Potential Interference to GPS from UWB Transmitters

Phase II Test Results

Accuracy, Loss-of-Lock, and Acquisition Testing for GPS Receivers in the Presence of UWB Signals

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Executive Summary

In 1999, the U.S. Department of Transportation ("DOT") approached Stanford University to research the compatibility of UWB and GPS and to conduct tests to help quantify any interference problems. This is the second report from Stanford to the Department on this task. This research effort is necessary because GPS has such a pivotal role in so many critical systems that the public depends upon for its safety and welfare.

The majority of the tests 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, a test set was designed to measured UWB impact on the *signal acquisition* performance of a third receiver, a *high-grade, general-purpose GPS receiver.* This third receiver used the same hardware as the aviation receiver, but the firmware was changed so that the receiver did not utilize an acquisition strategy suited for aircraft dynamics.

The principal findings are as follows:

- UWB interference to GPS can be successfully analyzed using a *noise equivalence factor*. For all tests, the *UWB interference impact relative to broadband-noise* was measured. The noise equivalence factor measures the UWB power level that causes a specified interference effect relative to the broadband-noise power level that causes the same effect. The determination of this factor is repeatable and corresponds to the results of theoretical analyses. This noise equivalence factor enables the computation of link budgets that correspond to a variety of operational scenarios. In fact, RTCA is using these results along with the results of other efforts to build appropriate link budgets, and the National Telecommunication and Information Administration (NTIA) has incorporated a similar approach in their work.

- The *noise equivalence factor* is a strong function of the UWB signal parameters. This report quantifies the noise equivalence factor for a large set of UWB waveforms, and the results are plotted and tabulated herein. This factor varies most strongly with the UWB pulse repetition frequency (PRF) and the spectral location of any discrete UWB spectral lines relative to the GPS signal.

- Low PRFs are defined as being significantly smaller than the front-end bandwidth of a typical GPS receiver (500×10^3 pulses per second (500 Kpps, or 500 KHz) or less). Since the pulses occupy a low duty cycle at the output of the GPS receiver front end, low PRFs can yield noise equivalence factors that are up to 33 dB less damaging than broadband noise. This specific result (33 dB) applies to the case of a PRF of 100 KHz, which was the lowest PRF tested, and it assumes that the noise power is measured across the entire 24 MHz GPS band.

- High PRFs are defined as being 2×10^6 (2 Mpps, or 2 MHz) or higher. If such a UWB signal includes discrete spectral lines and these lines fall within the GPS band, then UWB can be significantly more damaging than broadband noise. For example, a PRF of 19.94 MHz causes UWB to be 17 dB more damaging than broadband noise, when the broadband noise power is measured across the 24 MHz GPS band. In other words, a UWB signal that is 17 dB weaker than broadband noise is equally destructive to GPS, 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, than equal damage comes from a UWB signal that is approximately 3.2 dB weaker.

- Actual UWB degradations will be greater than those reported above for the high PRF signals with discrete spectral lines. A17 dB degradation was measured without making any effort to place the UWB signals on the more sensitive GPS spectral lines. In practice, UWB lines will frequently find more sensitive lines than found in these trials because (a) many GPS satellites will be in view; and (b) 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 worst line for GPS satellite PRN 21 is 6.5 dB more sensitive than the victim line in these measurements. When adjusted by these theoretical results for the most sensitive GPS lines, the noise equivalence factors become 23.5 and 9.7 dB respectively for 24 and 1 MHz noise bandwidths. These results agree closely with the results obtained by NTIA for UWB waveforms with discrete spectral lines.

- Under the best circumstances, UWB signals with high PRFs appear as broadband noise. In other words, the equivalence factor is approximately 0 dB, but only in the absence of in-band spectral lines. If the UWB dithering codes or modulation indices are not chosen carefully, and some spectral-line content remains, then the UWB waveform is more damaging than white noise.

All of the above-described trends and findings were observed in all three receivers: aviation receiver, general-purpose receiver, and OEM receiver. The noise equivalence factor is a robust and useful interference parameter for all three receivers and all three test criteria. All tests showed the same sensitivity to UWB signal type. For example, the worst interference cases for all three receivers occurred when a discrete UWB spectral line fell into the GPS band. The OEM tests must be more carefully interpreted, however, because the OEM front-end bandwidth is significantly narrower than the bandwidth for the aviation receiver and the standard filter used to measure noise power.

The noise equivalence factors supplied herein enable the analysis of a variety of operational scenarios. These scenarios define the power transmitted by the UWB device and the proximity of the UWB transmitter relative to the victim GPS receiver. They also define the number of visible GPS satellites and the satellite elevation angles. The scenarios also determine whether other interference sources are nearby (additional UWB transmitters, or other non-UWB transmitters). A goal of the testing effort was to provide data that would enable the analysis of a variety of scenarios without making assumptions about any of the operational factors. This goal was achieved.

As part of the original DOT request, this data will be made available to NTIA and to RTCA, specifically RTCA SC-159 WG6. DOT asked RTCA to develop the appropriate operational scenarios for aviation and non-aviation to the extent possible. This data will be used in the RTCA effort along with other useful data to build appropriate link budgets.

This report *does not* define or assume allowed levels of UWB transmissions, nor does it define the specific GPS interference scenarios of concern. In addition, the results are limited to determining the interference impact of a *single* UWB transmitter relative to broadband noise. It was recognized that the impact of *multiple* UWB emitters must be determined as part of the overall UWB interference analysis effort. Moreover, the impact of multiple UWB emitters cannot be precisely predicted based on the results of this report. Further investigation into this issue was beyond the scope of the task from DOT to Stanford as a result of available resources and timeframe. NTIA has collected data that will support the analysis of interference from multiple UWB emitters. Finally, this report does not address the deleterious effect of UWB signals with such high peak powers that they cause non-linear effects in the GPS receiver.

These test results are intended to aid in appropriate analysis efforts and should not form the sole basis for decision-making. They should be combined with the scenarios being generated by NTIA and RTCA, and they should be compared against similar test reports from other organizations (such as NTIA) in order to form the basis for effective spectrum-management decisions. However, these results strongly suggest that UWB transmissions that overlap or come near to the GPS band must be carefully regulated to insure that there is no adverse impact to GPS.

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1.0 Introduction

1.1 Background

The Global Positioning System (GPS) is a fundamental component of the information infrastructure in the United States and worldwide. Today, it is a fully operational service that provides a global source for accurate timing and positioning, 24 hours a day, in all weather conditions. GPS is used by aviation for the en-route and non-precision landing phases of flight. It is used as the sole means of navigation for oceanic flight. Augmented GPS is currently used within the U.S. for precision approach and landings, and two such systems are in the final stages of approval as a national and international standard. GPS-based system development for runway incursion and ground traffic management is also underway.

GPS-based public safety systems and services are also being deployed for use outside aviation. Planned or proposed systems, such as Enhanced 911 (E-911) and personal location and medical tracking devices will soon be commercially available. Additional future systems are planned for land, marine and space applications. The U.S. telecommunications and power distribution systems are dependent upon GPS for network synchronization timing. Furthermore, GPS is a powerful enabling technology that has created new industries and new industrial practices that are fully dependent upon GPS signal availability and continuity. Several critical industries, both aviation and non-aviation, would incur adverse impacts if GPS signal degradation were to occur.

Ultra-Wideband (UWB) is a potentially promising technology that has been defined by a large fractional bandwidth, although a sharper definition would be more useful. Many UWB systems are based on very short pulses of radio frequency energy. These systems are of greatest interest in this report, because they offer excellent multipath immunity and will find application in obstruction-rich environments. Indeed, UWB technology has potential in a variety of applications, including communication and ranging, and is expected to see increased civil use in the future. The Federal Communications Commission (FCC) under the Office of Engineering and Technology (OET) is currently gathering input under ET Docket Number 98-153, *In the Matter of Revision of Part 15 of the Commission Rule Regarding Ultra-Wideband Transmission Systems*.

Such a study is particularly important because UWB and GPS are complementary technologies and therefore are likely to operate in close proximity. Moreover, preliminary analysis and testing have indicated a likely interference impact to GPS reception from some types of UWB sources. These early results were based on uncontrolled field results but still suggested a threat to safety applications of GPS. In particular, UWB might threaten aviation receivers that have already been fielded and are relied upon to protect user safety to hazardous risk levels of 10^{-7} or lower per operation.

This second report includes some introductory material from the original test plan and first test report [1,2]. Note that the test plan itself has evolved based on requests from the aviation community, test time limitations, and constraints imposed by the available GPS receivers. The current report contains findings from a controlled set of bench tests that are aimed at determining the impact on GPS from a broad range of UWB signals.

The impact of UWB has been tested on:

1. The accuracy and loss-of-lock performance of a *high-grade GPS aviation receiver*. These tests were the strongest focus and were conducted in close cooperation with Working Group 6 of RTCA Special Committee 159. The aviation tests are based on a large body of developed and published technical standards for GPS that clearly define the applicable interference criteria. These tests use pseudorange accuracy and loss-of-lock as the measures of performance, and the receiver under test is designed to meet published aviation specifications. Specifically, the receiver is designed to meet the Minimum Operational Performance Standards (MOPS) for the Wide Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS). Allowable levels of interference are already specified in the LAAS and WAAS MOPS [4-10].

2. The signal acquisition performance for a *high-grade, general-purpose GPS receiver*. In fact, this receiver used the same hardware as the aviation receiver, but the acquisition firmware was changed so that the receiver did not implement an acquisition strategy based on aircraft dynamics.

3. The loss-of-lock performance for a *low cost, OEM receiver*. This 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.

