Interference to GPS from UWB Transmitters

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ABSTRACT

Ultra Wide Band (UWB) technology is based on very short pulses of radio energy. In theory, its wide signal bandwidth yields excellent multipath immunity. Hence, UWB has been used in a variety of applications, including communication and ranging, and is expected to see increased use in the future. Since signals from GPS satellites have very low power levels (-130 dBm or -160 dBW) near the surface of the Earth, potential interference from UWB to GPS receivers (and therefore to GPS-based system such as aeronautical safety-critical flight systems) is a serious concern.

Stanford University has designed and conducted a series of accuracy tests on an aviation-grade GPS receiver to study the impact of UWB. These tests quantify the impact of UWB signals relative to white noise of equal power. In other words, they determine whether a given UWB signal has more or less effect on accuracy than an equivalent amount of white noise. Here, white noise refers to continuous noise from a noise diode that has a power spectral density much broader than the RF front end of the GPS receiver. This noise is used to model thermal noise in the receiver, sky noise, and any other wideband interference processes other than UWB. UWB signals also have bandwidths that are greater than the front end of the GPS receiver, but they have an additional structure that may cause their effect to be very different than that of white noise. Accuracy is the metric of choice for aviation receivers because the most demanding precision approach operations require airborne pseudorange accuracies of approximately 15 cm [2]. Accuracy measurements also include the deleterious effects of cycle slips and are the most appropriate metrics for precision approach.

The effect of the UWB signal is sensitive to the details of the UWB signal design. This paper presents test results for the following UWB parameters: PRF (0.1, 1.0, 20.0 MHz), modulation (no modulation, random OOK, random PPM), burst duty cycle (10%, 50%, and 100%), burst-on time (10 us, 1 ms, 10 ms). In each case, the UWB power in the GPS L1 band was swept from –115 dBm to about −50dBm.

1.0 INTRODUCTION

A typical UWB pulse and its frequency spectrum are shown in Figures 1 and 2, respectively. UWB is based on very short radio pulses and is used for radar and communications. Its main advantages include:

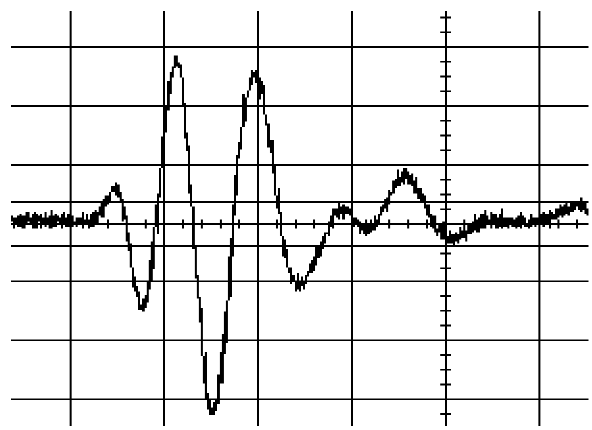


Figure 1: Typical UWB Pulse

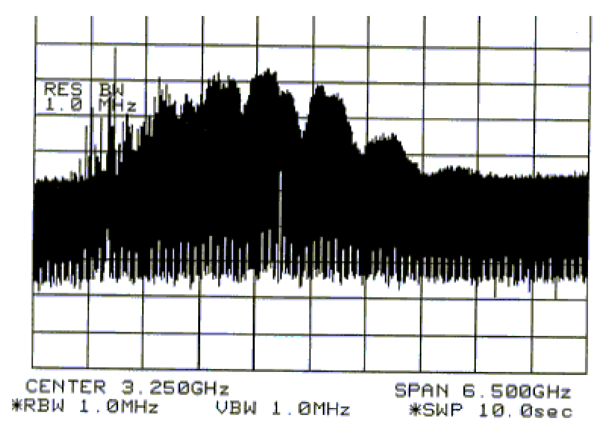


Figure 2: Spectrum of a Typical UWB Signal

- ability to distinguish multipath;
- ability to operate indoors;
- ability to operate in cities and obstructed areas;
- facilitates high-precision ranging and radar;
- wide bandwidth enables low probability of interception by undesired receivers.

UWB technology has being used in applications such as stud finding, ground penetrating radar (GPR), and military communications. Planned or proposed UWB applications include through-the-wall surveillance prior to drug busts, airport fence and airplane proximity security, aircraft navigation, communications over the "last 100 feet" from the Internet to mobile users, in-home connection from wireless microphones and cameras, connections from patients to medical monitors, car collision alerting, etc. It is projected that UWB will become such a widespread utility that there will some day be as many 10 UWB devices per person.

Though UWB could potentially have many applications, current FCC rules exclude intentional emissions from certain critical bands, including GPS. Preliminary field tests conducted at Stanford demonstrated that UWB transmitter could interfere with GPS receivers [5]. However, UWB has many different parameters such as Pulse Repetition Frequency (PRF), duty cycle, burst on/off time, modulation scheme, filter technology, etc. The UWB pulse train and its spectrum vary accordingly, as is shown by the examples in Figures 3, 4, and 5. In addition, there are many different kinds of GPS receivers, and GPS is used to serve a wide variety of applications, including safety-of-life aircraft precision approach guidance. The interference of UWB to GPS therefore depends on all of these variables. Careful testing and study are needed to evaluate potential interference to GPS and its dependence on these UWB parameters.

