Testing and Research on Interference to GPS from UWB Transmitters

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ABSTRACT

Ultra-Wideband (UWB) signal transmission is a potentially promising technology that is defined by a large fractional bandwidth. Most UWB systems are based on very short pulses of radio frequency energy. UWB technology has potential in a variety of applications, including communication and ranging, and is expected to see increased civil use in the future. Since signals from GPS satellites have very low power levels (–130 dBm or –160 dBW [1]) near the surface of the earth, potential interference from UWB to GPS receivers (and corresponding GPS-based systems such as aeronautical safety-critical flight systems) is a serious concern. Research and testing of this possible interference source is necessary because GPS has a pivotal role in so many critical systems that the public depends upon for its safety and welfare.

In interference testing, pseudorange measurement accuracy is the primary metric of choice for aviation receivers. The most demanding applications, such as aircraft precision approach, require one-sigma pseudorange errors of 15 centimeters or less [2,3]. Acquisition time is the metric of choice for land users, as emergency vehicles may need to quickly acquire the GPS signal after signal loss due to buildings, tunnels, or other obstructions. These users need to acquire the GPS signals and develop new position estimates before the vehicle moves behind the next obstruction.

The majority of the tests described in this paper measured UWB impact on the accuracy and loss-of-lock performance of a high-grade GPS aviation receiver. A smaller test set measured UWB impact on the loss-of-lock performance for two different receivers: the original aviation receiver as well as a low-cost OEM receiver. This OEM receiver is similar to the ones that will find application in cell phones and therefore will deliver E-911 location information in accord with the FCC mandate for such service. Finally, an additional test set was designed to measure UWB impact on the signal acquisition performance of a third receiver, which was a high-grade, general-purpose GPS receiver. In all tests, the UWB interference impact relative to broadband-noise was measured. These tests are crafted to provide input to a separate process that considers the operational scenarios that might place UWB and GPS equipment in proximity to each other. Other key factors were also examined such as antenna manipulation and spectrum whitening.

1.0 INTRODUCTION

The concept of Ultra-Wideband (UWB) application to radar and communications systems has been around since late 1950’s. It has been advanced rapidly in recent years due to the presence of cost-effective enabling technologies. UWB systems have been described using a variety of terms such as impulse radio (or radar), ultra wideband systems, time modulation systems, baseband (or pulse) systems and others. The UWB signal is defined by its fractional bandwidth:

$$B_f = \frac{B}{fc} = \frac{(f_h - f_l)}{(f_h + f_l)/2} \geq 0.25$$

Where f_h and f_l are the high and low cut-off frequency of the signal, respectively.

UWB systems are typically based on radio pulses of extremely short duration (one nanosecond or less); the resulting electromagnetic transmission is spread over a very wide band with extremely low power spectral densities (typically 10^{-9} to 10^{-14} Watts per Hertz) [4].

The main advantages of UWB include:

- minimization of reflection from clutter;
- the ability to penetrate structures with high data rates and high resolution;
- minimization of multipath to operate in cities, obstructed areas and indoors;
- support of high-precision ranging and radar;

- wide bandwidth, which enables low probability of interception by undesired receivers.

The potential applications of UWB include communications, wireless LAN or WAN, wide-area sensing, through-the-wall surveillance, mine detection, radar altimeter, foliage penetration radar and others. Though UWB is eager to get into the market, the current FCC Part 15 rules [5] only apply to unintentional radiators (whereas UWB devices are clearly intentional). While the FCC has been willing to consider relaxing the current rules to accommodate UWB, there are two primary obstacles:

1. The wide bandwidth of UWB systems emissions may result in emissions being transmitted into the TV broadcast and in other restricted frequency bands, which is prohibited under the Part 15 rules.
2. The current emission measurement procedures specified in Part 15 rules were developed for narrowband systems and may be inappropriate for UWB technology.

On September 1, 1998, the Federal Communications (FCC) adopted a Notice of Inquiry (NOI) to investigate the possibility of permitting, under Part 15, the unlicensed operation of ultra-wideband (UWB) radio systems. The inquiry is seeking comments regarding the application of UWB technology and what standards and operating requirements might be necessary to prevent interference to other users of the radio spectrum [6].

On May 11, 2000, the FCC issued a Notice of Proposed Rulemaking (NPRM) suggesting revisions to Part 15 of the Commission's rules regarding Ultra-Wideband transmissions [7]. To date, various parties have submitted more than 700 comments to respond to the FCC's NOI and NPRM and it is still an on-going process [8]. Many comments have expressed concerns of potential interference to existing services, including safety-of-life GPS-based systems [16-19].

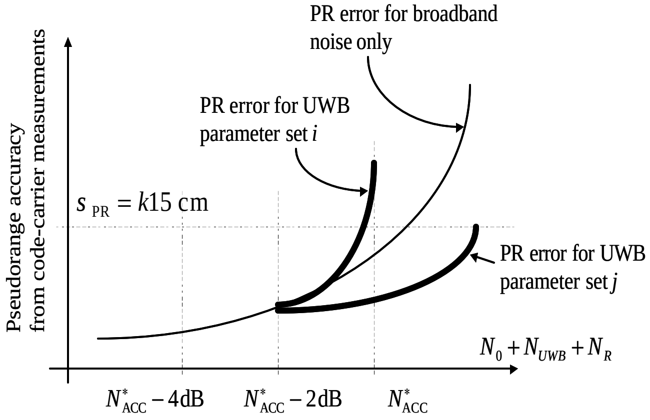
Since GPS is a weak signal with specified received power levels of –130 dBm [1], concern has been voiced as to what impact such a change may have on GPS performance. Preliminary field trials showed potential interference between the two systems [9]. As a result, the Department of Transportation (DOT) has funded a controlled study at Stanford University to investigate the potential interference of UWB devices to GPS. Two DOT reports can be found in [10,11]. This paper reviews Phase I testing briefly and describes Phase II testing in more detail. In addition, it introduces some new studies and presents their results.

2.0 REVISITING OF TEST PHILOSOPHY, UWB SIGNALS, AND PREVIOUS RESULTS

2.1 Test Philosophy

The goal of the UWB testing is to characterize the interference effects of UWB emissions on a typical GPS aviation receiver in a controlled test environment. An RFI-equivalence concept was developed to relate the interference impact of UWB signals on GPS over a range of UWB emission parameters to that of a known and well-understood RFI source, i.e., broadband "white" noise. The approach used in this test is to determine the UWB interference impact for a given UWB transmission that is equivalent to a known level of broadband noise input which causes the GPS receiver to just meet its performance criterion.

Pseudorange accuracy was chosen to be the primary test criterion for aviation receiver testing. The pseudorange accuracy requirement for aeronautical GPS receivers is a standard deviation of 15 cm or less. The equivalence concept test methodology consists of inserting broadband noise into the GPS receiver and increasing its level until a standard deviation of 15 cm of pseudorange error is measured. The broadband noise source is then reduced by 4 dB, and the UWB emission level is increased until the measurement returns to a 15-cm standard deviation of pseudorange error. Another UWB parameter (e.g. PRF) is then chosen, and the entire sequence repeated until all desired combinations of UWB parameters have been investigated. From this interference effect data, a profile of the UWB parameters that have the most significant effect on GPS accuracy performance will emerge (see Figure 1).



Note: error bars have been suppressed in this figure.