For all tests, *UWB interference impact relative to broadband noise* is measured. In fact, the *noise equivalence factor* for a large set of UWB waveforms is quantified, and the results are plotted and tabulated herein. In order to determine this factor, a three-path signal generator has been constructed. The first path is a GPS simulator that provides the GPS signal input for a single satellite. The second path is a broadband noise source, where the noise is white within the GPS band and the noise power is under operator control. The third path is a prototype UWB waveform generator where the many UWB signal parameters can be varied independently in a controlled manner. It is expected that the noise equivalence factor will depend strongly on the UWB signal parameters. Some UWB emissions may be well described as noise-like, while others may have discrete spectral lines near the GPS L1 frequency.

The impact of UWB on the aeronautical and non-aeronautical use of GPS also depends on the specific operational scenario. The scenarios define the power transmitted by the UWB device and the proximity of the UWB transmitter relative to the victim GPS receiver. They also define the number of visible GPS satellites and the satellite elevation angles. The scenarios also determine whether other interference sources are nearby. These tests make no assumptions about any of these operational factors. However, the noise equivalence factor enables the computation of link budgets that correspond to a variety of operational scenarios of this type. In fact, RTCA is using these results along with the results of other efforts to build appropriate link budgets.

This report *does not* define or presume allowed levels of UWB transmissions, nor does it define the specific GPS interference scenarios of concern. The results are limited to determining the impact of a single UWB transmitter relative to broadband noise. The impact of multiple UWB emitters cannot be precisely predicted based on these results. In addition, this data does not address the deleterious effect of UWB signals with such high peak power that they may excite non-linear effects in the GPS receiver.

1.2 Test Philosophy and Scope

The goal of this second phase of UWB testing is to further characterize the interference effects of UWB emissions on typical GPS receivers 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 term “broadband” or “white noise” is used to characterize a flat frequency spectrum across a particular region of interest. That region of interest in this case is the GPS L1 band.

The approach used in this testing is to determine the UWB interference impact for a particular UWB transmission relative to a known level of broadband noise. This relative comparison is conducted at multiple test points about the area where the GPS receiver meets its performance criterion. This allows a normalization of receivers tested, provides relative performance measurements, and the multiple data points allow for a noise equivalency factor determination of the added UWB transmission power. Relative performance is critical as it would be unfair to utilize a GPS receiver for testing with performance significantly better than the minimal required. Likewise, it would also be biased to conduct a test with a receiver that does not meet the minimum performance requirements. The noise equivalence factor measure is also quite important as it allows for the computation of link budgets and specific power levels for specific UWB waveforms which will be quite useful in later utilization of the results of this testing.

Pseudorange (PR) 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. Pseudorange accuracy, or the accuracy on the relative distance between the satellite and receiver, was chosen to be the primary test criterion for aviation receiver testing. Pseudorange measurement accuracy is influenced by degradations in both code-delay and carrier-phase tracking. Current standards for local area augmented system (LAAS) GPS-based landing of aircraft define this requirement as a PR measurement with a standard deviation of 15 cm or less [5,6]. As such, it is a sensitive metric for the aviation applications.

The equivalence concept test methodology consists of inserting broadband noise into the GPS aviation receiver and increasing its level until 15 cm of pseudorange error standard deviation is measured. The broadband noise source is then reduced by *n* dB and the UWB source is introduced into the channel. The broadband noise power remains fixed at the *n* dB back-off point and the UWB emission level is increased until a measure of 15 cm pseudorange error standard deviation is observed. The total power from both the broadband noise and UWB emitter is measured as UWB power is increased in order to obtain the equivalence. Two specific back-off points are utilized in testing each UWB waveform to provide a linearity measure. In this case the testing is designed to use two values for *n* of 2 & 4 dB back-off. Once equivalence is tested at both back-off points another UWB parameter (e.g. Pulse Repetition Frequency (PRF)) is then chosen, and the entire sequence repeated until all combinations of UWB parameters have been investigated.

This process is depicted in Figure 1.1 where one curve represents what would be expected from broadband noise and then two traces from UWB parameter set *i* and *j* both introduced at a 4 dB back-off. In the figure cases *i* and *j* indicate UWB results which would be worse and better than, respectively, the broadband noise measurement. There are a multitude of UWB parameters that need to be considered, many more than the two depicted by *i* and *j* in this hypothetical example. If the UWB waveform is particularly damaging, for example, the receiver may lose lock right at or shortly after its introduction with minimal power being added – thus no curve will be traced out for that particular harmful UWB waveform. A number of cases have already been investigated and the impact of such cases is documented in the first test report using a single back-off point of 4 dB [3]. For this phase of testing, the more interesting cases have been re-evaluated using both 2 and 4 dB back-off values.

This test procedure allows a ratio of broadband noise to UWB power to be determined. Finding this ratio allows UWB interference to GPS to be evaluated by standard link-budget techniques that typically assume the incoming interference is white-noise-like. Note that the amount of back-off is not critically important to this test plan, because the comparison is the UWB replacement power to the amount of broadband noise power that is removed. However, the back-off power must be chosen with some care for practical reasons. If the back-off is too large, then the test results will be dominated by the internal noise of the receiver. If the back-off is too small, then errors in measuring the UWB replacement power will be magnified.

A key addition to this second phase of testing was the inclusion of a second back-off point at which the UWB signal was introduced. This measure had been requested by the aviation community via RTCA Special Committee-159 Working Group-6 in order to provide a noise equivalency factor of the added UWB power [11]. A noise equivalency factor numerical value for each UWB waveform is determined as shown in Figure 1.2. 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]). The equivalency factor (in dB) is used in an RFI link budget to correct the actual UWB emission to give the same RFI effect as an allotment for a noise-like RFI signal. 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.

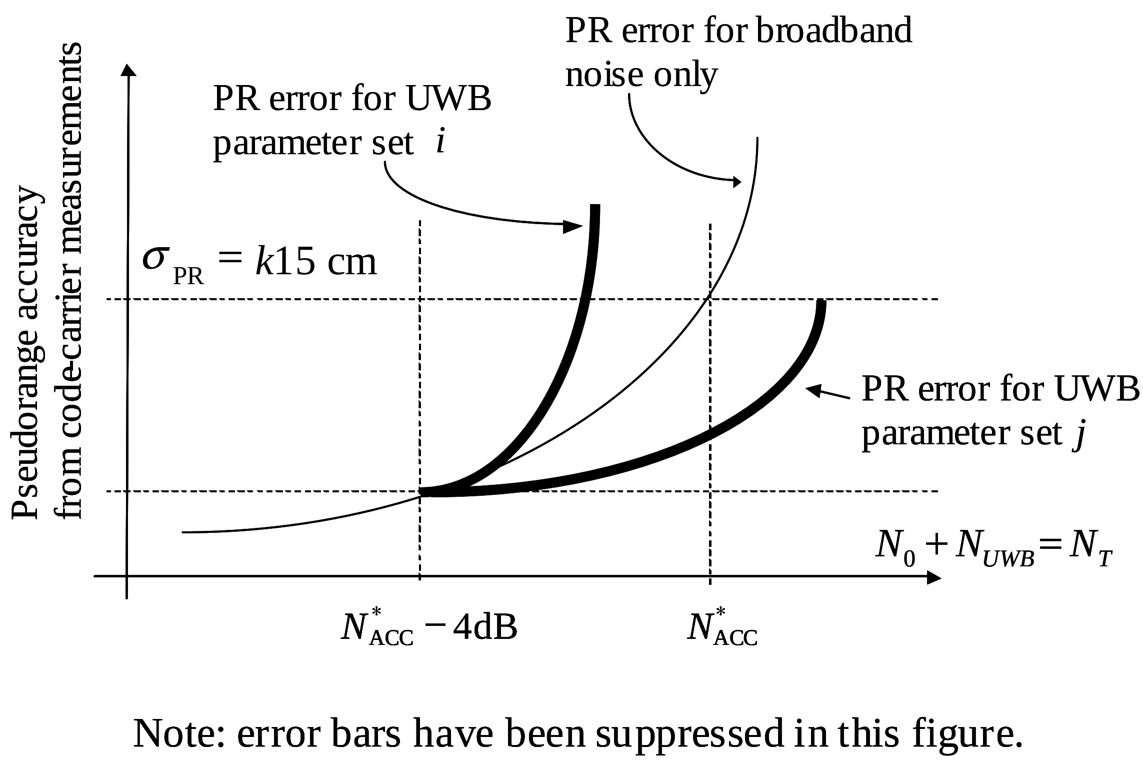


Figure 1.1. Pseudorange Accuracy as UWB Power is Added to Increase the Total Noise

Two additional test results are included in this second phase of testing that have been designed to report results that may be of interest to users of GPS outside the aviation community. Although aviation is likely to represent a category of the GPS users with little tolerance of additional interference in the band due to the high accuracy requirements, other users of GPS must be concerned regarding the impact UWB may pose. As an example, those systems being designed for E-911 positioning service that make use of GPS may even be more sensitive than the most stringent aviation application. This results from the long signal integration times and extremely weak signal-to-noise ratios that would be available for this technology indoors where the E-911 system must be designed to function. Both of these additional tests follow the equivalence measurement philosophy outlined in this section.