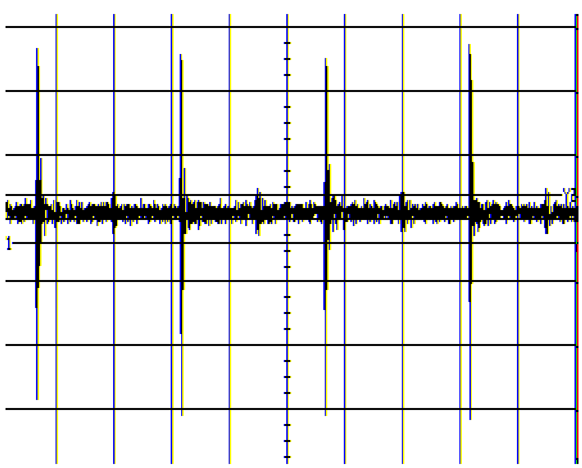


Figure 3: UWB Pulse Train

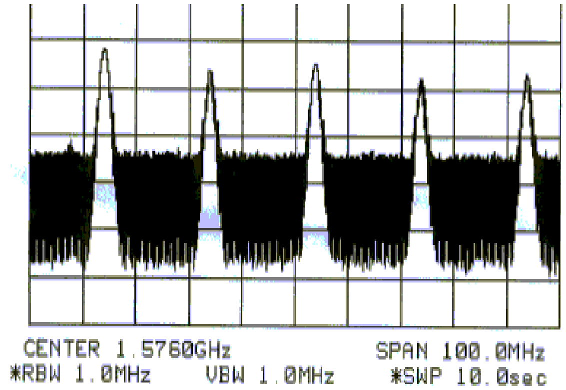


Figure 4: UWB Spectrum without Modulation

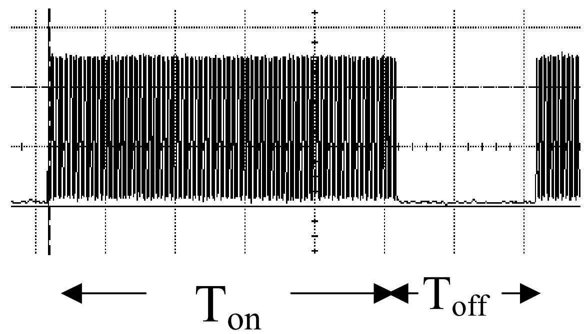
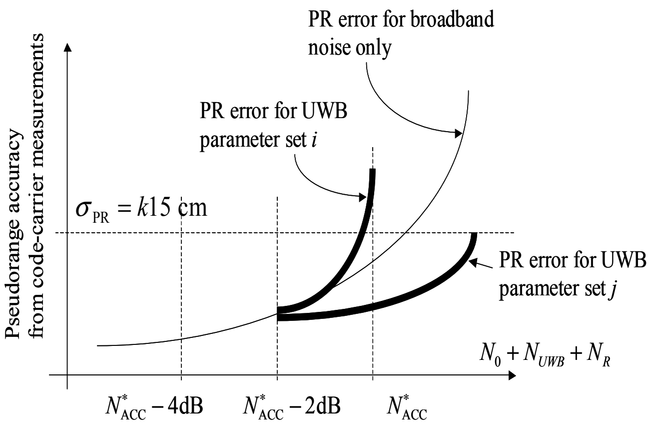


Figure 5: UWB with Burst Duty Cycle < 100%

2.0 TEST PHILOSOPHY AND SCOPE

The goal of UWB testing is to characterize the interference effects of UWB emissions on a typical aviation GPS receiver in a controlled test environment. Some UWB emissions may be well-described as noise-like, while others may have discrete spectral lines in the vicinity of the GPS L1 frequency. 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 plan 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. A significant level of broadband noise is input to give a faithful representation of the actual GPS environment.

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 15 cm of pseudorange error standard deviation is measured. The broadband noise source is then reduced by 4 dB, and the UWB emission level is increased until we return to a 15 cm pseudorange error standard deviation. Another UWB parameter (e.g. PRF) is then chosen, and the entire sequence repeated until all 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 6).



Note: error bars have been suppressed in this figure.

Figure 6: Pseudorange Accuracy as UWB Power is Added to Increase the Total Noise

Three potential benefits of determining the equivalence of UWB transmissions with broadband noise are:

1. The test procedure is straightforward;
2. The resulting UWB impact data can be used to evaluate specific interference scenarios (e.g., range from UWB transmitter to GPS user, antenna orientation and gain) and UWB source information to determine compatible UWB scenarios that satisfy the GPS user requirements; and
3. If, during the broadband noise equivalence test, a 4 dB increase in broadband noise also corresponds to a 4 dB increase in the UWB transmitter power for the same accuracy degradation value (15 cm), then the UWB emission being tested may be classified as noise-like. In such cases a simple calculation based on broadband noise sources can determine the UWB transmission power that is tolerable.

It should be noted that this test plan does not:

1. define or presume allowed levels of UWB transmissions; or
2. define the GPS interference scenarios of concern.

Further testing should include, at a minimum, other GPS receiver types such as fielded aviation equipment based on the TSO-C129 standard, include the aggregate effect of multiple UWB emitters, and address the additive affect of other (non-UWB) systems and their allowed out-of-band emissions. It is also important to test with actual UWB equipment to validate these results and to add tests of additional UWB emission parameters that reflect current UWB technology.

Pseudorange measurement accuracy (and the related integrity, or safety, of GPS positioning), acquisition and reacquisition times, and loss-of-tracking thresholds are the four important performance metrics to GPS users. For the tests reported here, the primary metric is accuracy performance in an aviation receiver. The most demanding precision approach operations require a pseudorange measurement standard deviation of less than 15 cm. Pseudorange measurement accuracy is influenced by degradations in both code-delay and carrier-phase tracking. As such, it is the most sensitive metric for the aviation applications.

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.

As noted above, the RFI impact of UWB signals will be sensitive to the details of the UWB signal design. Some of these relationships are depicted in Figure 7. We anticipate that our interference measurements will reflect the following quantitative trends:

- *Pulse Repetition Frequency (PRF)*: If UWB pulses are sent at a very low rate compared to the RF front-end bandwidth of GPS receivers, then the interference impact will be smaller than that due to UWB operation at high PRFs. Most GPS receivers have front-end bandwidths between 2 and 24 MHz. If the UWB PRF is less than 2 million pulses per second (MPPS), then the pulses will still be distinct at the output of the receiver front end, and the interference will probably be relatively small. If the UWB PRF is higher than the bandwidth, then the GPS front end will smear the pulses together, forming an effectively continuous input to the GPS receiver; thus the interference effect will probably be larger. In general, GPS receivers are less sensitive to

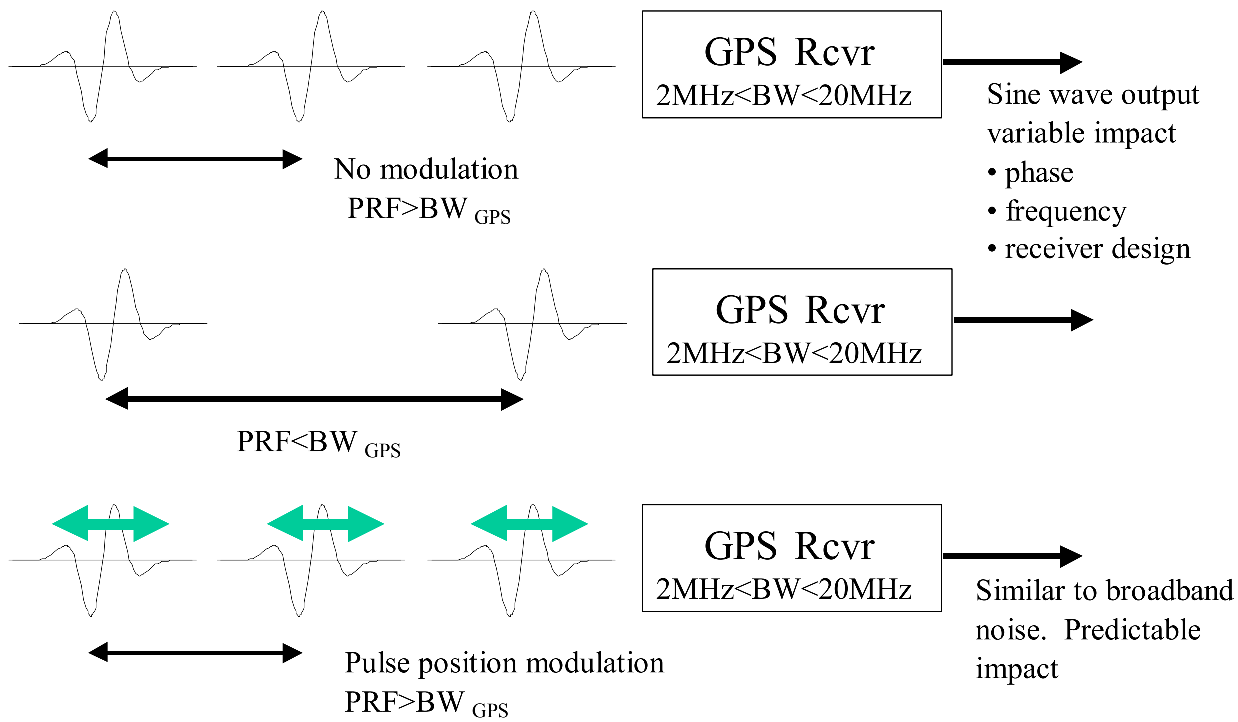


Figure 7: Sensitivity to UWB Signal Parameters

pulsed interference than they are to continuous interference.