Figure 1: Illustration of Noise-Equivalence Concept

These tests were crafted to provide input to a separate process that considers the operational scenarios that might place UWB and GPS equipment in close proximity. UWB interference scenarios might, for example, place

UWB transmitters close to GPS/cellular phone equipment required in the future to provide position reports with all E-911 calls. They may also include the use of GPS for precision approach of aircraft and for runway incursion avoidance. Each interference scenario will have a link budget that assumes that the presence of certain types of interference. The tests described here will not develop these scenarios or the associated link budgets. Rather, they will provide data on the interference effects of various combinations of UWB signal parameters, allowing scenario designers to evaluate the impact of given levels and types of UWB transmissions on real-world GPS users.

2.2 UWB Signal Under Test

There are different types of UWB systems. The interference from UWB to GPS will depend on the type of UWB and its associated parameters. Through our tests, a UWB transmitter prototype was used that consists of three main components: A pulse generator (HL 9200), a 800 MHz high-pass filter, and an amplifier with bandwidth of 2-8 GHz (see Figure 2):

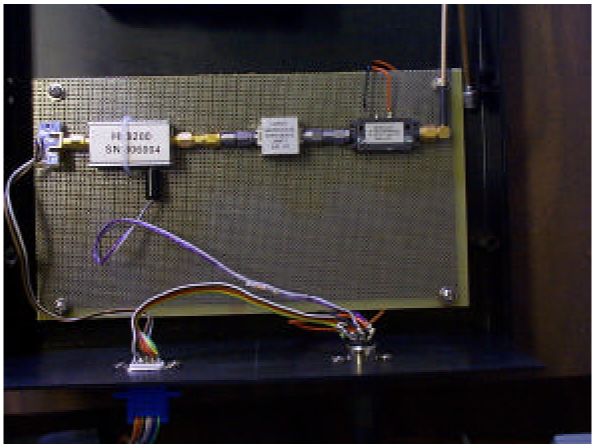


Figure 2: UWB Transmitter Prototype

A single pulse shape and the UWB signal spectrum are shown in Figures 3 and 4.

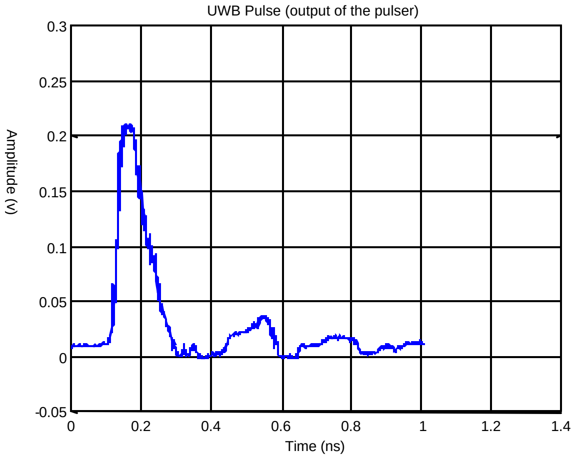


Figure 3: A Single UWB Pulse

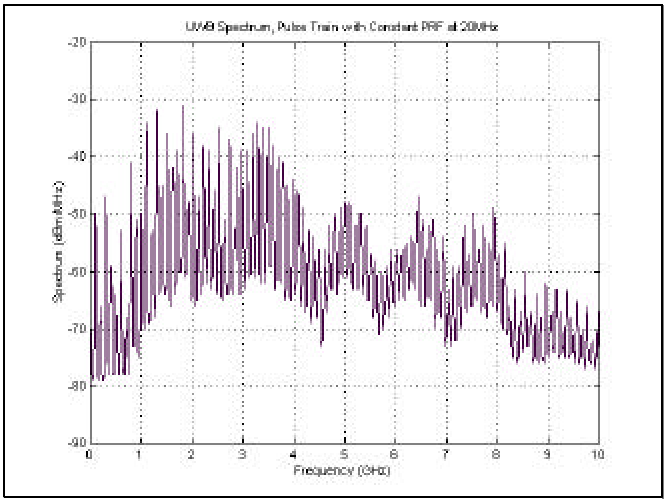


Figure 4: UWB Spectrum

2.3 Summary of Previous Results

A total of 81 UWB waveforms were tested in Phase I that covered various combinations of Pulse Reputation Frequency (PRF), burst duty cycles, random On-Off Key (OOK) and Pulse Position Modulation (PPM). The detailed procedure and test results can be found in [12]. Since the Phase II test is a natural extension of the Phase I test, a summary is presented here to form the basis of this paper. Figure 5 shows an example plot that summarizes the results of unmodulated UWB tests for PRFs between 100 KHz and 20 MHz. It initially appears to suggest that the UWB impact increases while PRF is higher. When the PRF is 5 – 20 MHz, the impacts of UWB are similar to that of broadband white noise. When the PRF is getting lower (100 KHz – 1 MHz), the impact of UWB decreases. Besides the observed general trend, it is also noticed that GPS is extremely sensitive to the PRF of 19.94 MHz case: The receiver lost lock with a minimal addition of UWB power!

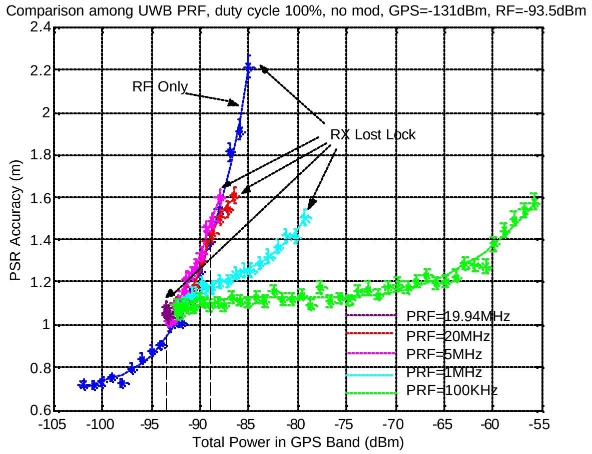


Figure 5: Comparison of UWB among Different PRFs

In order to take a careful look at the spectral line sensitivity, three cases with similar PRFs but different spectral line structures were compared (see Figure 6). It is clear that a large spectral spike hits the peak of GPS L1 main lobe when the UWB PRF = 19.94 MHz. This spike hits the side of the main lobe when PRF = 19.95 MHz and hits about the 5th GPS side lobe when PRF = 20 MHz. This explains why the PRF = 19.94 MHz case does the most severe damage to GPS – the receiver loses lock (making the satellite unusable) way before the accuracy requirement is exceeded.

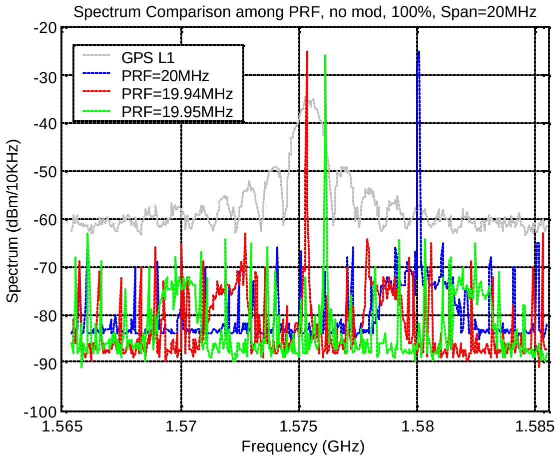


Figure 6: Spectrum Comparison among PRF = 20 MHz, 19.94 MHz, and 19.95 MHz

The main findings from the Phase I tests were:

1. In testing the first aviation receiver, the potential interference from UWB to GPS was demonstrated along with the expected dependence on UWB parameters;
2. The impact depends on the location of spectral lines relative to GPS;
3. Lower PRF tends to result in less interference;
4. For relatively high PRFs UWB can, at best, impact performance equivalent to an increased noise floor.