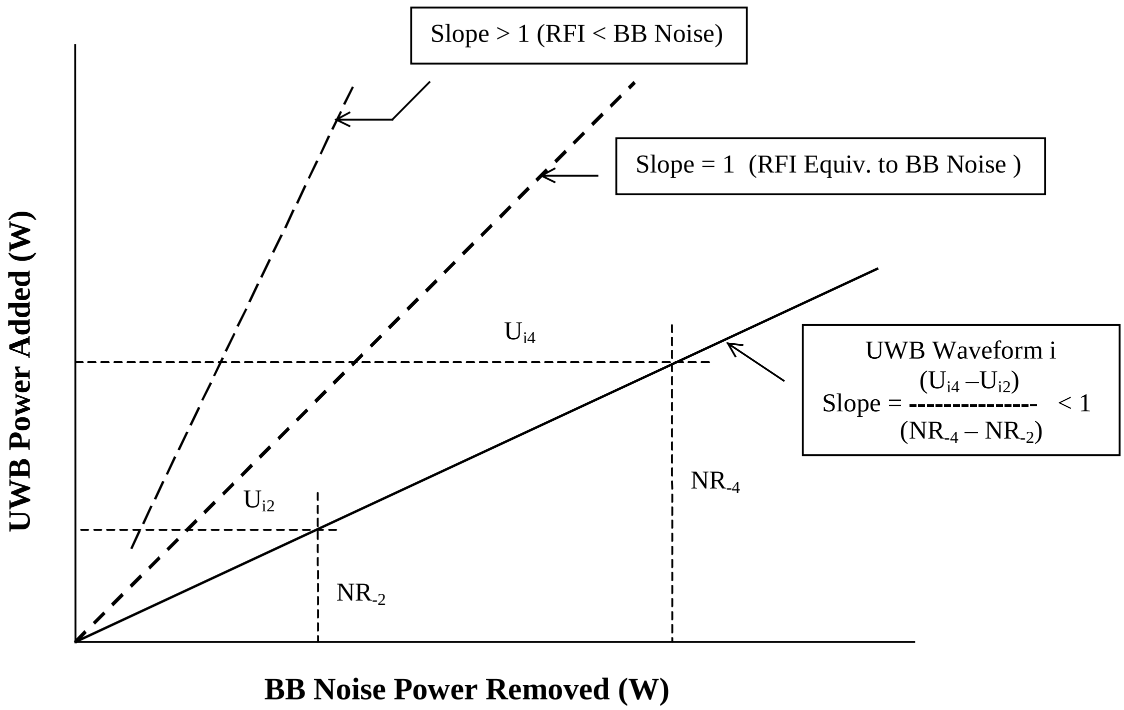


Figure 1.2. Noise Equivalency Factor of the Added UWB Power

The first of these added tests is a loss of lock test. The pseudorange accuracy measurement in Figure 1.1 was simply extended to provide this measurement. The broadband noise power is increased, driving the accuracy measurement beyond the *k*15 cm accuracy test to the point at which the receiver loses lock. This power level where this occurs is recorded, the broadband noise power is then reduced to the *n* dB back-off point from accuracy testing and UWB power is introduced into the channel. The UWB power is increased beyond the accuracy threshold until the receiver loses lock and this power level is also recorded to provide an equivalent power level for the particular UWB waveform. This data has been recorded for the aviation receiver used in accuracy testing but also recorded for a second receiver, an OEM GPS receiver likely to be used in higher volume applications such as the automotive market. The result of which will likely be of interest to non-aviation users.

The second new test is an acquisition test. It is well understood that GPS signal acquisition is a more sensitive process than GPS signal tracking. This implies that a higher signal-to-noise ratio is required for acquisition than is needed to maintain tracking. The accuracy and loss of lock testing are conducted once the receiver has already achieved the tracking state. Accordingly it is critical to consider the impact UWB transmissions will have on the more sensitive acquisition process. These tests are 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 1 minute attempts to acquire the signal, recording an “acquired” or “not acquired” result. This is done over a range of noise values that allow all five attempts to be successful in acquiring the signal to zero successful attempts to acquire 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 1 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 the performance in the presence of broadband noise.

The controlled bench testing described in this report follows a set of "over-the-air" UWB field tests conducted in 1999. The results of these tests are reported in [1]. Bench testing in a controlled environment is needed to remove variations that occur in the field. For example, transmitted GPS satellite power levels observed today are typically a few dB greater than the minimum C/A power levels promised by the U.S. Department of Defense in the GPS Standard Positioning Service (SPS) Signal Specification [12]. In addition, ambient broadband interference observed in the field will vary and is often below the required noise levels at which GPS users must meet all performance requirements. Thus, bench testing is needed to control satellite signal and broadband interference power levels so that they are relevant to the requirements placed on GPS users.

When conducting field tests, it is tempting to think that the fundamental requirement for GPS positioning is simply the maintenance of signal lock and acceptable pseudorange accuracy on four satellites, with additional satellites being redundant so that their loss due to interference is tolerable. This is a serious misunderstanding of GPS user requirements for aviation. To achieve high availability, GPS users must meet accuracy, continuity, and integrity requirements for satellite geometries with only four satellites in view (where this "redundancy" is absent). To be relevant to all possible satellite geometries, GPS requirements are specified for individual satellites, and this test procedures use a single-satellite simulator to provide results in the same range domain to which the GPS requirements apply. The continuity requirements that apply to GPS aviation users make losses of individual satellites (due to interference or any other unpredictable cause) intolerable beyond an allocation probability of 10^{-6} or lower per 15-second interval that is occupied by actual GPS satellite failures [5,6,7,9].

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

1. The test procedure is straightforward;
2. The receivers are normalized, so that the results do not depend on how much better (or worse) the particular receiver under test is beyond the minimum operating performance standards;
3. 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;

4. 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; and

5. The data extracted using the single satellite testing can be readily extended for the evaluation of multiple satellite scenarios.

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 GPS testing, beyond that being conducted at Stanford 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, address the additive affect of other (non-UWB) systems and their allowed out-of-band emissions, and evaluate the possible non-linear effects from UWB signals with high peak powers.

These tests developed have been 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 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.

2.0 UWB Signals and Key Parameters

A UWB pulse and its frequency spectrum are shown in Figures 2.1 and 2.2, respectively. This characterization is based on a prototype UWB transmitter used in initial field testing [1]. UWB can be interpreted to have a very broad definition. The basis for this testing is a UWB signal that is based on very short pulses with applications in radar and communications. Its main advantages include:

- ability to mitigate multipath as a result of its short duration;
- ability to operate indoors as well as in cities and obstructed areas;
- facilitatation of high-precision ranging and radar;
- low-power, wide-bandwidth characteristic enables low probability of interception by undesired receivers.

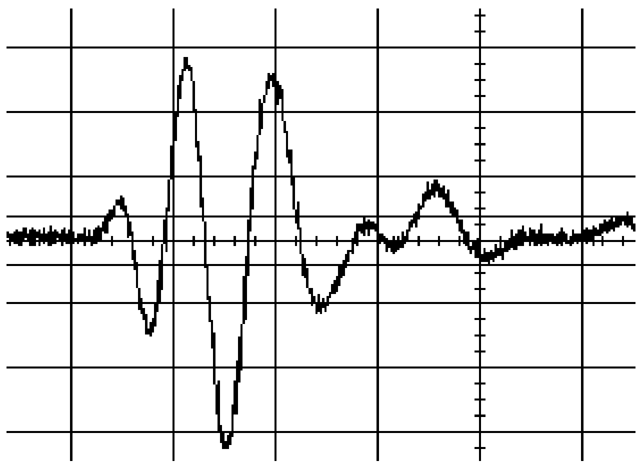


Figure 2.1. A Typical UWB Pulse in the Time Domain

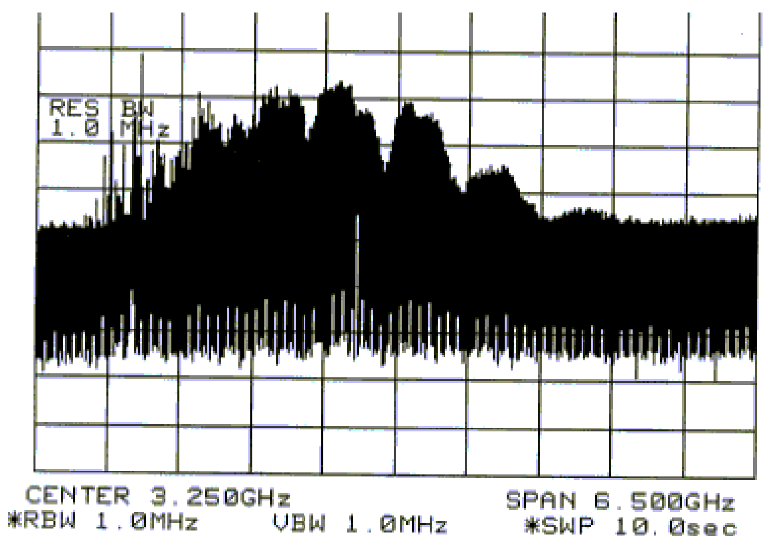


Figure 2.2. Frequency Spectrum of a Typical UWB Signal

UWB technology has potential in applications such as stud/support beam finding, ground penetrating radar (GPR), and military communications. Planned or proposed UWB applications include through-the-wall surveillance prior to drug raids, 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. In an article from Aerospace Online by D. Caera from 31-January-2001 it is projected that UWB will become such a widespread utility that there will someday be as many eight UWB devices per person [13].

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 in cooperation with potential UWB manufacturers demonstrated that UWB transmitter could interfere with GPS receivers [3]. However, UWB has many different parameters such as Pulse Repetition Frequency (PRF), duty cycle, burst on/off time, modulation scheme (including pulse dithering and pulse on/off keying (OOK)), filter technology, etc. The UWB pulse train and its spectrum vary accordingly, as is illustrated by the examples in Figures 2.3, 2.4, and 2.5 and in more detail by the Phase I test results [3]. In addition, there are many different 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 and controlled testing and study are needed to evaluate potential interference to GPS and its dependence on these UWB parameters.