- *No Modulation*: In this case, the UWB signal is a pulse train with a constant time between pulses. This case is shown in Figure 3, and the resulting line spectra are also shown in Figure 4. The GPS C/A - code also has line spectra. UWB interference will probably be greatest when the UWB lines fall on top of the GPS spectral lines. UWB interference should be small when the UWB lines fall between the GPS lines or are far away from the peak of the GPS spectral envelope. The locations of UWB spectral lines will change based on the specific UWB transmit parameters; thus the UWB effect on GPS will vary.

- *Pulse Modulation*: If the UWB pulses are modulated randomly in pre-defined ways and with long codes, then the UWB line spectra will be reduced and may possibly disappear. If modulation is used with sequences that are continuous and have high PRFs, then the interference effect may be similar to that of broadband (white) noise of equal power.

- *Pulse Bursting*: As shown in Figure 5, UWB pulses may be transmitted in bursts with prescribed on-times and off-times. If the duty cycle (fractional on-time) of these bursts is less than 40 percent or so, then we expect that the effect of one UWB transmitter on a GPS receiver will be reduced. The interference effect will also depend on the on-time of the pulse bursts.

- *Pulse Shaping*: The overall UWB spectrum depends on the pulse shape. It may be possible to craft the shape of UWB pulses so that the UWB spectrum avoids certain critical bands (such as GPS L1).

All of these theoretical predictions must be quantified and validated. To this end, our test cases varied the UWB signal parameters and attempted to determine how the UWB-to-broadband noise equivalence depends on the UWB signal parameters.

3.0 TEST SETUP AND PROCEDURE

3.1 UWB Transmitter Prototype

The UWB transmitter prototype consists of three main components (see Figure 8):

Pulse generator:	HL 9200
High-pass filter:	800 MHz F_C
Amplifier:	2 – 8 GHz 20 dB gain 4 dB NF

The pulse shapes at different stages of the UWB transmitter circuitry are shown in Figures 9 and 10. Note that the pulse in the bottom two plots in Figure 10 (after the filter) has more ringing. This is closer to real UWB pulses since no practical UWB transmitter will have unlimited bandwidth.

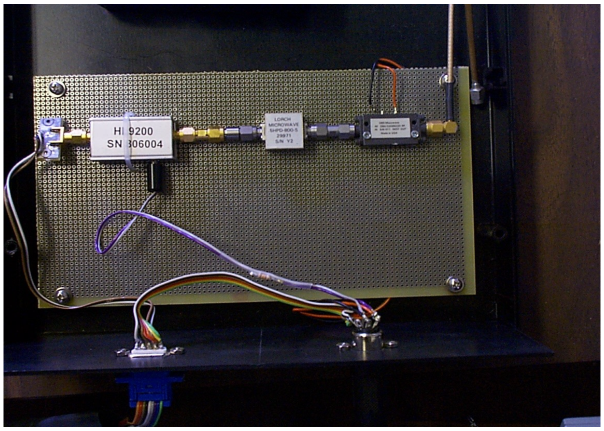


Figure 8: UWB Transmitter Prototype

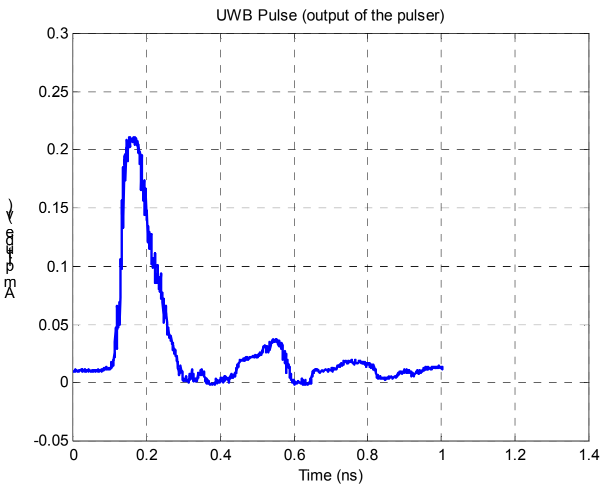


Figure 9: A Single UWB Pulse

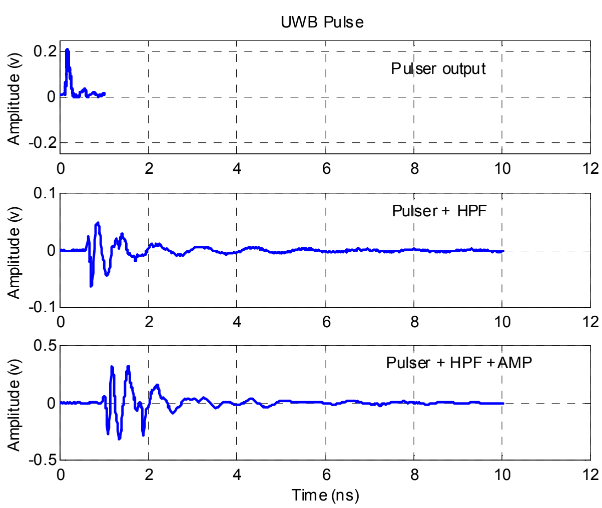


Figure 10: UWB Pulse at Various Transmitter Stages

3.2 Broadband Noise Normalization

The aviation-grade GPS receiver used in these tests is operated with the minimum RTCA received GPS satellite signal level as generated by a single-channel GPS signal simulator [2,3]. Compensation is applied to adjust for room temperature, satellite simulator noise output, or the effects of a remote antenna preamplifier as needed. Broadband (white) random noise is added to the simulated GPS satellite signal at the receiver input. The center frequency of the broadband noise is set to the GPS L1 center frequency (1575.42 MHz). The starting value of broadband noise is the RTCA/DO-229B WAAS MOPS level required for initial satellite acquisition [3]. Once this level of broadband noise power is set, the GPS receiver is given time to acquire and track the satellite and to reach steady state. We then record the unsmoothed pseudorange (the internal receiver carried-added-smoothing time is set to 0.5 seconds) and estimate the one-sigma pseudorange error by computing the standard deviation of the code-minus-carrier test statistic after removing a 2nd-order polynomial fit to the mean, using the algorithm defined in [4]. For each fixed broadband power level, we collect raw code and carrier data for one hour at a 2 Hz sampling rate. To be conservative, we assumed 1 independent sample every 4 seconds (every 8τ of internal smoothing), which gives 900 independent samples per hour. The number of samples was set so that the results allow us to distinguish the impact of a 1 dB power difference in the pseudorange accuracy measurements with statistical precision. The normalization curve shown in Figure 11 was then obtained. Note that there is a difference (k in Figure 6) between variance measurements from raw pseudorange (PSR) and from 100-sec carrier-smoothed PSR. It is much more time-efficient to use raw PSR to increase the number of independent samples. We found that 1.4 m of raw PSR accuracy is consistently equivalent to 15 cm of carrier-smoothed PSR accuracy.