3.0 TEST SETUP AND SCOPE

As shown in Figure 7, the GPS signal, broadband noise, and UWB are combined before being injected into a GPS bandpass filter. A single-channel WelNavigate GS-100 GPS simulator is used to generate the GPS signal with satellite PRN 21 for Phase II testing. The GPS signal attenuator was set such that the GPS signal at the receiver port was ?131.3 dBm. A NoiseCom 111A noise generator and a low-noise amplifier are used to generate broadband noise, and a manually adjustable attenuator is used to vary the RF noise power. A Tektronics AWG 2021, which triggers the UWB pulse generator, is used to trigger the pulsar to provide the desired UWB pattern. A programmable attenuator is used to sweep UWB power within the desired range. The power meter and the spectrum analyzer are used for real-time monitoring. The test has been automated using Labview and IEEE GPIB buses.

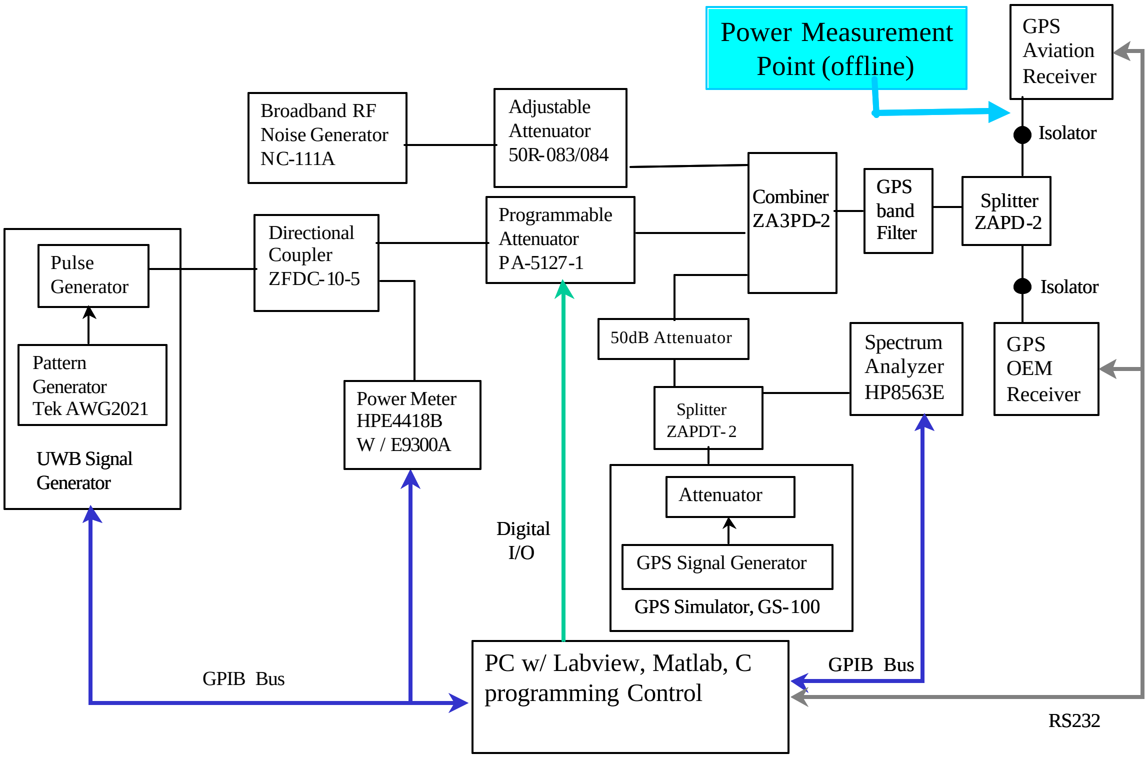


Figure 7: UWB Interference Test Setup

Note that a GPS L1 filter is inserted between the combiner and the GPS receiver. All power (RF and UWB) is measured in the GPS band so that they can be combined and compared later. The GPS L1 filter also controls the bandwidth of the interference. It is important to note that narrow band receiver front ends will further limit the UWB power being processed.

In this phase of test, several aspects were investigated following the previous testing:

1) Data collection for both 2 and 4 dB back-off points to render UWB noise equivalence factors;
2) Loss-of-lock testing from an OEM receiver in addition to the aviation receiver;
3) Acquisition testing of a general-purpose receiver.

A subset of initial UWB waveforms was used in testing:

1. PRF = 20 MHz, no modulation
2. PRF = 19.94 MHz, no modulation
3. PRF = 100 KHz, no modulation
4. PRF = 15.91 MHz, 2-position PPM
5. PRF = 15.94 MHz, 2-position PPM
6. PRF = 2 MHz, 10-position PPM
7. PRF = 1.994 MHz, 10-position PPM

4.0 TEST RESULTS

4.1 Accuracy Test with Multiple Back-off Points

In addition to testing the accuracy versus total noise power from the 4 dB back-off point, a 2 dB back off point was also tested. Rather than using precisely 2 and 4 dB back-off values, settings of 1.54 and 3.54 dB were used as the exact back-off values (this is not critical as the important aspect of the testing is to determine performance at two specific known measurement points in order to construct the equivalence test). The values 1.54 and 3.54 dB correspond to the nearest possible desired fixed attenuator setting available in the testing for the specific step attenuator utilized (“2 dB” and “4 dB” are used through the paper without further clarification).

Figure 8 and 9 are the test results for constant PRFs of 20 MHz and 19.94 MHz respectively. As should be expected, the 4 back-off trace approximately follows the 4 dB back-off trace reported in Phase I testing (Figure 5). This shows the consistency of the results being recorded since the configuration had been reconstructed and re-calibrated, yet the results remain the same. Also note the similar curves traced out by both back-off trials, thus it could be predicted that additional back-off point testing would produce similar results.

