H0}<VAL. Consequently, for the worst case geometry, the nominal 1 sigma vertical

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[34] Murphy, T., et. al. "Considerations for GBAS to Support CAT II/III Operations", WP 19, ICAO GNSSP WG B, October 2000, Yokohama, Japan

accuracy is given by: VAL/K_{ffmd}. From the LAAS MASPS, for PT 2 & 3, VAL = 5.3 meters and K_{ffmd}=6.641. Using these values, the accuracy for the worst case acceptable geometry is 5.3/6.641 $\approx$0.8 meters 1 sigma.

There are 2 issues with using this requirement for the NSE.

1. The VAL requirement in the MASPS may be overly stringent. This could result in a significant penalty in service availability. Poor service availability could drive cost and complexity into the GBAS design (e.g. by requiring the addition of pseudolites to achieve useful levels of availability).

2. The use of the worst case geometry implicitly assumes that the continuity requirement (i.e. that the probability of a continuity event) is applicable to every single exposure interval and not representative of an average rate. Continuity requirements applied to every exposure interval are referred to as 'specific continuity' requirements, where continuity requirements that relate to an average rate are referred to as 'average continuity'. In some cases it is appropriate to use specific continuity rather than average continuity. In other cases, average continuity is the appropriate interpretation. For the case of CAT II/III operations, the choice between interpretation of continuity as specific continuity or average continuity is still somewhat controversial. A significant discussion on this topic by the international community will be required as a step in developing CAT II/III requirements for GBAS. Consequently we will examine the ramifications of both interpretations.

D.3 Accuracy of Worst Case Geometry vs. Accuracy Averaged Over all Geometries.

The instantaneous vertical accuracy depends on the satellite geometry, which varies as a function of time. Therefore the true distribution of errors when observed over a long period of time will be different than the distribution of errors for a specific worst case geometry. This is important because the worst case geometry should by definition be relatively rare for a system with good availability. In other words, the vast majority of the time the system will be operating much better than would be predicted by looking only at the worst case geometry that meets the VAL requirement.

Figure D1 illustrates the vertical error distribution averaged over time as it compares to the assumed distribution for the worst case geometry. We assume that for each geometry, the error is normally distributed with a 1-sigma variation equal to the VPL/6.641. An availability analysis was run to look at the probability distribution of the values of VPL over all time. This was done by computing the satellite geometry at 1 minute intervals using the Martinez constellation, and accounting for up to 4 satellite failures. This pdf of the VPL is then used to develop a weighted sum of normal distributions which represents the time averaged vertical error distribution.

From the figure it can be seen that the distribution of vertical error averaged over all time and constellation states is significantly tighter than the normal distribution corresponding to the worst satellite geometry that would meet a VAL of 10 meters. The circles on the plots show the 'equivalent 5-sigma points" or the points for which the integration of the tails gives a probability mass equal to the mass in the tails of a Gaussian distribution outside 5 sigma.