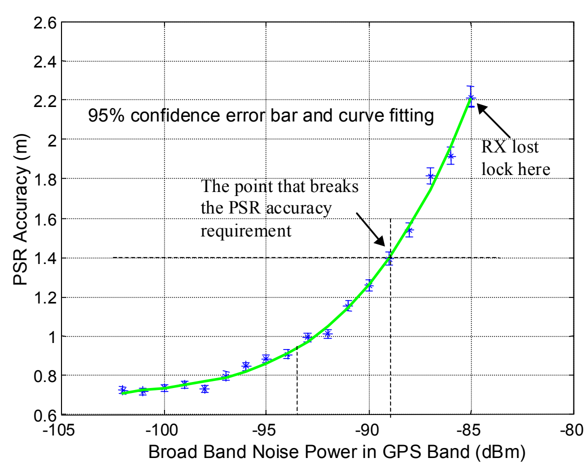


Figure 11: GPS Receiver Normalization

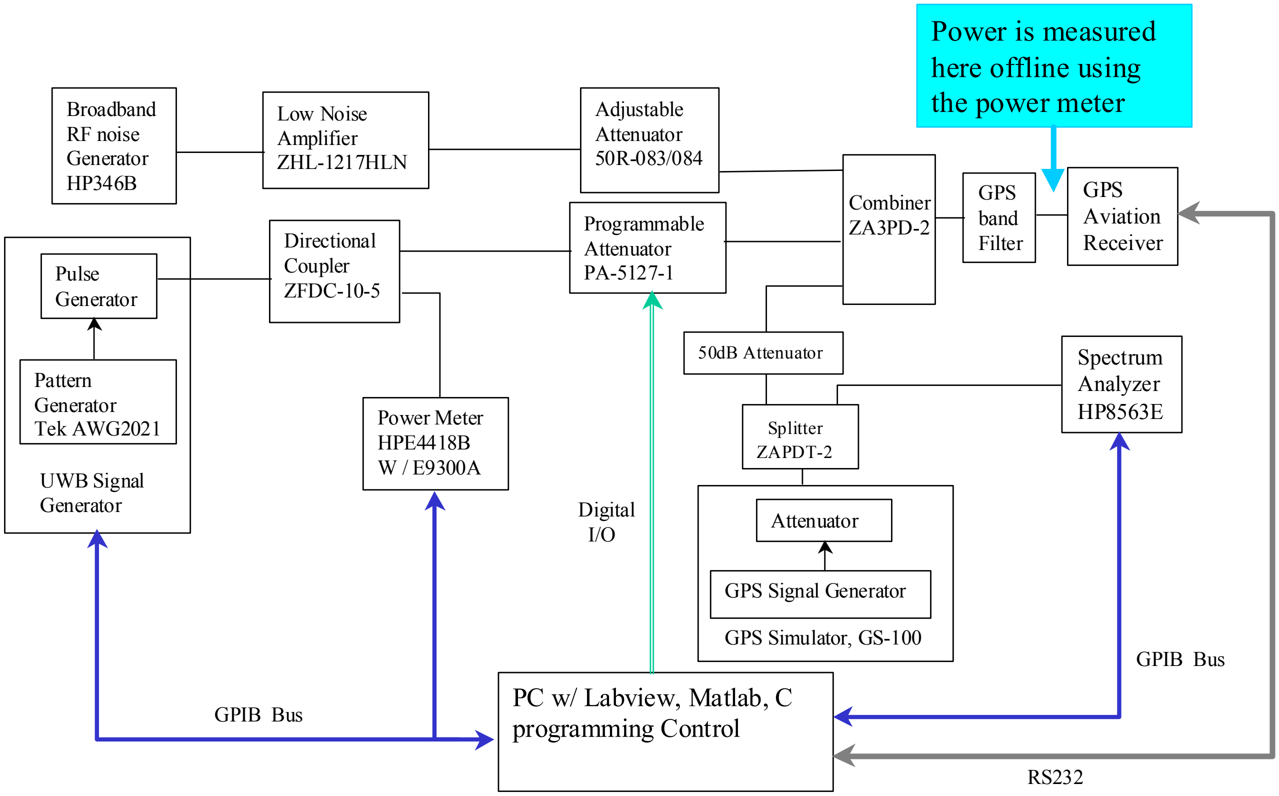


Figure 12: UWB Interference Test Setup

3.3 Test Setup

As shown in Figure 12, the GPS signal, broadband noise, and UWB are combined before being injected into the GPS receiver. A single-channel WelNavigate GS-100 GPS simulator is used to generate the GPS signal with satellite PRN #1. The GPS signal attenuator was set such that the GPS signal at the receiver port was –131 dBm. An HP 346B 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 Tectonics AWG 2021, which triggers the UWB pulse generator, was used to generate the desired UWB pattern. A programmable attenuator was used to sweep UWB power within the desired range. The power meter and the spectrum analyzer were used for real-time monitoring. The test is automated using Labview and IEEE buses.

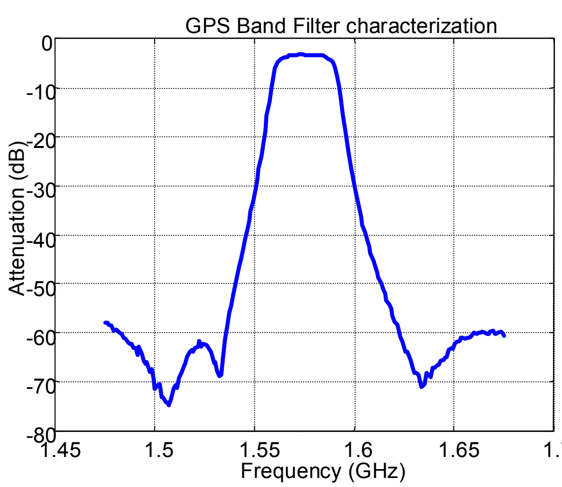


Figure 13: GPS L1 Filter Characterization

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. Therefore, the test results will not depend as much on the front end of each individual receiver. The L1 filter used in our tests has the frequency characteristic shown in Figure 13.

4.0 TEST RESULTS

4.1 PRF Comparisons

Figure 14 shows the results of unmodulated UWB tests for various PRFs between 100 KHz and 20 MHz. It initially appears to suggest that when the PRF is high (5 – 20 MHz), the impact of UWB was similar to that of broadband white noise. When the PRF is lower (100 KHz – 1 MHz), the impact of UWB decreased, as the GPS

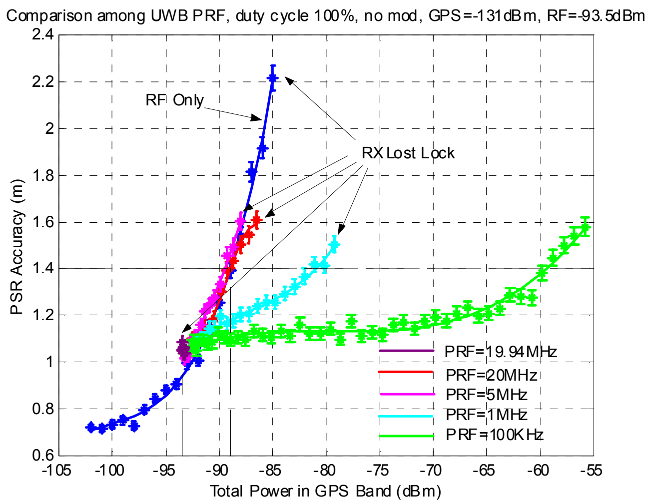


Figure 14: Comparison of UWB for Different PRFs

signal is designed to be robust against pulsed interference. When the PRF is low, each UWB pulse has sufficient separation from each other; thus the impact to GPS is small. We can also explain the above results by looking at the UWB spectrum shown in Figure 15. When the PRF is 20 MHz, there is a large spectral spike in the GPS L1 band (the gray-colored background). When the PRF is small, e.g., 1 MHz, the spectral lines become much denser but are also smaller. Therefore the impact on GPS accuracy is less severe.