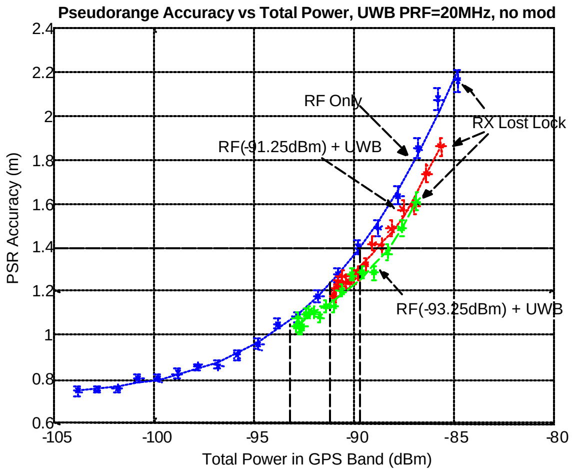


Figure 8: Multiple Back-Off Points with a 20 MHz Constant-PRF UWB Waveform

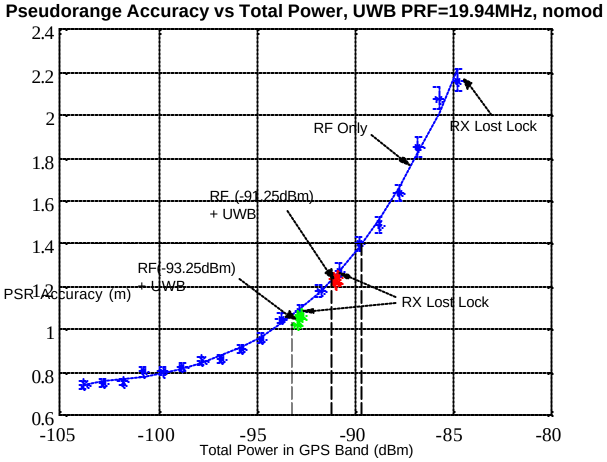


Figure 9: Multiple Back-Off Points with a 19.94 MHz Constant-PRF UWB Waveform

It was reported in Phase I testing that a 20 MHz constant PRF places two distinct spectral lines at 1560 MHz and 1580 MHz about the GPS band. As such, the 20 MHz constant PRF waveform results in spectral lines away from the majority of the GPS spectral energy. However, if that constant PRF were changed slightly, to 19.94 MHz, the UWB spectrum results in a distinct continuous wave (CW) line that falls at an integer multiple (79) times the PRF which is at 1575.26 MHz or right within the main spectral lobe of the GPS signal (Figure 6). It shows again that in this case the performance is significantly worse, the receiver loses lock with an additional –101.27 dBm of UWB energy at either of the two back-off points and cannot achieve the desired accuracy point. This is consequence of a UWB waveform that appears as CW interference rather than broadband noise-like interference. The performance difference between broadband and CW interference is well understood and according to the MOPS for aviation receivers, CW interference masks are 10 dB more restrictive than those for broadband interference.

Note that when only broadband noise was applied, the receiver lost lock at –83.8 dBm. As stated earlier, all power measurements were taken after a GPS L1 filter, which has a bandwidth of approximately 24 MHz. By comparison, UWB is as much as 17 dB more damaging than broadband noise. In other words, a UWB signal that is 17 dB weaker than broadband noise is equally destructive, when the noise is measured at the output of a 24 MHz band pass filter. If the broadband noise power is measured at the output of a 1 MHz band pass filter (as in more traditional GPS interference study), than equal damage comes from a UWB signal that is approximately 3.2 dB weaker (which must be qualified by the PRN characteristics under test).

Such degradation was found without making particular effort to place the UWB signals on the more sensitive GPS spectral lines. The closest spectral line of PRF=19.94 MHz to GPS L1 band is at 1575.260 MHz. In the current test, PRN 21 was used and its highest C/A line is at 1575.365 MHz, which is 105 KHz away from the UWB spectral line. This is plotted in Figure 10. A detailed examination of the resulting spectral lines for PRN 21 has been done to investigate the relative magnitude of the various C/A code lines. It shows that the C/A code line at 1575.260 MHz (that line that will have the most overlap with the generated 19.94 MHz UWB spectral line) is 6.5 dB down from the most sensitive C/A code line at 1575.365 MHz. With that compensation, it was concluded that the worst UWB case tested is 9.7 dB more damaging than white noise.

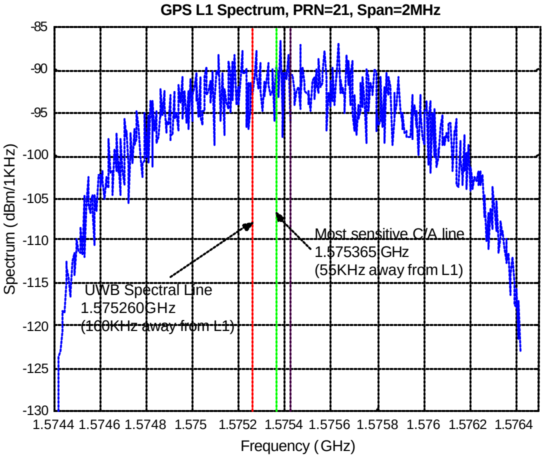


Figure 10: Compensation for Spectral Line Locations

In practice, UWB lines will frequently find more sensitive lines than those in these trials because: (1) many GPS satellites will be in view; and (2) the Doppler frequency for each satellite will change as the satellite moves across the sky, causing the frequency of the more sensitive lines to shift. Eventually, sensitive lines from one satellite or another will fall on the spectral lines from any nearby UWB transmitter that has such lines.

The next case of interest is the 100-kHz constant-PRF UWB waveform. For this signal, the UWB waveform appears as pulsed interference, even after the GPS L1 bandpass filter. GPS receivers are more tolerant of pulse interference and this aspect was first highlighted in the Phase I testing. The results for the multiple back-off tests repeat this assertion and are shown in Figure 11.

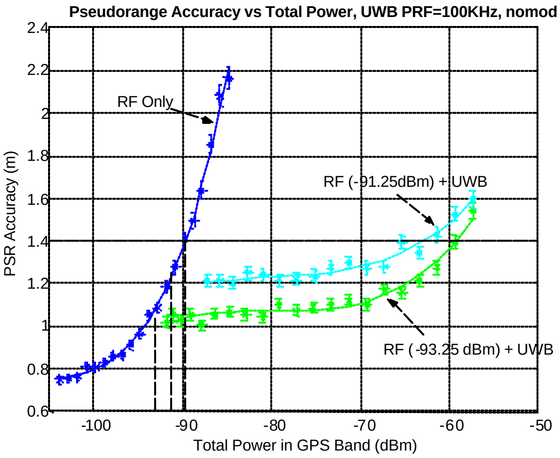


Figure 11: Multiple Back-Off Points with a 100 kHz Constant-PRF UWB Waveform

In this 100 kHz PRF test a significant amount of UWB energy can be added prior to the accuracy threshold being crossed. In both back-off cases tested, the maximum output power of the UWB transmitter (-57.3 dBm) did not result in a loss of GPS receiver lock despite the high power levels in band. A detailed look (see the Table 5.1 for exact figures) shows how much less damaging the UWB is than broadband noise in this case. From the 4 dB back off point, an additional –92.25 dBm of broadband noise or –59.17 dBm of UWB are required to force the receiver to exceed the accuracy requirement. The credit to UWB is 33.08 dB. From the 2 dB back off point, an additional –94.96 dBm of broadband noise or –61.82 dBm of UWB would make the receiver cross the threshold. The credit to UWB is 33.14 dB. Again, the results are quite consistent.

Since the spectral lines resulting from the constant, relatively high, PRF UWB waveforms resulted in predictable yet significant GPS performance degradations. Methods were investigated as to minimize the spectral lines that result from the UWB waveform. Both 2-position and 10-position Pulse Position Modulation (PPM) was re-examined in this test.

In the two-position random PPM scenario illustrated in Figure 12, the pulse takes either the early position (nominal –d) or the late position (nominal +d). The minimum separation of two pulses is 50 ns. A sequence of 252,000 points with d = 2 ns and a = 56 ns (when the clock frequency is 250 MHz) was constructed. The ratio of position dithering (d/a) is 1/28 (3.57%).