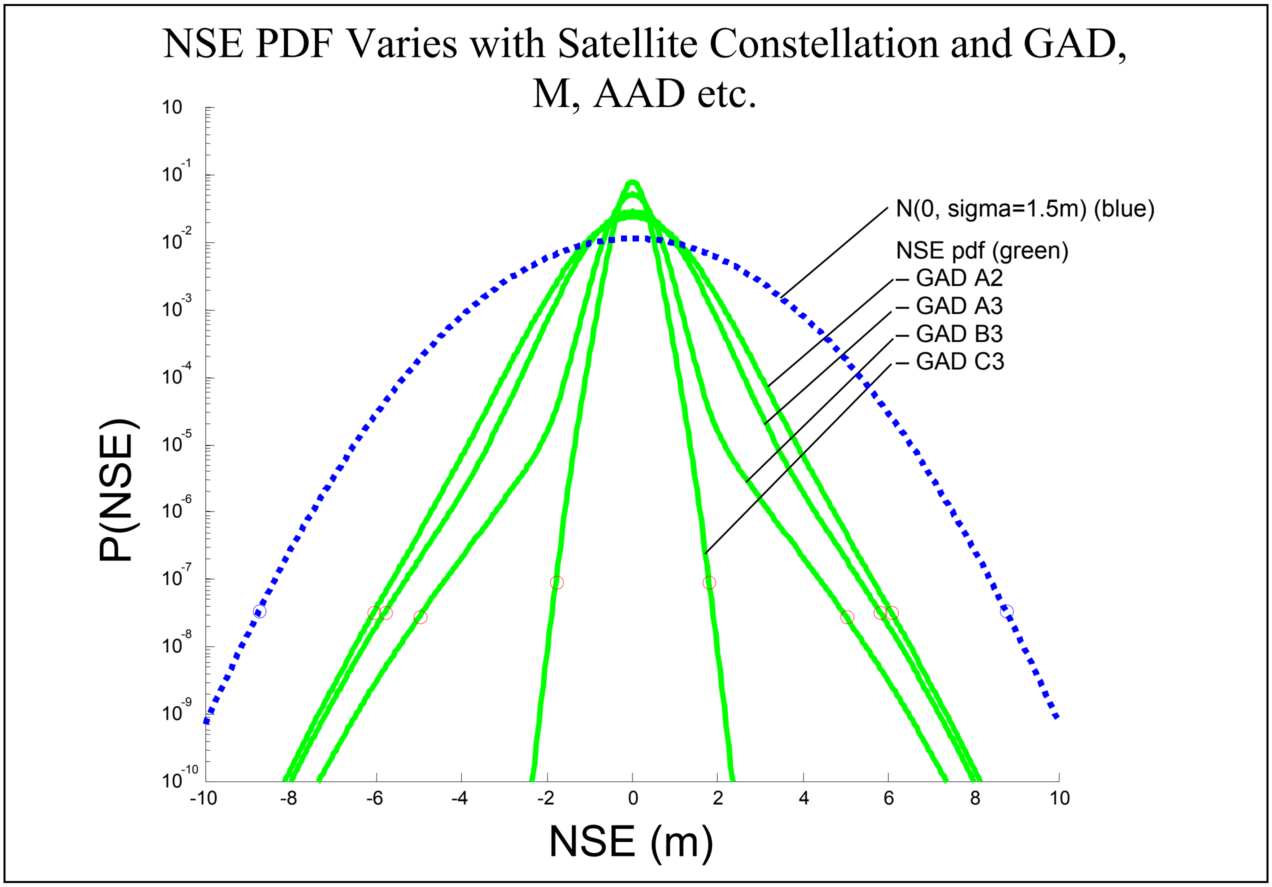

Figure D1 GBAS NSE Distribution Averaged over All Geometries that Meet VAL<10 Meters

D.4 Total System Error Calculation

The TSE distribution is based upon the FTE and NSE distributions. FTE and NSE add, so the distribution of TSE can be obtained by convolving the distributions for FTE and NSE. Five cases were considered. The assumed distributions for each of the cases are listed in Table D1. Two different Gaussian distributions were assumed for FTE: one with σ_{FTE}=6 ft and the other with σ_{FTE}=3.65ft. Both distributions were truncated to +/-12 ft. The cases with σ_{FTE}=6 ft correspond to performance that just meets the required tracking accuracy (i.e. +/-12 ft 95%). The cases with σ_{FTE}=3.65 ft represent tracking accuracy which is better than the requirement and results in 99.9% of the approaches remaining within the +/-12ft window. This is believed to be a more realistic case as the rate of go-arounds is clearly less than 1 in 20 approaches as would be implied by performance that just meets the 95% requirements (assuming the pilot would typically do a go around when FTE exceeds one half full scale).

Three different cases for NSE are considered:

1. Vertical NSE Gaussian distribution with σ_{vert} =0.8 meters. This corresponds to the case where VAL = 5.3 meters.
2. Vertical NSE Gaussian distribution with σ_{vert} =1.5 meters. This corresponds to the case where VAL = 10 meters (and VPL is computed using the K factors appropriate for PT 2).