To take a careful look at the spectral line sensitivity, we compared three cases with similar PRFs but different spectral line structures (see Figures 16 and 17). It is clear from Figure 17 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 at about the 5th sidelobe when PRF = 20 MHz. This explains why the PRF = 19.94 MHz case

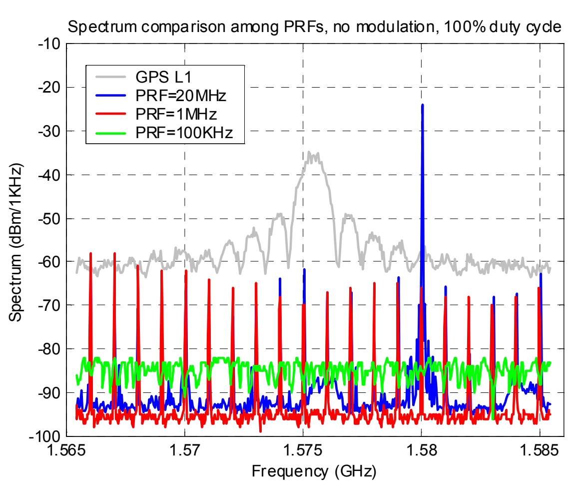


Figure 15: Spectrum Comparison among PRFs

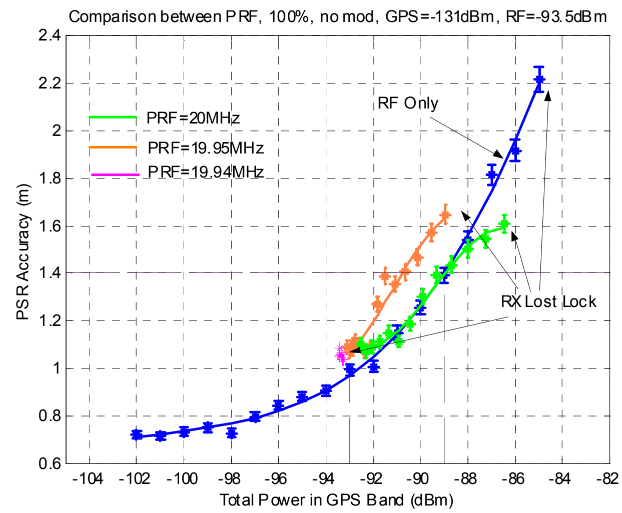


Figure 16: Accuracy Comparison among PRF = 20 MHz, 19.94 MHz, and 19.95 MHz

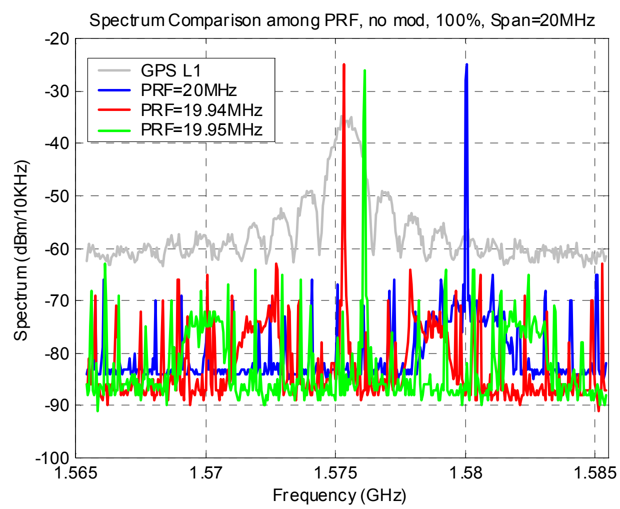


Figure 17: Spectrum Comparison among PRF = 20 MHz, 19.94 MHz, and 19.95 MHz

does the most severe damage to GPS – the receiver loses lock (making the satellite unusable) well before the accuracy requirement is broken. The 19.95 MHz PRF is less threatening, as it leads to violation of the accuracy requirement at a total interference power of –90 dBm and then causes loss-of-lock at –88 dBm. The PRF = 20MHz case has the smallest impact among these three cases, as it is about 2 dBm better than the 19.95 MHz case. This indicates that these higher PRFs do not impact the receiver solely as increased thermal noise but rather as a combination of thermal noise and discrete line spectra.

Note that for any practical UWB transmitter, some variation around the nominal UWB PRF is unavoidable due to imperfect clock components. Thus, a transmitter designed with a 20 MHz PRF may wander over to 19.94

MHz (a difference of only 0.3%) and cause loss of GPS satellite tracking. Loss of tracking is even worse for GPS than violation of the accuracy requirement for precision users, as it affects all users of GPS and makes it very difficult for precision users to meet their continuity (loss of navigation) requirement. All nominal UWB PRF's of 5 MHz and above tested without modulation have similar "Achilles heel" PRF's near the nominal PRF that cause a spectrum line to fall in the main GPS lobe, leading to rapid loss of lock. UWB designers must take steps to remove the possibility of spectral lines overlapping the GPS band in this manner.

4.2 Comparison of UWB Duty Cycles

For a fixed PRF of 20MHz, we ran tests with duty cycles of 100%, 50%, and 10%, and the results are compared in Figure 18. The difference between 100% and 50% is fairly minor, while a 10% duty cycle has much smaller impact on GPS then the higher duty cycle cases tested. Note that the UWB power in the GPS band has been normalized. In other words, the UWB power in the GPS band for a given *x*-axis value is the same for all three cases. Also note that when the PRF is changed from 20 MHz to 19.94 MHz, the receiver lost lock at lower UWB power level even for the 10% duty cycle case. This indicates that the GPS receiver remains vulnerable to overlapping spectral lines even for low duty cycles.