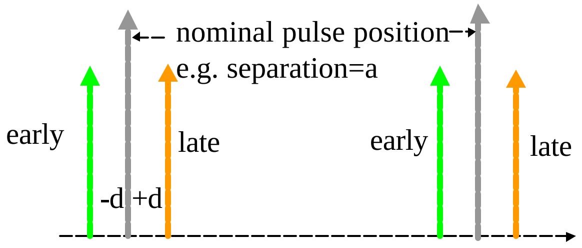


Figure 12: Two-Position Random PPM

However, even with modulation and a reduced PRF, it is still possible to find a specific PRF that results in a distinct spectral line that falls within the GPS spectrum. The modulation did not completely remove the presence of the spectral lines. The test case of 15.91 MHz PRF with 2-position pulse position modulation places a spectral line at 1575.09 MHz, which is again in the primary spectral lobe of the GPS signal (Figure 13). As a result, the GPS receiver loses lock quite early for both back-off points as is shown in Figure 14. At a slightly different PRF, 15.94 MHz, the spectral line adjacent to the GPS lobe falls at 1578.06 MHz, or outside the primary GPS spectral lobe. As such, the performance is significantly improved over the case with a frequency of 15.91 MHz. The impact of UWB approximates that of white noise, as is shown in Figure 15.

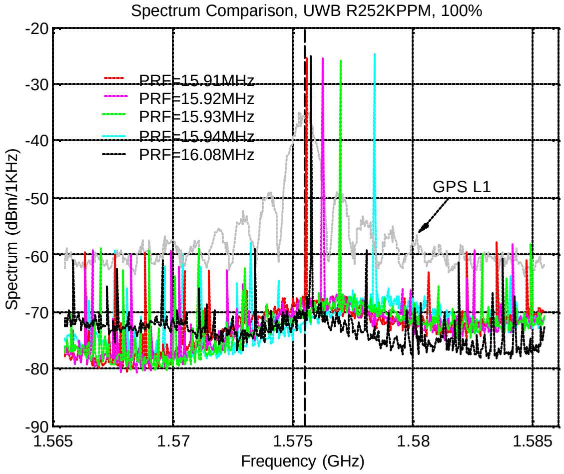


Figure 13: Spectrum Comparison among PRFs with Two-Position PPM

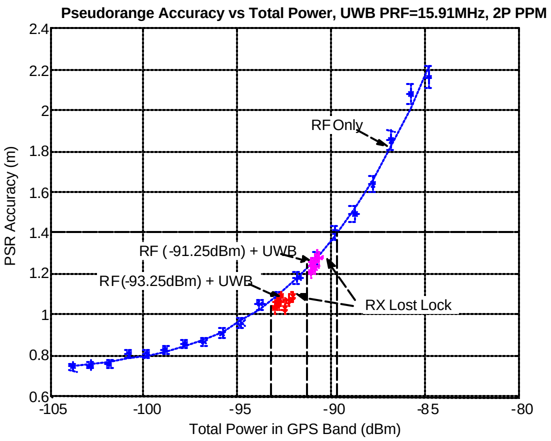


Figure 14: Multiple Back-Off Points for a 15.91 MHz PRF 2-Position PPM UWB Waveform

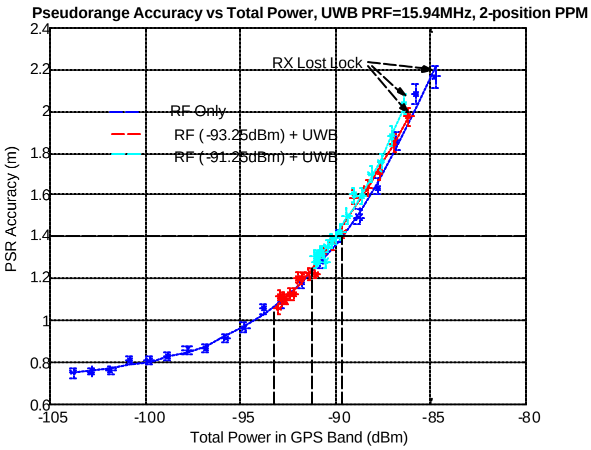


Figure 15: Multiple Back-Off Points for a 15.94 MHz PRF 2-Position PPM UWB Waveform

Again, it is important to note that with a slight change in PRF, one that could result from clock drift from an inexpensive oscillator, there can be significant performance variations in the GPS receiver. The specific impact depends on the exact oscillator, PRN code, and UWB PRF.

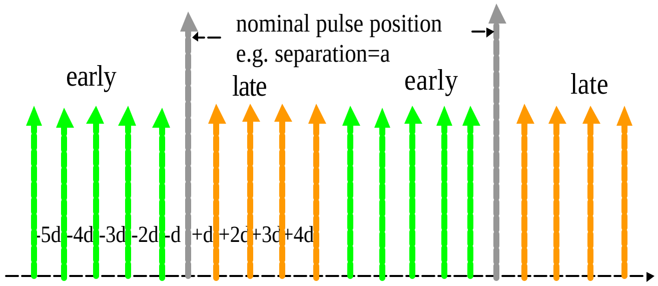


Figure 16: Ten-Position Random PPM

In the ten-position modulated case illustrated in Figure 16, the pulse will randomly take one of ten positions: the early positions (–d to –5d), the nominal position, or the late positions (+d to +4d). The minimum separation of two pulses is 50 ns (this is limited by the capability of the pulser in the test setup). A sequence of 250,000 points was constructed. The maximum PRF that can be supported is 2 MHz, which yields d = 50 ns with a clock frequency of 40 MHz). The ratio of position dithering was from –50% to +40%. The test results are shown in Figure 17. Since there are ten evenly spaced positions for each nominal pulse location, when PRF is set to 2 MHz, the actual spectral lines would look as if the PRF were 20 MHz in the no-modulation case. But each pulse position only has one chance in ten to actually happen; thus the spectral spikes are much smaller, and the noise floor is higher, as shown in Figure 18. The energy from the distinct spikes is translated to the noise floor.