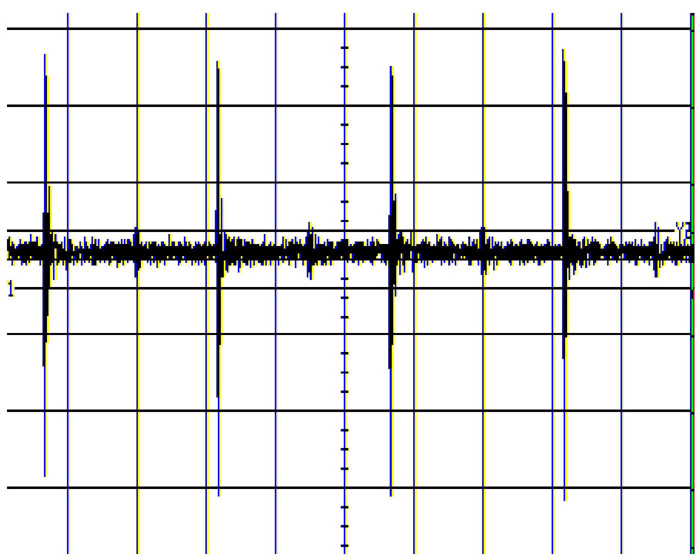


Figure 2.3. UWB Pulse Train

The goal of the testing is to provide such an investigation, and to characterize the interference effects of UWB emissions on multiple GPS receivers in a controlled test environment. Of particular interest is the testing of aviation receivers where well defined standards and performance expectations already exist. Some UWB emissions are reasonably noise-like while others have more distinct spectral lines in the vicinity of GPS. An RFI equivalence concept was developed to relate the interference impact of UWB signals on GPS over this range of UWB emissions to that of a known and well understood RFI source, i.e., broadband noise. The method chosen for this test plan is to determine the UWB interference effect for a given set of emission parameters that is equivalent to a known portion of the broadband noise input over a range of power levels around the point at which the GPS receiver achieved its required performance criterion. A sufficient level of broadband noise is input to represent the actual GPS environment.

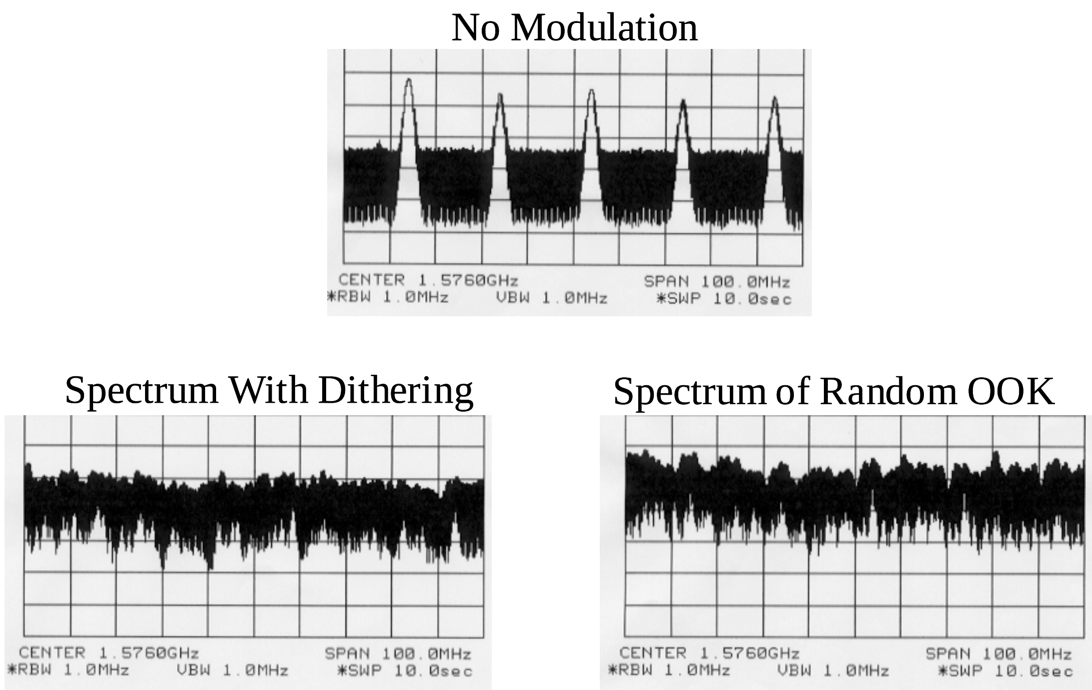


Figure 2.4. UWB Spectrum Examples

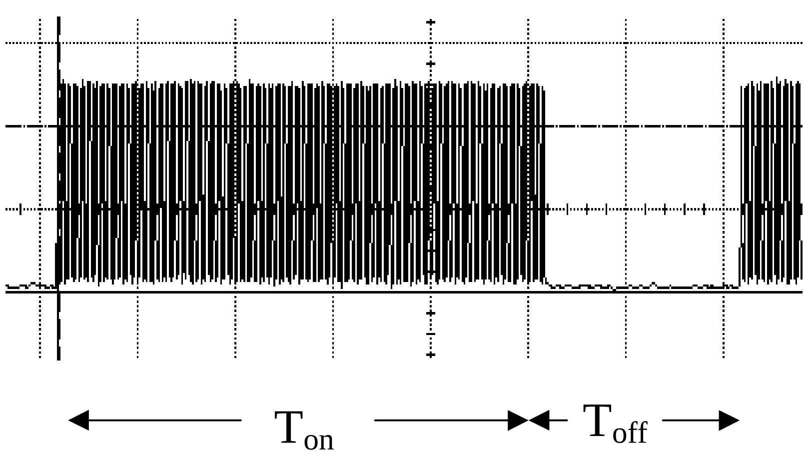


Figure 2.5. UWB with Burst Duty Cycle < 100%

The RFI effect of the UWB signal will be sensitive to the details of the UWB signal design. Some of these trends are depicted in Figure 2.6. From existing theory and previous testing, the impact of a UWB waveform on GPS is affected by the following characteristics of the waveform:

- *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 500 kHz, then it has been shown from previous testing that the pulses will still be distinct at the output of the receiver front end, and the interference will 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.

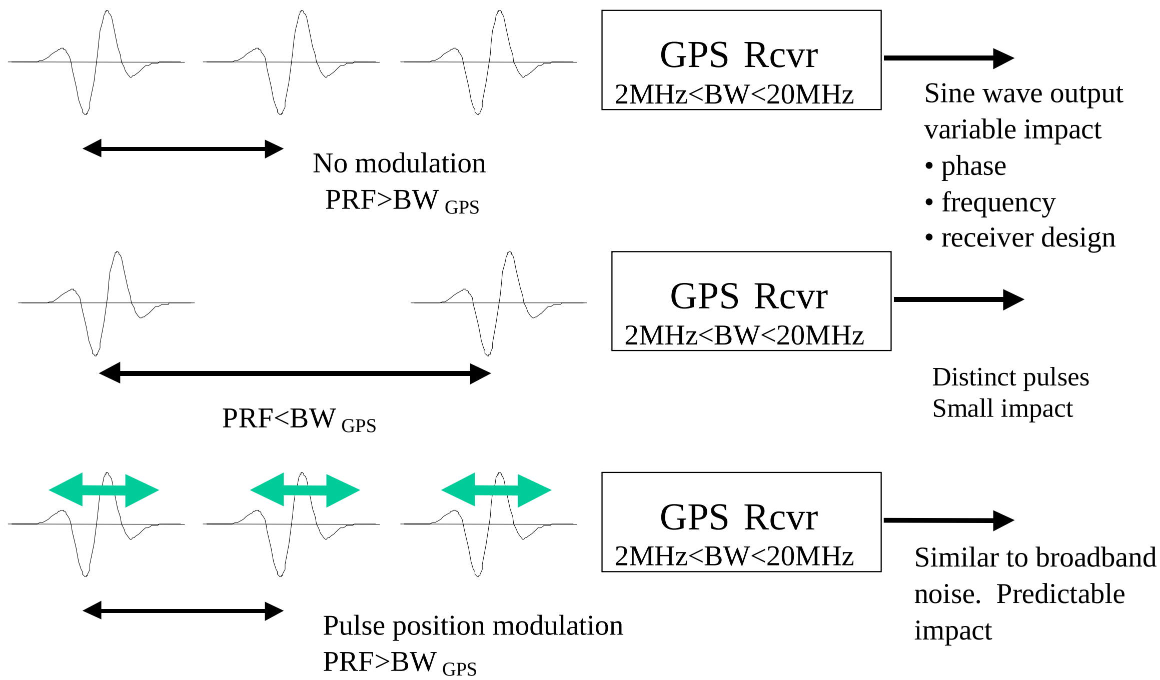


Figure 2.6. Sensitivity to UWB Signal Parameters

In general, GPS receivers are less sensitive to 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 2.3, and the resulting line spectra are shown as the "no modulation" case in Figure 2.4. The GPS C/A-code also has line spectra. UWB interference will 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 bandwidth of the particular GPS receiver under test. The locations of UWB spectral lines will change based on the UWB transmitter 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 noise of equal power.

- *Pulse Bursting*: As shown in Figure 2.5, 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 small, it has been observed that the effect of a single UWB transmitter on a GPS receiver will be reduced.

- *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 the GPS L1 frequency).

All of these characteristics have been validated in the first phase of testing [3]. The Phase I test cases varied a wide number of UWB signal parameters and provided an initial indication of how the UWB-to-broadband noise equivalence depends on the UWB signal parameters. As a result of previous testing, a subset of UWB waveforms from Phase I testing has been identified for Phase II testing. These specific UWB waveforms are the following:

1) 20 MHz constant PRF
2) 19.94 MHz constant PRF
3) 100 kHz constant PRF
4) 15.91 MHz 2-Position Pulse Position Modulation
5) 15.94 MHz 2-Position Pulse Position Modulation
6) 2 MHz 10-Position Pulse Position Modulation

The specific UWB waveforms listed above represent the best and worst of those tested in Phase I along with those that provided fairly unique results in that space. They include the high PRF, low PRF, and various modulations cases with varying PRFs to test the spectral line impact. Results for these test cases are provided in Sections 4.0, 5.0, 6.0, and 7.0 of this report.