With a fixed PRF and duty cycle, the UWB transmitter can be set to different burst-on times, or different pulse periods. This parameter also effects the impact on GPS, as shown in Figure 19. This figure compares the impacts on GPS of burst-on times of 10 µs, 1 ms, and 10 ms for a 50% duty cycle. It appears that increasing the burst-on time helps reduce the impact of UWB on GPS. We suspect that increasing the burst-on time (yielding longer periods) yields denser but smaller spectral lines in the sensitive GPS L1 band, thus the harm to GPS is less

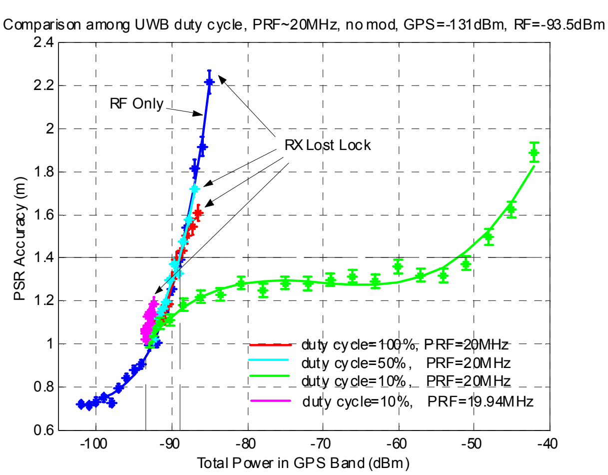


Figure 18: Impact of Duty Cycle Variation

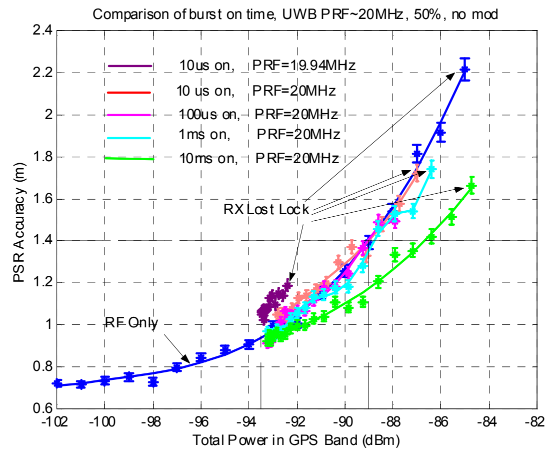


Figure 19: Impact of Burst-on Time Variation

severe. Also note that the overlapping spectral lines of the PRF = 19.94 MHz case remain damaging.

4.3 Pulse Position Modulation (Random PPM)

In order to test the capability of pulse position modulation to reduce the impact of UWB on GPS, we constructed the ten-position modulated case illustrated in Figure 20. 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 our test setup). We constructed a sequence of 250,000 points. The maximum PRF we can support 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 21. 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 (~ 20 dB lower), and the noise floor is higher, as shown in Figure 22.

From the zoomed-in spectrum comparison of Figure 23, we can more easily understand the results in Figure 21. Though the spike of the PRF = 1.994 MHz case hits the

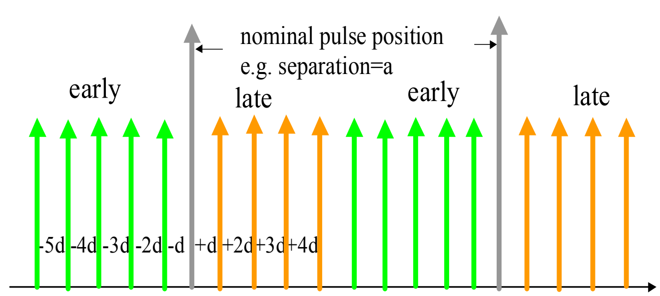


Figure 20: Ten-Position Random PPM

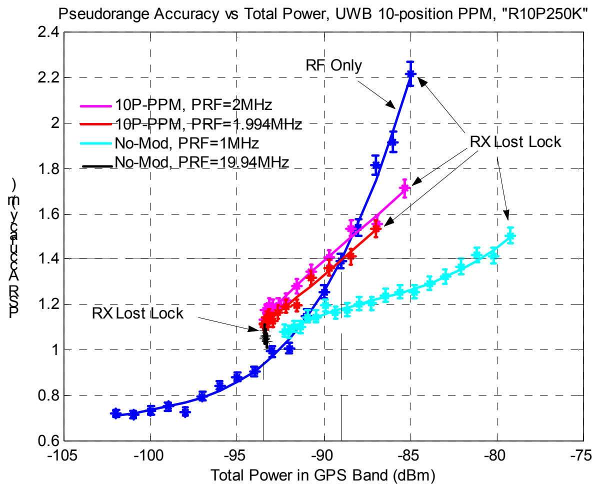


Figure 21: Test Results for Ten-Position PPM

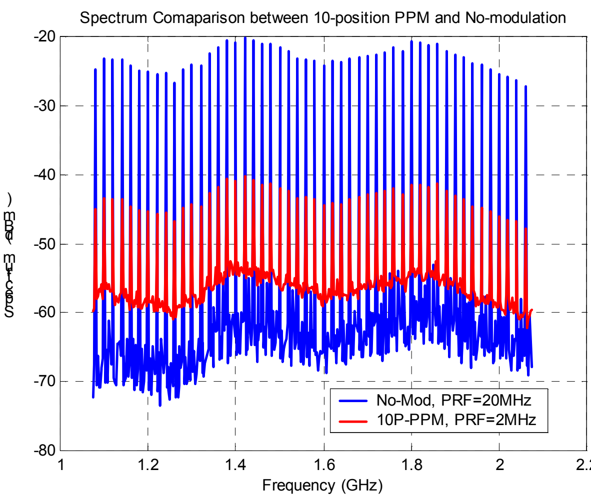


Figure 22: Spectrum Comparison between Ten-Position PPM and No Modulation

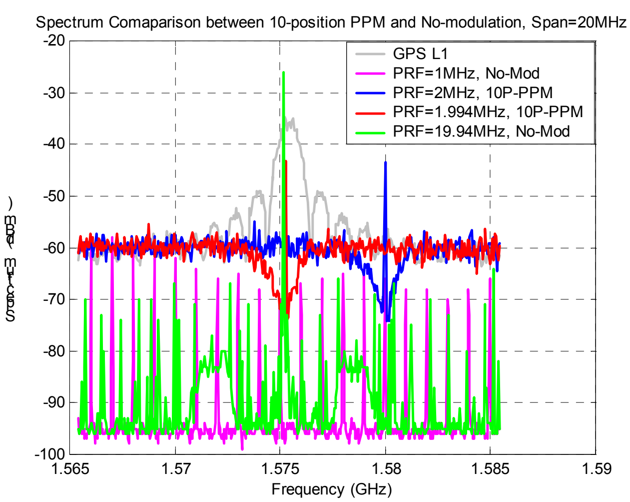


Figure 23: Spectrum Comparison between Ten-Position PPM and No-Modulation in GPS L1 Band

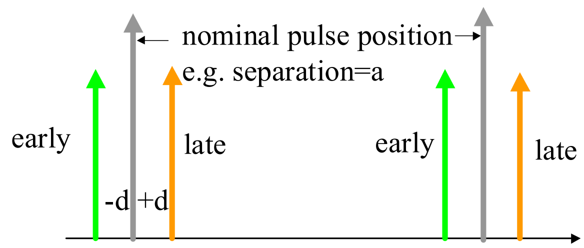


Figure 24: Two-Position Random PPM

GPS main lobe, its strength is 18 dB smaller than for PRF = 19.94 MHz in the no-modulation case; thus the impact to GPS is much less severe. The lower magnitude of these spikes makes the exact location of the spikes less important, which explains why the 2 MHz PRF and 1.994 MHz PRF cases yield similar results. These impacts are worse than for low PRF in no-modulation case (1 MHz is shown in the plot), as the 1 MHz no-modulation PRF case has no spike nearby L1 to match those of the two ten-position PPM cases.