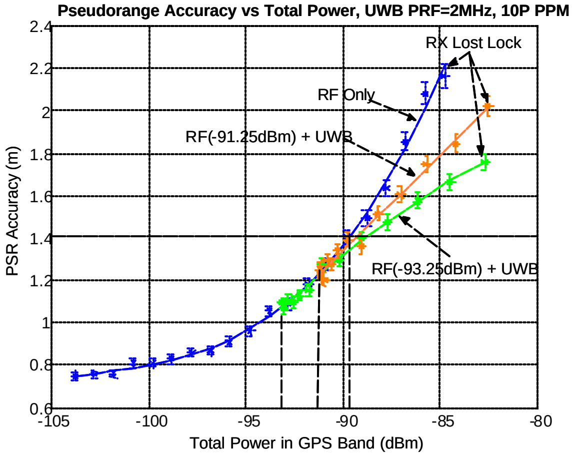


Figure 17: Test Results for Ten-Position PPM

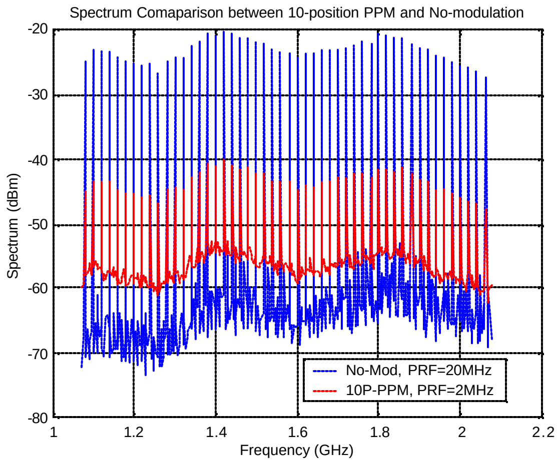


Figure 18: Spectrum Comparison between Ten-Position PPM and No Modulation

The goal behind both of these modulations is to make the appearance of the pulses more random in nature, removing the periodicity and as a result minimizing the undesired spectral lines. The more random the appearance of the pulses can be made, the greater the reduction in the height of the spectral lines. In all of the modulation cases tested, none were able to completely remove the visible spectral lines but all did result in some reduction in their magnitude. Also it is important to recognize that with the position modulation methods, the base PRF needed to be scaled downward to ensure the required 50 ns recycle time for the pulsar. As such, any decreased interference potential should be attributed both to the modulation as well as the reduction in the PRF.

In conclusion, this testing repeated the accuracy test on the desired subset of UWB waveforms. The performance for the 4 dB back-off was very similar to that observed in Phase I testing, thus the results can be called repeatable. In addition, results from 2 dB back-off points also follow closely with the results of 4 dB back-off.

Table 1 provides a summary of the resulting values obtained for Phase II testing for those UWB waveforms in which the desired GPS accuracy levels could be obtained. For this reason the more damaging UWB waveform cases, in which a loss of lock occurred shortly after the UWB signal introduction, are not included in the table.

RF Power Backoff	dBm		1.54	3.54
	mW		0.3192E-9	0.5959E-9
UWB Power at the Cross Point (where the accuracy just exceeds the requirement)	*No Mod PRF = 100 KHz*	dBm	-61.8202	-59.1745
		mW	6.5763E-7	1.2093E-6
	No Mod PRF = 20 MHz	dBm	-92.8137	-89.8223
		mW	5.2315E-10	1.0418E-9
	2P PPM PRF=15.94 MHz	dBm	-95.6357	-92.8432
		mW	2.7317E-10	5.1961E-10
	10P PPM PRF = 2 MHz	dBm	-93.4333	-90.8903
		mW	4.5360E-10	8.1465E-10

Table 1: Multiple Back-off Points Accuracy Test Summary

Using the tabulated values, it is possible to construct a plot of the noise equivalency factor for the UWB waveforms based on these results. The equivalency plot in Figure 19 shows the amount of removed broadband noise power relative to the amount of injected UWB power for selected waveforms. Thus, it provides an indication of the equivalence of the two signals and should aid those preparing link-budget analysis in the future.

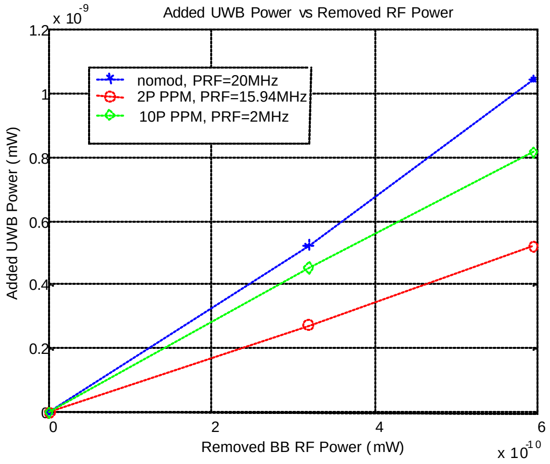


Figure 19: Noise Equivalence Factor

4.2 Loss-of-Lock Test

The platform/experiment used to test accuracy for the aviation receiver can be easily extended to also check the loss-f-lock performance of the GPS receiver in the presence of UWB signals. It is critical to recognize that loss of lock is not a suitable metric for testing aviation receiver performance as a result of the high performance demands on such receivers. Typically accuracy performance degrades beyond useful measures long before lock on the specific signal is lost. However, in the case of an OEM receiver where performance demands may not be as stringent, loss of lock may be considered worst-case acceptable criteria, but it is likely accuracy on this receiver will be impacted as well.

Recall the test configuration from Figure 7. This had changed from the Phase I testing in that a second GPS receiver has been included in parallel with the aviation receiver. This second receiver is an OEM GPS module and has been designed to target the high-volume lower-cost market segment. As such, it is incapable of providing the measurements necessary to determine accuracy performance used in this testing, but it is possible to determine a loss of lock point for this receiver.

It is possible to extend the accuracy test procedure to stress the receivers under test to the loss of lock condition, which typically takes place beyond the accuracy thresholds (this is true with the exception of those UWB waveforms which placed a discrete spectral line directly in the GPS band and forced a loss of lock condition prior to meeting the accuracy bound). Thus the threshold is replaced with loss-of-lock as opposed to the original *k*15 cm pseudorange accuracy.

The loss of lock metric is best presented in tabular format and is shown in Table 2. As a reference point, the loss-of-lock power measurement for broadband noise for the aviation receiver was –83.8 dBm and for the OEM receiver this occurred at a power measure of -87.8 dBm. Thus for the case of broadband noise, the OEM receiver provides lower performance as it loses lock with lower broadband noise power. This is also true, in general, for all of the UWB test cases where data is available. Note that this data came directly out of the accuracy testing. The overall focus of Phase II testing had been on the primary goal of obtaining the multiple back-off accuracy test data and as such less attention was given to obtaining a complete set of loss of lock power measurements as a result of the limited test time available. Thus not all loss-of-lock data points have been recorded for the OEM receiver, but sufficient data is available to make the generalization that the aviation receiver, which was used as the baseline for all testing to date, can be considered to have higher performance and is more robust against interference including UWB than the OEM receiver.

RF Power (dBm)		-91.25	-93.25
UWB Power at the RX-lost-lock Point (dBm) **Aviation GPS RX**	***No Mod PRF = 20 MHz***	-86.03	-87.03
	No Mod PRF = 19.94MHz	-101.27	-101.27
	2P PPM PRF=15.91MHz	-98.38	-97.38
	2P PPM PRF=15.94 MHz	-87.10	-86.10
	10P PPM PRF = 2 MHz	-81.14	-81.14
UWB Power at the RX-lost-lock Point (dBm) **OEM GPS RX**	***No Mod PRF = 20 MHz***	NA	NA
	No Mod PRF = 19.94MHz	-105.27	-104.27
	2P PPM PRF=15.91MHz	-101.38	NA
	2P PPM PRF=15.94 MHz	-88.10	NA
	10P PPM PRF = 2 MHz	NA	-94.14

Table 2: Summary of Loss-of-Lock Power Measurements from Phase II Testing

These results show that the OEM receiver experiences the same sensitivities to the UWB signal (most importantly, the discrete spectral lines) as does the aviation receiver that has been used for all previous testing to date at Stanford University. Across all UWB waveforms tested, the OEM receiver provides lesser performance than that offered by the aviation receiver.