3.0 Test Setup and Procedures

3.1 UWB Transmitter Prototype

The UWB transmitter prototype consists of three main components cascaded as shown in Figure 3.1. This is the same prototype used for the radiated testing [1], the Phase I testing [3], and the results contained within this report. The pulsar is the primary component in the system and actually generates the UWB pulse when triggered. The trigger is accomplished using an Arbitrary Waveform Generator (AWG). All modulation and duty cycle control comes via the AWG in the manner in which the pulsar is triggered. The next component is a high pass filter designed to pass frequencies above 800 MHz. The final component is an amplifier to provide gain to the signal prior to transferring power to the antenna. Interestingly the interference to GPS from this prototype observed in [1] occurred even though the GPS band, 20 MHz centered about 1575.42 MHz, is not in the specified bandwidth, 2000 MHz – 8000 MHz, of the amplifier. It is likely that UWB frequency energy within the GPS band still experienced some amount of amplification in the lower rolloff gain from this amplifier.

Pulse generator:	HL 9200
High-pass filter:	800 MHz cutoff frequency (F_C)
Amplifier:	2 – 8 GHz 20 dB gain 4 dB Noise Factor (NF)

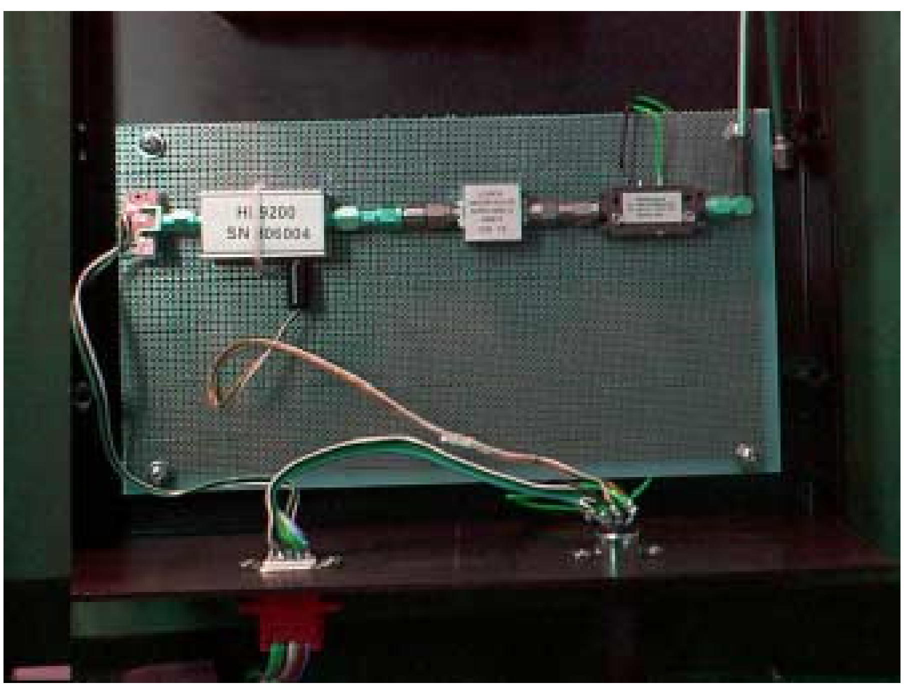


Figure 3.1. UWB Transmitter Prototype

In this previous radiated testing, the UWB emitter was treated as a “black box”. For the test results documented in this report, a more-controlled experiment has been conducted where all components are connected using shielded RF cables and are carefully calibrated (described in more detail in Section 3.3 and [2]). Treating the prototype as a “black box” provided the depiction of the pulse in Figure 2.1. However, it should be noted that this is the pulse as a result of the shaping by the components described above (filter and amplifier). For these more controlled experiments, it is possible to view the pulse at the various stages of its generation. This also allows a representation of the pulse shaping which arise from the additional RF components.

An individual pulse directly from the pulsar measured in the time domain is depicted in Figure 3.2. Note that this picture fits the description of a “pulse” much better than that of Figure 2.1 as it truly looks like a single pulse. In Figure 3.3, a single pulse is measured at the various output stages all plotted along the same time scale. The bottom plot of Figure 3.3 is the pulse measurement taken at the same stage as the pulse depicted in Figure 2.1. Thus even in this prototype, the pulse undergoes some shaping, primarily bandlimiting, as a resulting of the additional RF components.

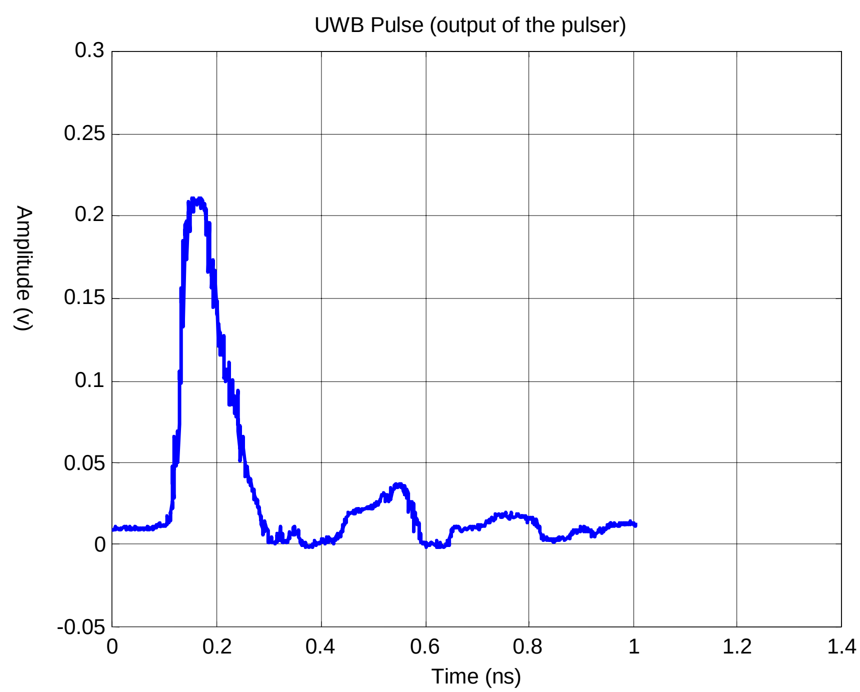


Figure 3.2. A Single UWB Pulse

3.2 Broadband Noise Normalization

The aviation-grade GPS receiver used in these tests is operated with a received GPS satellite signal level of –131.3 dBm as generated by a single-channel GPS signal simulator. Compensation is applied to adjust for room temperature, satellite simulator noise output, or the effects of a remote antenna preamplifier as needed. This level is higher then absolute specified minimum signal level in [5,6], but allows for testing in the transition region of the accuracy curve that will be shown later in this section in Figure 3.4. Broadband 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 [6]. 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. The unsmoothed pseudorange (the internal receiver carried-added-smoothing time is set to 0.5 seconds) is then recorded and an estimate is derived of the one-sigma pseudorange error by computing the standard deviation of the code-minus-carrier test statistic after removing a 2^{nd}-order polynomial fit to the mean, using the algorithm defined in [4]. For each fixed broadband power level, raw code and carrier data is collected for one hour at a 2 Hz sampling rate.

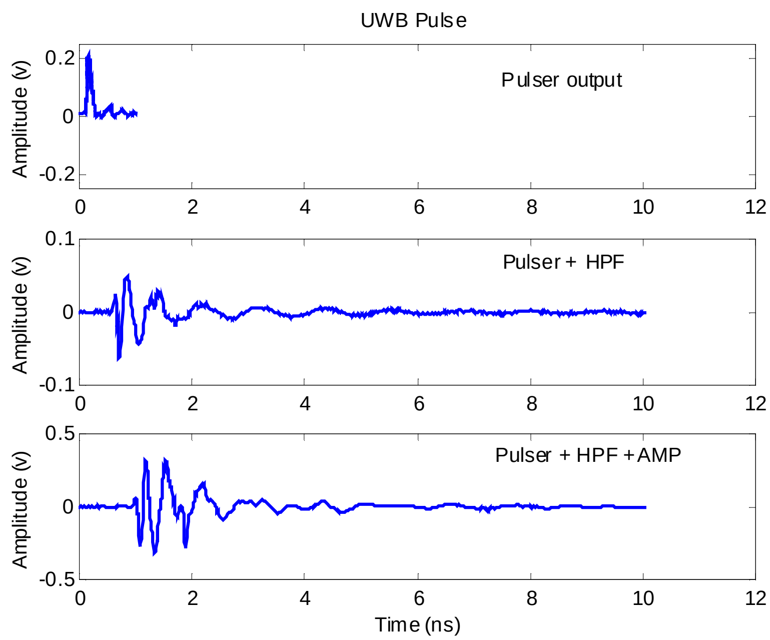


Figure 3.3. UWB Pulse at Various Transmitter Stages

To be conservative, one independent sample is assumed to occur every four 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 3.4 was then obtained. This curve indicates the GPS receiver accuracy as a function of the level of broadband noise. Note that there is a difference (*k* in Figure 3.4) 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. It was found that 1.4 m of raw PSR accuracy is consistently equivalent to 15 cm of carrier-smoothed PSR accuracy.

3.3 Test Setup

As shown in Figure 3.5, the GPS signal, broadband noise, and UWB are combined before being injected into the 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.