We also tested a two-position random PPM scenario that is illustrated in Figure 24. The pulse takes either the early position (nominal –d) or the late position (nominal +d). The minimum separation of two pulses is 50 ns as in the ten-position case. We constructed a sequence of 252,000 points with d = 2 ns and a = 56 ns when the clock frequency is 250 MHz. The ratio of position dithering (d/a) is 1/28 (3.57%). The relation of PRF/clock frequency is 1/14. The test results are plotted in Figure 25. From this plot, we see that the order of UWB impact to GPS (from most severe to least severe) is 15.91 MHz, 16.08 MHz, 15.93 MHz, 15.94 MHz, and 15.92 MHz. Figure 26 and 27 show the UWB spectra of these PRFs relative to the GPS L1 band. The order of the power level where the UWB spectral peak hits the GPS spectrum matches the above order very well. This is explained to a

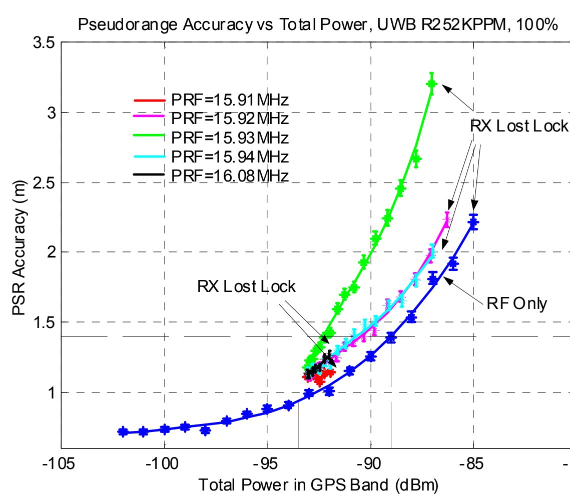


Figure 25: PRF Comparison with Two-Position PPM

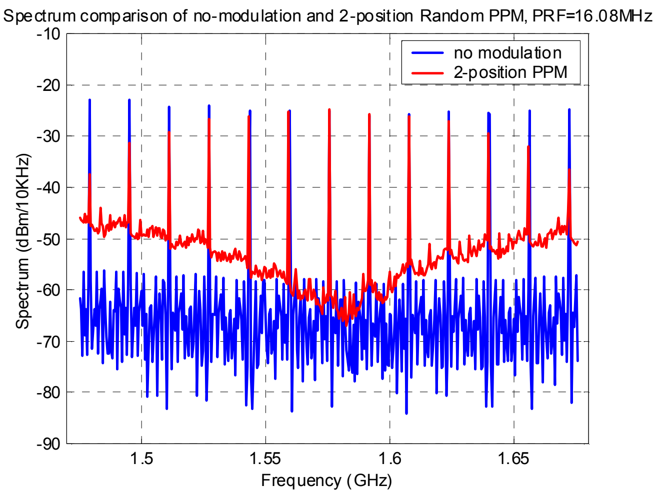


Figure 26: Spectrum Comparison between Two-Position PPM and No-Modulation

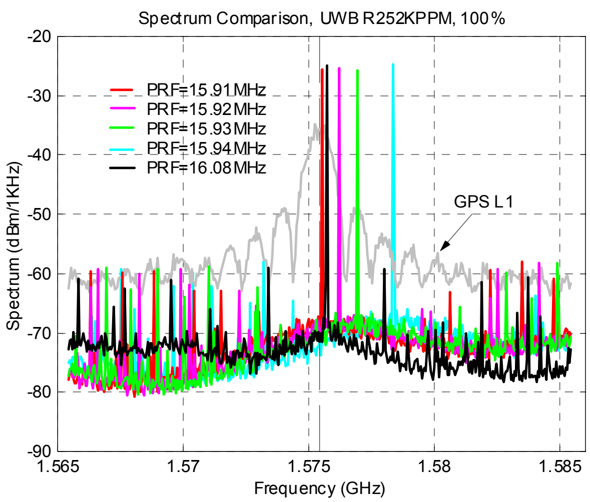


Figure 27: Spectrum Comparison among PRFs with Two-Position PPM

large degree by viewing the UWB spectral lines relative to the GPS spectrum near L1.

It is important to recall that GPS signals also have line spectra. The separation between two neighboring GPS C/A-code spectral lines is 1 KHz. Also note that UWB spectral lines are not infinitely thin. They have finite width due to imperfect UWB transmitter components (e.g., clock jitter or other component instability). In our experiments, the width of these UWB spectral lines was measured to be 2 – 3 KHz (see Figure 28). As a result, when the UWB spectral line lays on top of the GPS spectral line, it will always cover 2 – 3 lines as opposed to just one. Therefore, the sensitivity of GPS to UWB interference depends on where the UWB spectral lines lie within the GPS spectrum, not which specific spectral line of GPS is overlapped.

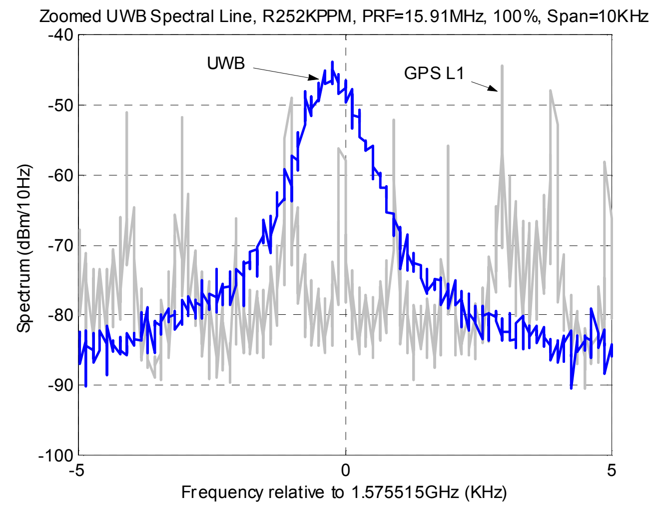


Figure 28: Zoomed-in UWB Spectral Lines

4.4 Random On-Off Key (OOK) Modulation

In random on-off-key (OOK) cases, the UWB pulses retain their nominal positions, but each individual pulse is turned on or off randomly. This pattern is illustrated in Figure 27. The pulse train is evenly spread. Each pulse is randomly set to be on or off with a 50% probability. The minimum separation of two pulses is 50 ns as noted before. We constructed a sequence of 256,000 points with d = 50 ns with a clock frequency of 40 MHz.

The test results and the resulting spectra for OOK modulation are shown in Figures 30 and 31. Not surprisingly, the location of the UWB spectral lines explains these results. When these lines hit the main lobe of GPS L1 (the 19.94 MHz PRF case), the UWB still has a significant impact on GPS. Compared to the no-modulation scenario with the same PRF, the GPS receiver survives slightly better with random OOK. The reason is that with this type of modulation, the spectral lines retain the same positions, but the their strength becomes smaller, and the spike "noise floor" moves higher. In other words, OOK modulation makes UWB behave more like white noise than the no-modulation cases (see Figures 31 and 32 for details). We also tested a 50% duty cycle with random OOK modulation. The difference between 100% and 50% duty cycles with OOK is similar to the difference between 100% and 50% duty cycles without modulation.