3. Vertical NSE as observed over all time and satellite constellation states (appropriately weighted by the probability of being in each particular state). For this case, the vertical NSE pdf will depend on the characteristics of the GBAS ground station and airborne equipment (i.e. Ground Accuracy Designator (GAD), Airborne Accuracy Designator (AAD), and number of reference receivers in the GBAS ground station). We assume in all cases that the performance of the ground station is characterized by GAD B3, and the airborne is characterized by AAD B. (It is unlikely that GAD A ground stations will provide useful availability for PT 2 service and that 3 reference receivers will be needed to meet the overall continuity requirements. Consequently, GAD B3 is representative of the worst case ground facility to support CAT II operations). (Figure D1)

Table D1 Assumed FTE and NSE Distributions for the Five Cases Considered

Case	Assumed FTE Distribution	Assumed NSE Distribution	Comments
A	N(0 , σ_{FTE}=6 ft) Truncated at +/- 12 ft	N(0, 0.8 m) Truncated at 5 ∑	Baseline assumptions
B	N(0 , σ_{FTE}=6 ft) Truncated at +/- 12 ft	N(0, 1.5 m) Truncated at 5 ∑	Baseline assumptions except NSE consistent with VAL of 10 m for PT 2 .
C	N(0 , σ_{FTE}=3.65 ft) Truncated at +/- 12 ft	N(0, 1.5 m) Truncated at 5 ∑	FTE such that 99.9% of approaches remain within +/- 12 ft window. NSE consistent with VAL of 10 m for PT 2.
D	N(0 , σ_{FTE}=6 ft) Truncated at +/- 12 ft	Vertical Error pdf averaged over time and satellite constellations. No truncation	FTE such that 95% of approaches remain within +/- 12 ft window. Time averaged NSE with GAD B3 and AAD B.
E	N(0 , σ_{FTE}=3.65 ft) Truncated at +/- 12 ft	Vertical Error pdf averaged over time and satellite constellations. No truncation	FTE such that 99.9% of approaches remain within +/- 12 ft window. Time averaged NSE with GAD B3 and AAD B.

For each case in Table D1 the convolution of the assumed FTE and NSE distributions was computed. Figure D2 illustrates the assumed distributions and the result of the convolution of the distributions for Case E in Table D1. The TSE distribution function corresponding to the random variables FTE and NSE will not be Gaussian. Next, the probability that the magnitude of the TSE exceeds x was computed based on the following relationship:

$$p(|TSE| > x) = 1 - \int_{-x}^{\infty} pdf_{TSE}(y)dy$$

where:

$pdf_{TSE}(y)$ - is the result of the convolution of the FTE and NSE distributions.

For RFI considerations of ground-based mobile emitters we are only interested in the deviations below the glide path.

Figure D3 shows a plot of the probability that TSE exceeds an arbitrary number of feet for the 5 cases listed in Table D1. The point of interest is where each curve crosses 21.9 ft. Case A (based on the assumptions in earlier work) results in a very low probability that TSE exceeds 21.9 ft below the flight path[35]. Increasing the NSE to correspond to a VAL of 10 meters (case B), results in a significantly higher probability that TSE will exceed 21.9ft (i.e. on the order of $2x10^{-3}$).