The comparisons between the interference impact from UWB waveforms and from white noise are summarized in Table 3. The negative sign indicates that the UWB is more damaging than white noise. The entries were colored in red, yellow or green respectively for three kinds of outcomes: UWB is more damaging, similar to, or less damaging than broadband noise. The results from accuracy test and the loss-of-lock tests are reasonably close when both data are available. Note that in one case, only accuracy test result was used since the receiver never broke lock even with the full power of UWB (no attenuation). In some other cases, only lost-of-lock results were obtained since the receiver lost lock before the accuracy requirement was exceeded.

UWB Waveform	**D (dBm/ 24MHz)**	**Note(s)**
No Mod PRF = 100 kHz	+33.1	Accuracy test comparison only. RX never broke lock with max UWB power
No Mod PRF = 19.94 MHz	-17.0	Loss-of-lock comparison only. RX lost lock before exceeding acc. requirement
No Mod PRF = 20 MHz	+2.4	Accuracy test comparison.
	-2.7	Loss-of-lock comparison
2P PPM PRF = 15.91 MHz	-13.1	Loss-of-lock comparison only. RX lost lock before exceeding acc. requirement.
2P PPM PRF = 15.94 MHz	+0.6	Accuracy test comparison.
	-1.8	Loss-of-lock comparison
10P PPM PRF = 2 MHz	+1.4	Accuracy test comparison.
	+3.16	Loss-of-lock comparison

Table 3: Summary of Comparisons between UWB and White Noise in a 24 MHz Band

4.3 Acquisition Test

It is well understood that GPS signal acquisition is a more sensitive process than GPS signal tracking [15]. Accordingly, it is critical to consider the impact UWB transmissions will have on the more sensitive acquisition process. These tests were conducted with a high-end general purpose GPS receiver. A broadband noise calibration curve is initially generated to maintain the equivalence-measurement concept in the testing. The GPS signal is introduced along with a specific broadband noise power, and the GPS receiver is given five one-minute attempts to acquire the signal, recording an "acquired" or "not acquired" result. This is done over a range of noise values that allow zero to five attempts to be successful in acquiring the signal. Once the noise curve is complete the highest noise power that resulted in five successful acquisition attempts is reduced by 4 dB and a specific UWB signal is introduced. The UWB signal power is increased to the point at which all five one-minute attempts fail to result in acquiring the GPS satellite. In this way, acquisition performance in the presence of the various UWB signal parameters can be compared with performance in the presence of broadband noise.

Results from all UWB signals as well as the broadband noise cases have been plotted in Figure 20. The top plot shows the percentage of trials that resulted in a successful acquisition attempt as a function of total power. The lower plot indicates the resulting average C/N_0 value reported by the receiver after a successful acquisition attempt at a specific measured power level within the GPS band. The results show a definite correlation with those obtained in the accuracy testing. The UWB waveform that has the least impact is the 100-kHz constant PRF. On the opposite extreme, the most damaging UWB waveform was the same as that which was most damaging in the accuracy testing, the 19.94-MHz constant PRF. This indicates that the distinct spectral lines resulting from the UWB signals will also be the primary issue impacting GPS acquisition performance. Lastly, the strong correlation between the most and least damaging cases for both acquisition and accuracy testing gives evidence that the performance trends observed are not isolated to one mode of receiver operation. Rather, the presence of UWB signals will impact all phases of GPS signal processing.

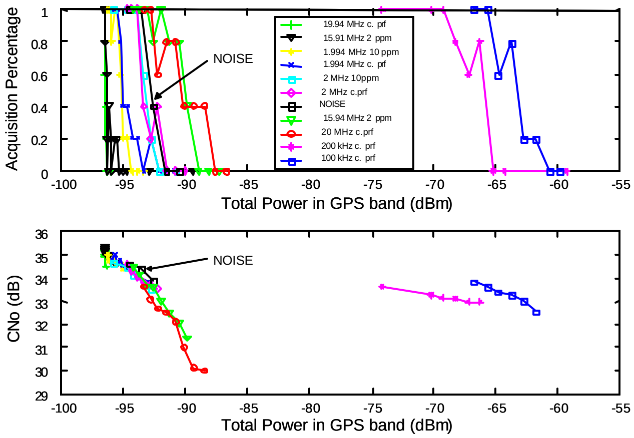


Figure 20: Acquisition Test Results

4.4 Other Factors

4.4.1 Burst Gating Effect

All the UWB signals discussed so far were with 100% burst duty cycle. In another word, the signal (pulses) were emitting in a continuous way. In reality, UWB devices may be operated with partial on-and-off period, i.e. a duty cycle less than 100%. There is a belief that the gating will reduce the inteference impact. The effects of several gated UWB waveforms were examined and the spectrums were plotted to compare with the un-gated versions.

Figure 21 shows a case of 19.94 MHz PRF with 50% duty cycle with the burst on time of 2 ms. The UWB signal was set to be on for 2 ms then off for 2 ms, repeatedly. Since this setting introduced a 4 ms period into the signal, it is not surprising to see many fine spectral lines generated. Those lines are 250 Hz apart and clustered together with the main spectral spike. In a sensitive case such as 19.94 MHz PRF, the one spectral line near the GPS main lobe is joined by many small lines in the sensitive GPS band as well. The combination effects may be more complicated than simply stating that there is "less impact due to gating".

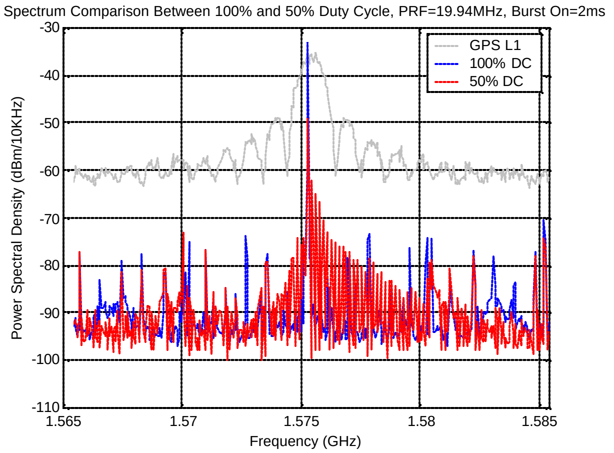


Figure 21: Gating Effect - Spectrum Comparison Between 100% and 50% Duty Cycle

Figure 22 shows another example with the same setting except that the burst on time is changed from 2 ms to 10 µs. Now the gating-introduced spectral lines are 50 kHz apart and much clearer to see. It worthwhile to note that qlthough it is theoretically possible to construct a "noise-like" UWB, the gating effect, finite sequence length, imperfection of the components, and unpredictable long term stability that occur in practice can still produce spectral lines.

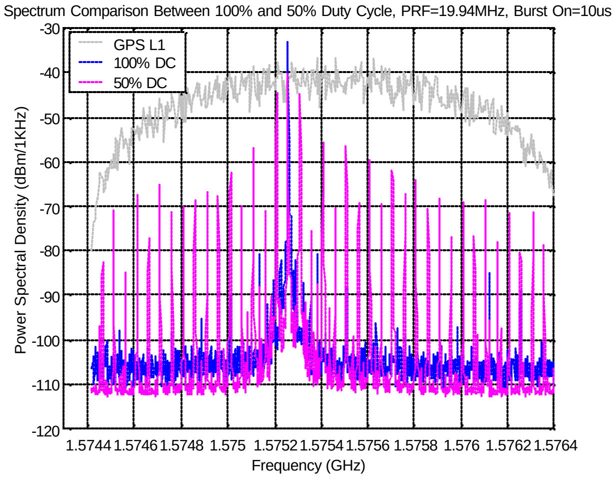


Figure 22: Gating Effect -- Spectrum Comparison Between 100% and 50% Duty Cycle (Burst On 10ms)

4.4.2 Antenna Manipulation

There have been some discussions about the effect of antenna manipulation on UWB signals [12]. A preliminary investigation has been done using the UWB prototype. As showed in Figure 23, the two UWB antennas were placed about 3 feet apart and face-to-face. An object (a person, in one case) was put in between the poles and at approximately the same height as the antennas. A UWB signal with constant PRF of 20 MHz was used in this test.