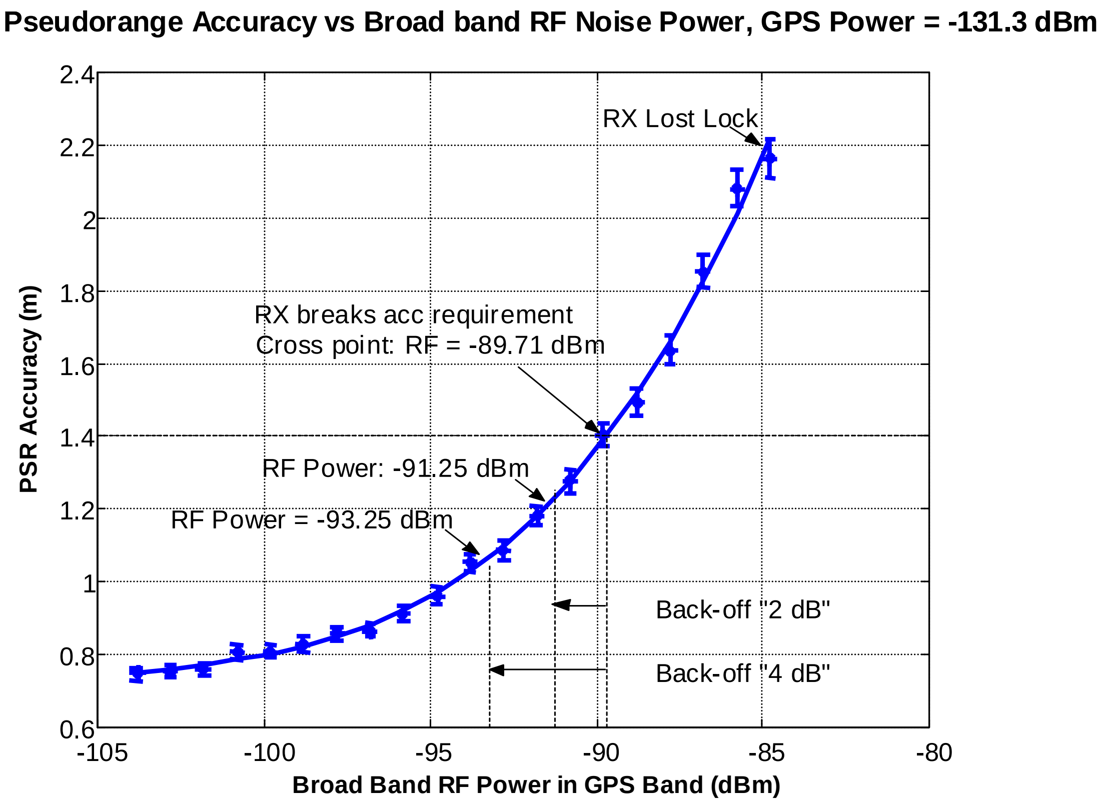


Figure 3.4. GPS Receiver Normalization

A Tektronics AWG 2021, which triggers the UWB pulse generator, was used to trigger the pulsar to provide 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 has been automated using Labview and IEEE buses.

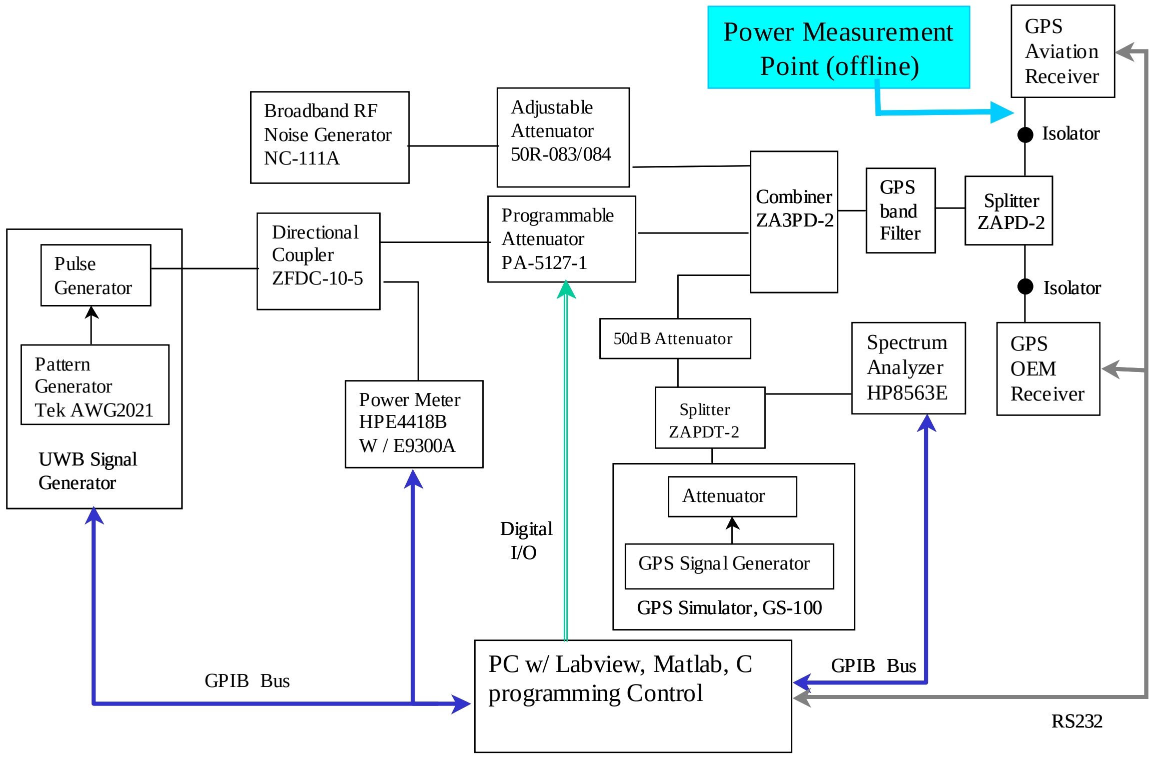


Figure 3.5. UWB Interference Test Setup

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 and allows for a precise power measurement. The L1 filter used in these tests has the frequency characteristic shown in Figure 3.6.

It is important to note the differences in this test configuration versus that used for Phase I testing. Most noteworthy is the second receiver that has been added to the test configuration. This required an additional signal splitter in the construction and RF isolators were included to ensure there was no coupling between the receivers. The GPS receiver normalization curve in Figure 3.4 is based on the GPS aviation receiver as it is the component used for accuracy testing. Also this curve is not the same curve as that used in Phase I testing, but rather regenerated version for this phase of testing. As a result of the modifications in the hardware configuration, all measurements had been recalibrated with the generation of a new broadband noise curve that closely resembles the Phase I curve. This demonstrates the repeatability of the measurement even with the redesign test configuration.

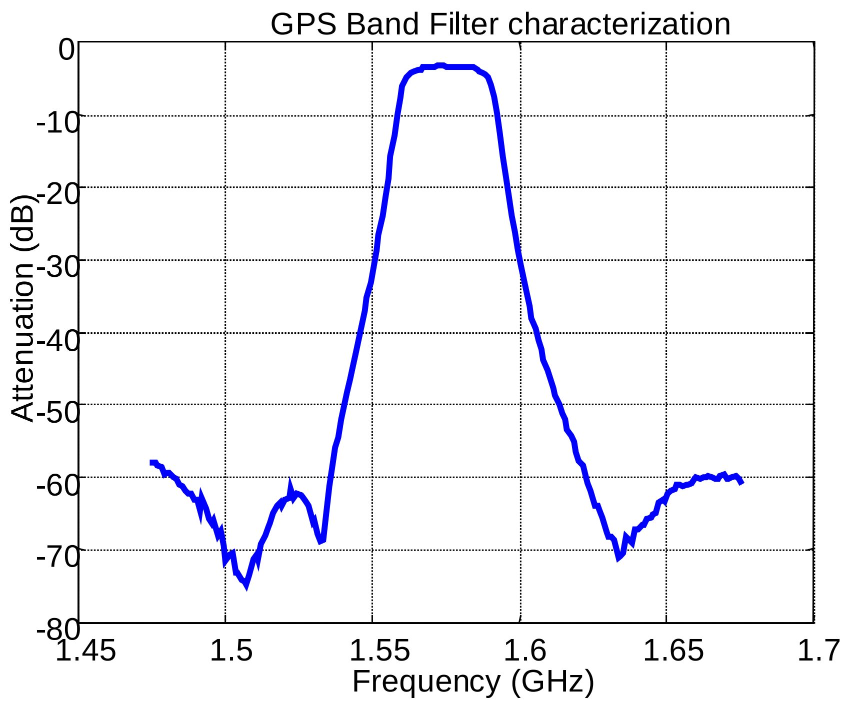


Figure 3.6. GPS L1 Filter Characterization

4.0 UWB Spectral Line Re-Visitation

A fundamental insight to explain the impact the UWB signal has on the GPS receiver was gained through the research conducted at Stanford University during Phase I testing [3]. The UWB frequency spectrum, although very broad, can contain distinct spectral lines rather than appear as a flat spectrum as would be the case for broadband noise. Thus the UWB spectrum can be classified as a combination of a broadband-like flat component with distinct spectral lines. When strong discrete spectral lines fall within the GPS band, they are particularly damaging to the GPS receiver performance. This observation was a crucial result from Phase I testing and was investigated thoroughly.

In the Phase I test report the following figure was used to show evidence of the spectral lines.