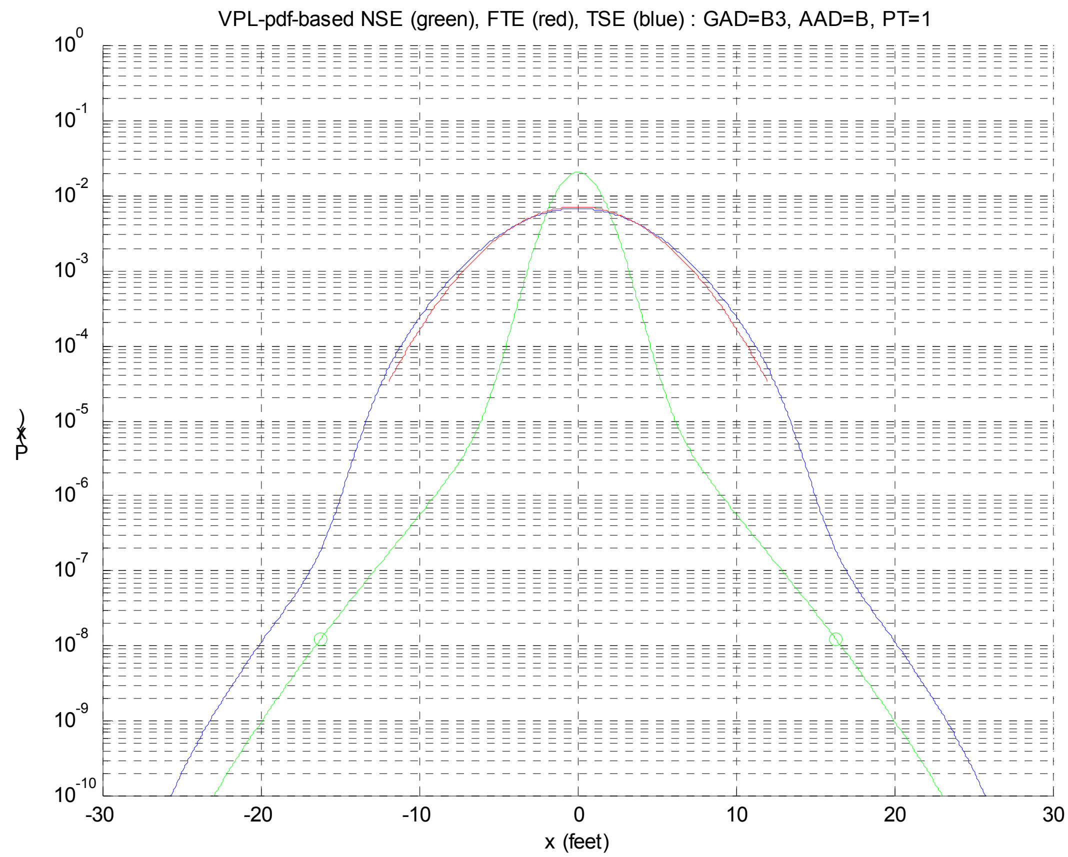

Figure D2 Convolution of Assumed FTE and NSE distribution

Assuming a lower variance of FTE (Case C) improves the situation somewhat, but the probability that TSE exceeds 21.9 ft is still high (i.e. on the order of $4x10^{-4}$). If the time average NSE distribution is used with the more pessimistic FTE assumptions (Case D), the probability that TSE exceeds 21.9 ft is again appropriately low ($\approx 3x10^{-6}$). Using the average NSE in conjunction with the more realistic FTE, (Case E), the probability that TSE exceeds 21.9 ft is even smaller than the baseline case described in earlier work ($\approx 7x10^{-7}$).

[35] The analysis in earlier work apparently did not use integration of a single tail. Consequently the probability values ($2.87x10^{-7}$) are lower than those computed in this analysis given the same assumptions ($\approx 2x10^{-6}$).