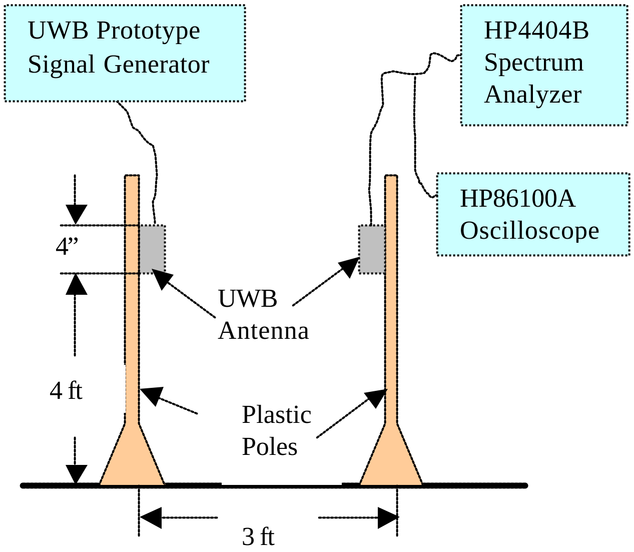


Figure 23: Setup for Antenna Manipulation Test

Figure 24 shows the spectrum of three cases: (1) the nominal setting where the received antenna is an UWB antenna and there are no physical obstructions; (2) a person standing about a foot away from the transmitter as an obstruction; and (3) a GPS patch antenna (~5” diameter) was placed close to the UWB antenna at about one foot away. As shown in the plots in Figure 24, the general trend of the spectra follow one another, but they can easily differ by 3-6 dB at any given frequency (e.g. L1 band). The results qualitatively confirmed that the UWB spectrum (therefore its interference impact on others) is sensitive to the antenna manipulation and obstacles that may be in the line of sight path.

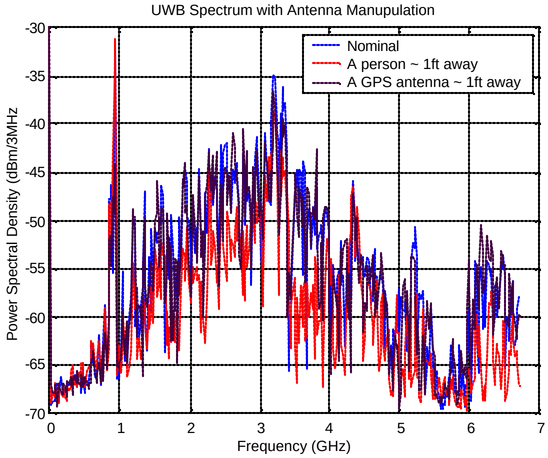


Figure 24: Effect on UWB Spectrum of Antenna Manipulation

4.4.3 Spectral Line Screening

Since the CW-like component of UWB signals is about 10 dB more damaging than white noise-like variants, it seems natural to consider screening for spectral lines for those systems that are most sensitive to additional noise/interference. From the GPS perspective, it is important to realize that not only the main lobe (2 MHz wide centered at L1) needs to be protected, but also the side lobes of the signal spectrum. PRN 21 can be used as an example. Figure 25 shows the amplitude difference between the worst (strongest) C/A code line and the highest lines in the side lobes. Even as far as the 5th lobe, the highest C/A line is only 9.4 dB lower than the worst C/A line in the main lobe, which is less than the punishment for CW-like noise, namely 10 dB. Thus, whatever method is chosen for spectral-line screening, it should be applied across the whole GPS band (1559 – 1610 MHz), rather than only the main lobe.

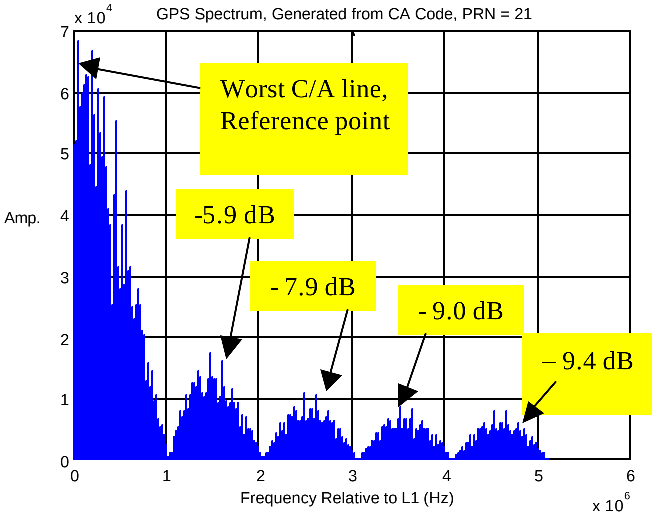


Figure 25: Spectral Line Screening

5.0 SUMMARY AND CONCLUSIONS

The accuracy testing utilizing 4 dB and 2 dB broadband noise back-off points confirmed the main findings from our previous testing (Phase I). UWB interference to GPS can be successfully analyzed using a noise equivalence factor which is a strong function of the UWB signal parameters. Low PRFs (pulse-like) can yield noise equivalence factors that are up to 33 dB less damaging than broadband noise (100-KHz constant-PRF case). The worst case (CW-like) can cause UWB to be about 10 dB more damaging than broadband noise in a 1 MHz noise bandwidth (with a constant PRF of 19.94 MHz). Under the best circumstances (no distinct spectral line visible), UWB signals with high PRFs appear as additional broadband noise in the resulting spectrum.

Loss-of-lock testing was conducted with an OEM receiver in addition to the aviation receiver. The results obtained from the two GPS receivers tend to follow the same trend. UWB signals that generated spectral lines continue to be the problematic cases for the OEM receiver as well as the aviation receiver. This confirms the supposition that these UWB waveforms will likely be damaging for most GPS receivers rather than being a problem for only a specific receiver type. It was also evident that the OEM receiver was less capable, in terms of overall performance, than the aviation receiver used in the bulk of the testing to date.

The acquisition testing again confirmed the problematic cases. Those UWB signals that impacted accuracy and loss of lock most significantly also caused the most problems for GPS receivers trying to acquire the signal. In addition, the UWB signals that had little impact on GPS accuracy performance had little impact on acquisition performance. Overall, the trends of the results observed from accuracy testing closely matched the results that were obtained from other testing modes (acquisition, loss of lock).

A preliminary examination demonstrated that the UWB spectrum is subject to factors such as gating and bringing an object close to the UWB transmit antenna.

Note that what has investigated is by no means a comprehensive set. It is possible that there are cases not tested that could lead to more damaging results. More study and extreme caution are needed to fully address the UWB interference issue.

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