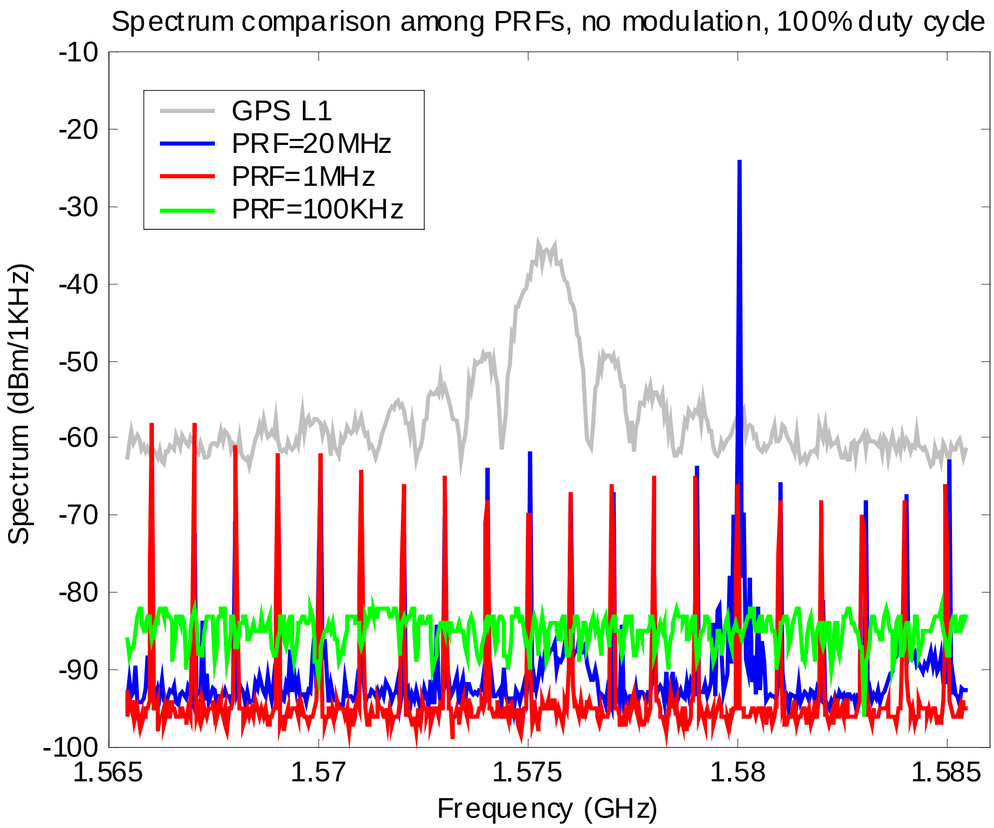


Figure 4.1. Spectral Comparison Among PRFs (from Phase I report)

This figure shows the UWB spectra for various constant PRF waveforms with the GPS spectrum overlaid. Its primary purpose is to illustrate the characteristics of the UWB spectral lines for various PRFs. No attempt was made to show the relative power levels between the GPS signal and UWB signals. While the UWB power levels are relatively proportional, this proportionality does not factor into account the PRF of the UWB signal, and this is a source of potential confusion. The relative levels between the

UWB spectra are simply the outputs of the UWB transmitter into the spectrum analyzer. Since the PRFs differ, and no power compensation is utilized, the high-PRF cases result in a higher average output power simply due to the greater number of pulses generated per unit of time. This was verified using various constant PRFs and measuring the power out of the pulser. A plot resulting from this verification testing is shown in Figure 4.2.

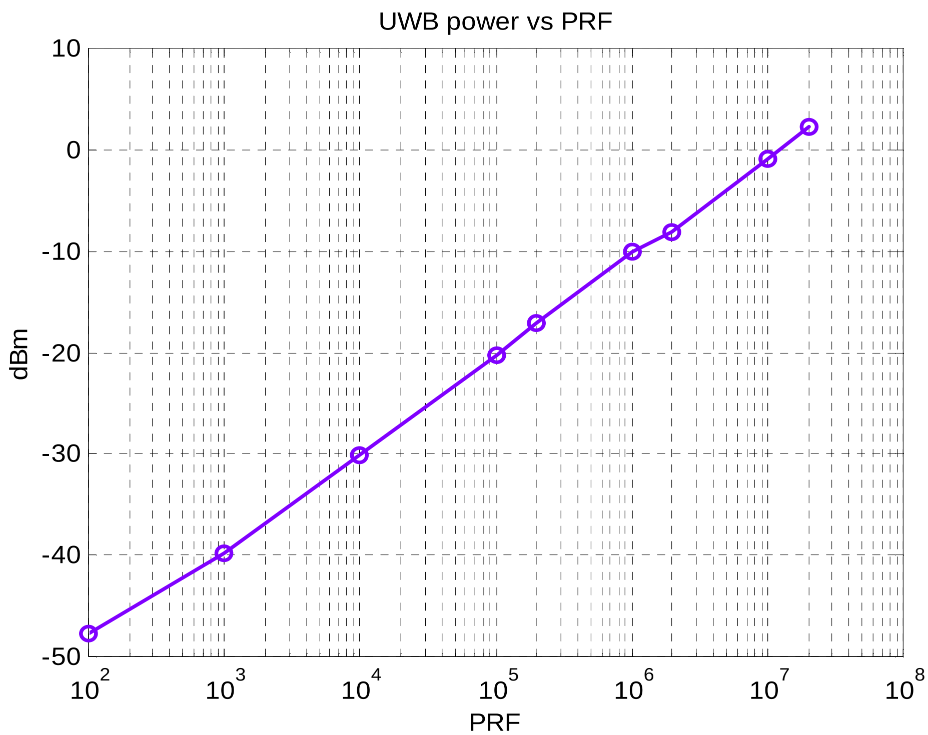


Figure 4.2. Measured Output Power of the Pulsar for Various PRFs

In order to confirm this hypothesis and clarify the previous explanation, two additional trials were conducted during Phase II testing. Each trial used a set of PRFs that differ by a factor of 10. There will be two consequences of such testing. First, the PRF multiplied by 10 will have a single spectral line in the span, while the lower PRF will have 10 lines. Thus, the spectral energy of a single line is distributed across 10 lines. Second, the PRF that is multiplied by 10 is generating ten times the number of pulses, so it will have a proportionally higher output power. These results are depicted in Figure 4.3.

In conclusion, the measured power levels are as would be expected, and the expected power relationships between various PRFs hold. The purpose of this data is to clarify any confusion that may have resulted from the spectral-line plots in the Phase I report as well as to promote a more detailed understanding of the spectrum of the UWB signal.

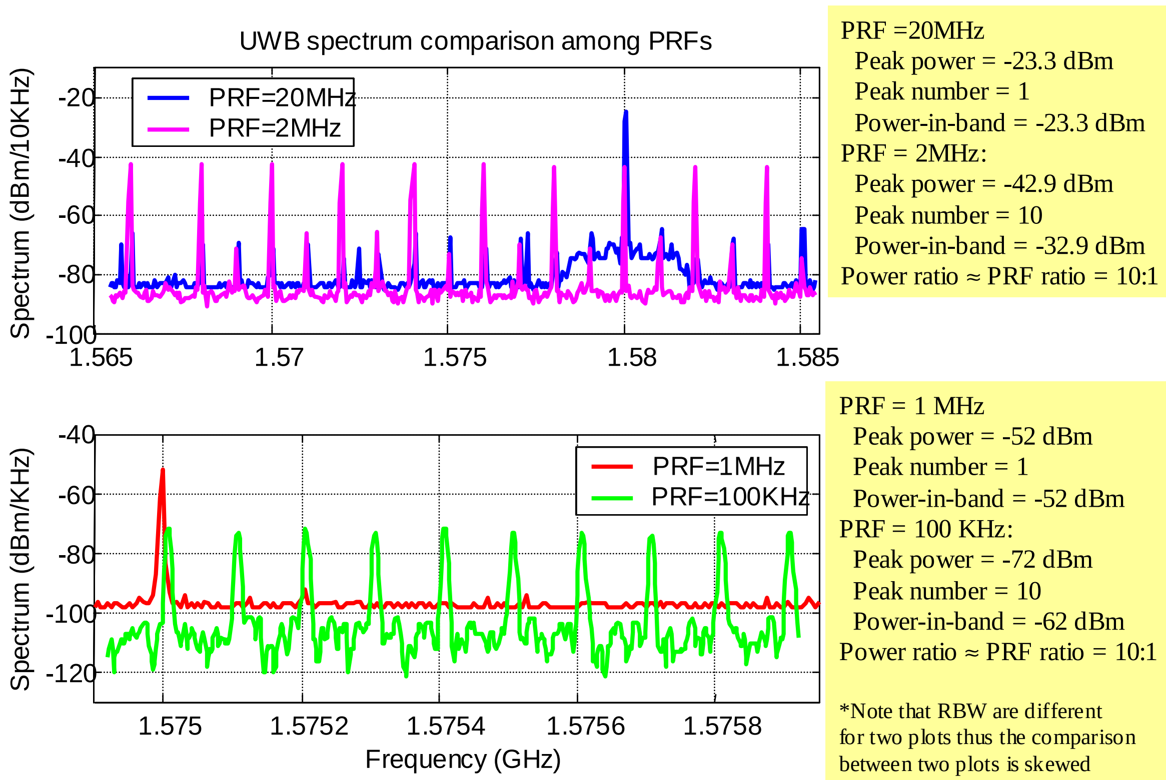


Figure 4.3. Spectral Line Comparison for Various PRFs

5.0 Multiple Back-off Points for Accuracy Testing of GPS Aviation Receivers

There continues to be an interest in accuracy results of aviation GPS receivers in the presence of UWB signals. This topic was first investigated in the Phase I testing at Stanford University and the aviation community had requested additional data from these tests. As such, accuracy testing has continued to be the focus of Phase II testing at Stanford University. Initial work had shown a heavy dependence between GPS receiver performance and the resulting UWB spectral lines. The goal of this continued testing is to examine a specific subset of waveforms of interest with two different broadband noise back-off values at which the UWB power is added and increased.

5.1 Test Procedure

The accuracy test procedure is described in the following two subsections. This test procedure is adapted from Section 2.5.8 of RTCA DO-229B, the *Minimum Operational Performance Standard for Avionics Using the Wide Area Augmentation System (WAAS).* As described above, it includes the following steps: calibration, normalization with white noise only, UWB interference measurements, and reporting. Sections 5.1.1 and 5.1.2 detail the broadband random noise normalization and the UWB interference measurements, respectively.