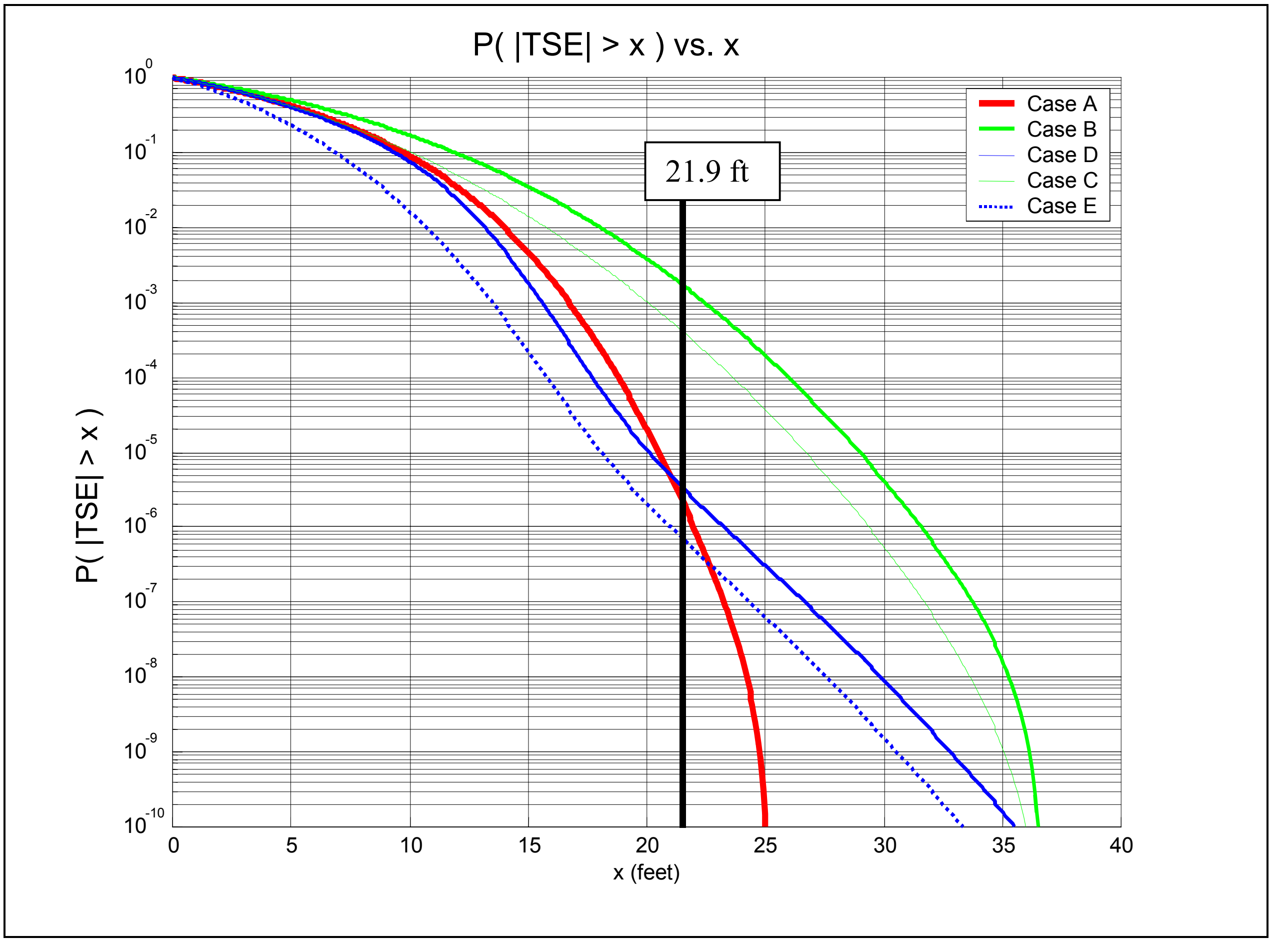

Figure D3 Probability that |TSE| > X Given the Assumed Distributions of FTE and NSE.

D.5 Summary and Recommendations

Examination of Figure D3 shows that the probability that TSE exceeds 21.9 ft, given the assumed distributions of NSE and FTE, is appropriately low for Cases A, D and E. As Case A is based on worst case, specific continuity risk (rather than average continuity) and the assumed NSE is possibly smaller than what is required.

Use of average continuity risk rather than (specific continuity risk) results in probabilities that the minimum separation distance is exceeded on the order of 10^{-6}. This seems like a very reasonable allocation for the continuity risk for this RFI event. The single-sided LAAS system continuity is $2x10^{-6}$ per 15s. Both of these contributors are arguably insignificant when compared to the probability of a go-around due to FTE alone ($1x10^{-3}$ to $5x10^{-2}$ according to the assumptions used in this analysis).