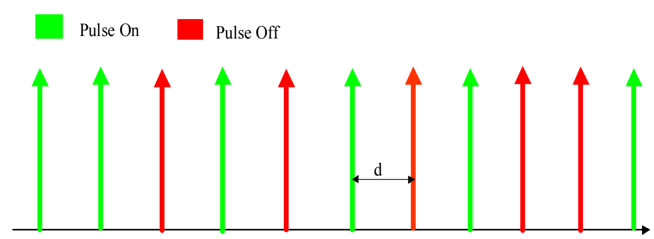


Figure 29: Random OOK Illustration

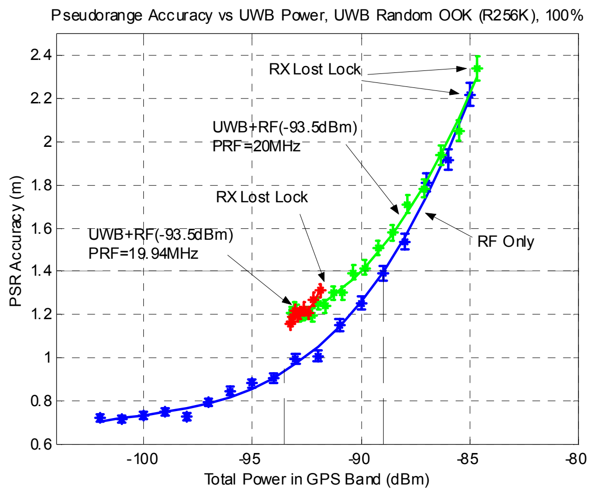


Figure 30: Accuracy Test Results for Random OOK

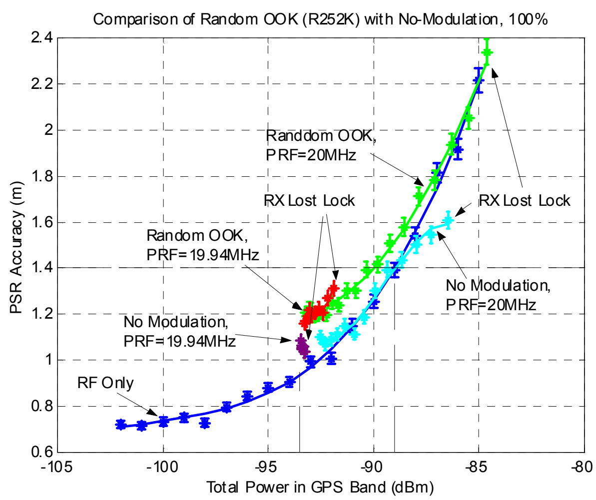


Figure 31: Accuracy Comparison between Random OOK and No-Modulation Cases

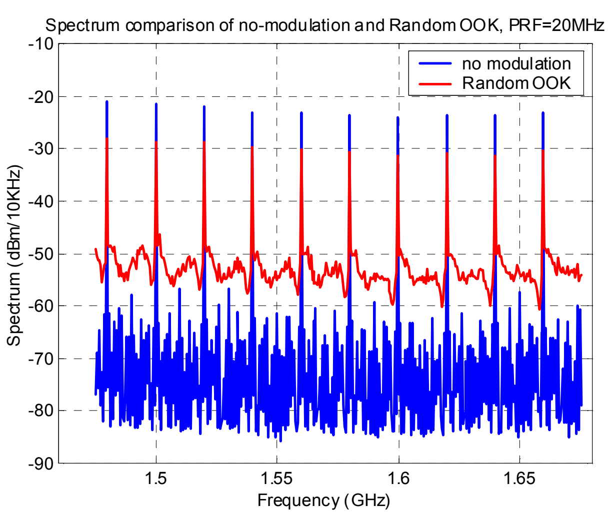


Figure 32: Spectrum Comparison between Random OOK and No-Modulation Cases

5.0 SUMMARY AND CONCLUSIONS

For a single aviation-grade GPS receiver, Stanford University has developed a test plan to study the impact of UWB transmissions on GPS users by relating it to the impact of broadband noise. By carrying our these tests, we have demonstrated how the impact of UWB interference on GPS depends on several sets of UWB signal parameters, including PRFs, duty cycles, on-times, and modulation variations. The impact of UWB is strongly dependent on the presence and location of UWB spectral lines relative to GPS. To a large degree, the impact of UWB can be explained (and predicted) by examining where the UWB spectral lines are relative to the GPS spectrum around L1 and the power of these lines.

When the UWB PRF is low, specifically when the post-filter UWB pulses occupy less than 10% duty cycle (as in the 100 KHz case), UWB has less impact on GPS receivers than does broadband noise of the same power level. This is due to the fact that the UWB spectral lines in this case are much closer together, and as a result, each line is much less powerful. When the PRF is this low, the impact on GPS is less sensitive to small variations in PRF or modulation. However, we observed many cases where the impact of UWB on GPS accuracy is worse than broadband noise, and some of these cases make the GPS receiver lose lock at very low power levels. When the UWB PRF is high (e.g., above 5 MHz), a small variation in PRF (which could easily be caused by clock imperfections) makes a large difference on the impact of interference to the GPS receiver. These variations in impacts on GPS are well-explained by the locations of the UWB spectral lines relative to GPS. Since the impact of small variations in the location of these lines can lead to severe consequences to GPS, UWB signals should avoid having powerful spectral lines of this type. Note that these tests were limited by our pulser to a maximum PRF of 20 MHz; thus there was always at least one spectral line in the GPS L1 band.

In the modulated cases that we tested, the UWB spectral lines did not disappear. In other words, the impact of UWB did not become "white-noise-like". Different types of UWB modulation have different spectral-line characteristics, which therefore result in varying impacts on GPS:

1. Random OOK does not change the location of spectral lines relative to the no-modulation case with the same PRF. It only reduces the power of the spectral lines by a few dB.

2. Multiple-position random PPM makes the larger spectral lines more sparsely spread and generates more small lines closer to each other.

3. Two-position random PPM changes the shape of the spectral noise floor, while the spectral lines remain at the same locations they are in without modulation.

Because the impact of UWB on GPS varies considerably with UWB signal characteristics, and because it is easy to generate very-low-power UWB that causes GPS to lose lock, UWB transmissions must be carefully regulated to prohibit broadcast of UWB signals with large spectral spikes, even when these spikes are designed not to fall within the main lobe of the GPS signal. In order to better clarify what these restrictions should be, Stanford is now pursuing further tests with a commercial land receiver and will support tests of a second aviation receiver. At the same time, standards boards such as RTCA SC-159 WG-6 are devising specific UWB-GPS interference scenarios in which these test results will be utilized. More time and more testing are needed before the full impact of UWB on GPS is understood, and the threat of UWB interference demonstrated in this paper shows that this time will be well-spent.

ACKNOWLEDGMENTS

The authors would like to thank the following people for their help during this research: Dr. A. J. Van Dierendonck (AJ Systems/GPS Silicon Valley), Bob Kelly (RTCA), Gerald Rogerson (Fantasma), and Konstantin Gromov and Jaewoo Jung (Stanford University). The advice and interest of many other people in the Stanford GPS research group is appreciated. We also like to thank the U.S. Department of Transportation for funding support as well as the help and interest given to us by RTCA and the Federal Aviation Administration.

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