5.1.1 Broadband Noise Normalization

1) Set up the test equipment as shown in Figure 3.5.

2) The GPS receiver is operated with a minimum received satellite signal level. Compensation is applied to adjust for room temperature, satellite simulator noise output, or the effects of a remote antenna preamplifier as needed. In other words, set the GPS power to –131 dBm+G_{LNA} where G_{LNA} is the gain of any equipment that might nominally appear between the antenna and the receiver under test.

3) Broadband random noise is added to the simulated GPS satellite signal at the receiver input. Set the center frequency of the broadband noise to 1575.42 MHz. Adjust the broadband noise power such that the noise power is –103.5 dBm+G_{LNA} as measured in the standard filter described earlier. The gain G_{LNA} accounts for the gain that appears between the antenna and the receiver under test. As a rough check on power levels, measure the carrier to noise density (C/N_0) as reported by the receiver.

4) Let the GPS receiver track the satellite and reach steady state (for at least 10 seconds).

5) Measure the unsmoothed pseudorange and estimate the one-sigma pseudorange error by computing the standard deviation σ_r of the code-minus-carrier test statistic after removing a 2^{nd}-order polynomial fit of the mean. Use the sample size required to achieve the confidence levels described above. Also recall that the unsmoothed pseudorange error is larger than the smoothed pseudorange error by a factor of *k*.

This factor is the ratio of the noise bandwidth for the code loop to the noise bandwidth when 100 seconds of carrier smoothing is used.

6) Increase the broadband noise power in 1 dB steps until the accuracy just exceeds the *k*15 cm accuracy requirement. Record the noise power setting (N^{*}_{ACC}). Record also the C/N indicator from the GPS receiver.

5.1.2 Procedure for Testing Potential UWB Impact on GPS Accuracy

1) Setup the test equipment as shown in Figure 3.5.
2) Set the noise attenuator to approximately 4 dB below the value obtained in Section 5.1.1, Step 6.
3) Select one set of UWB signal parameters from the test matrix described earlier and set the UWB noise power (N_{UWB}) at least 10 dB below the broadband random noise power (N_0).
4) Let the GPS receiver track the satellite and reach steady state (for at least 10 seconds).
5) Measure the unsmoothed pseudorange and estimate the one-sigma pseudorange error by computing the standard deviation σ_r of the code-minus-carrier test statistic after removing a 2nd-order polynomial fit of the mean. Use the sample size required to achieve the confidence levels described above and recall that the unsmoothed pseudorange error is larger than the smoothed pseudorange error by a factor of *k*.
6) Increase the UWB power until the *k*15 cm pseudorange accuracy is just exceeded. Record that power setting. Record also the C/N_0 indicator from the GPS receiver. Also find and record the accuracy when the total power (UWB plus broadband) equals the threshold power for broadband noise alone.
7) Reset the initial UWB power to the starting value from step 3) and now decrease the noise attenuator to a setting of 2 dB below the value obtained in Section 5.1.1, Step 6 and repeat steps 4) through 6) for this reduced back-off value.
8) Change the UWB signal parameters to the next value of interest and repeat steps 3) through 7) until all desired combinations of UWB signal parameters are tested.

5.2 Multiple Back-off Points Accuracy Testing Results

The specific UWB waveforms described in Section 2.0 of this report were utilized in the testing. Rather than use precisely 2 and 4 dB back-off values, a setting of 1.54 and 3.54 dB were used as the exact back-off values. Using exact values of 2 & 4 dB 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.

The first result presented is for the 20 MHz constant PRF case. This is shown in Figure 5.1.

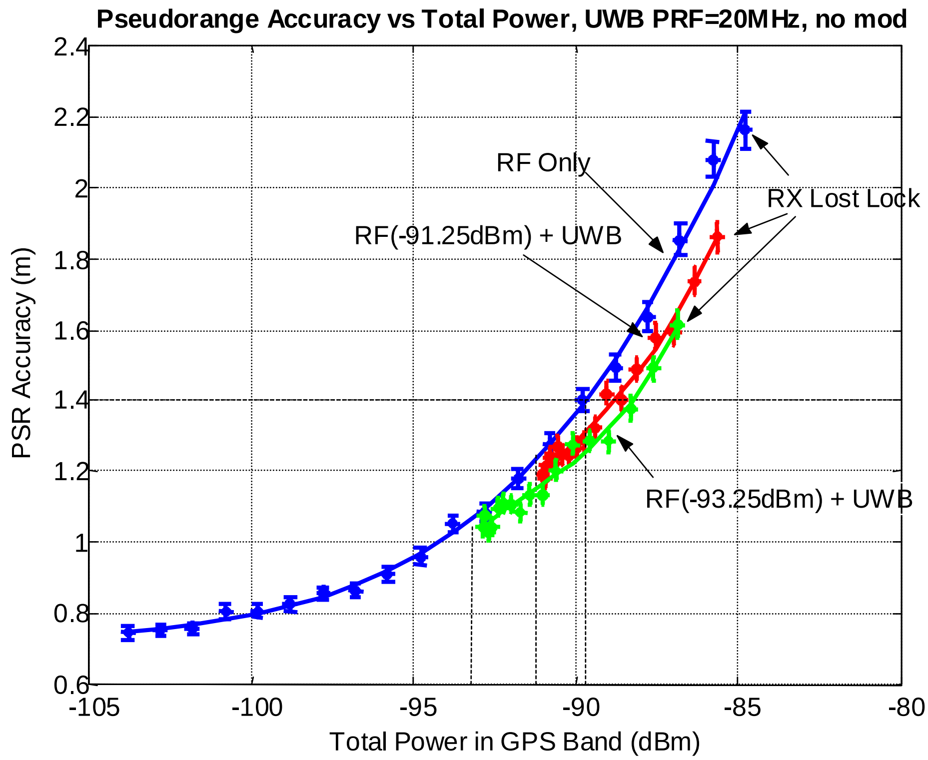


Figure 5.1. Multiple Back-Off Points with a 20 MHz Constant PRF UWB Waveform

As should be expected, the 3.54 back-off trace approximately follows the 4 dB back-off trace reported in Phase I testing. This shows the consistency of the results being recorded since the configuration had been reconstructed and recalibrated, yet the results remain the same. Also note the similar curved traced out by both back-off trials, thus it could be predicted that additional back-off point testing would produce similar results.

It is possible to view the broadband noise back-off points in greater detail. A zoomed view about this region is shown in Figure 5.2. Rather than continue to show zoomed views of all the cases tested, a final table of values will be presented at the end of this section.

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 was 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. As such, the performance is significantly worse, the receiver loses lock with an additional –101.27 dBm UWB energy at either of the two back-off points and cannot achieve the desired accuracy point. This accuracy testing result for the

19.94 MHz constant PRF is shown in Figure 5.3. 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.

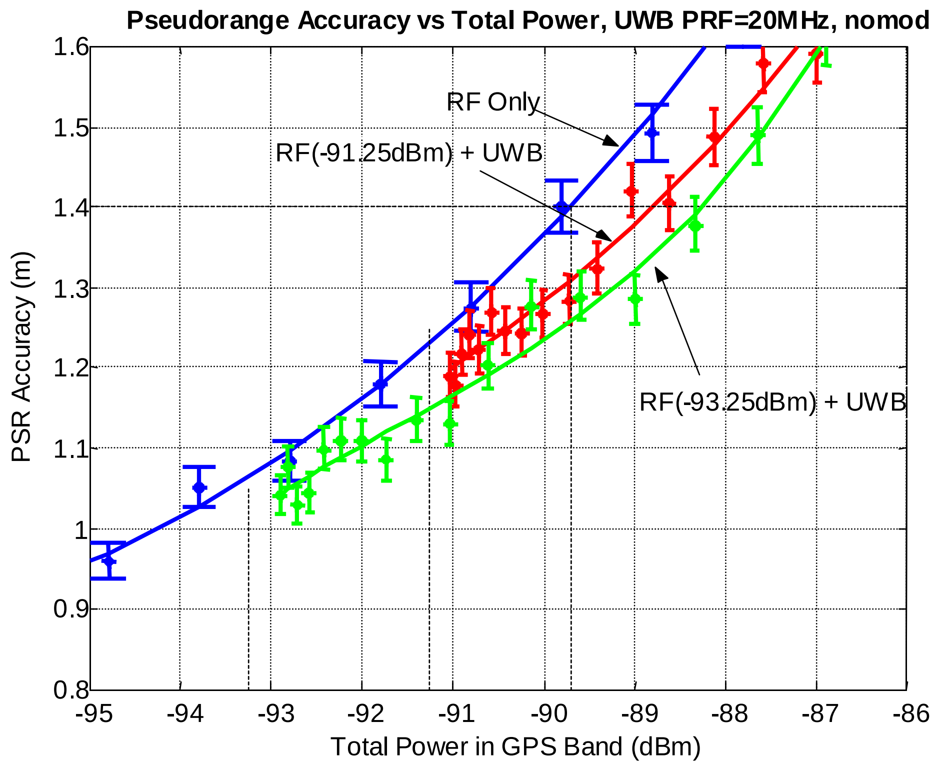


Figure 5.2. Zoomed View of Multiple Back-Off Points
with a 20 MHz Constant PRF UWB Waveform

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 (see Fig 3.6). By comparison, UWB with discrete spectral lines is as much as 17 dB more damaging than broadband noise in a 24 MHz bandwidth. 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), then 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 any 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. PRN 1 was used for testing in Phase I trials. The highest C/A line for PRN 1 is at 1575.378 MHz, which is 118 kHz away from the UWB spectral line. In the current test, PRN 21 is used and its highest C/A line is at 1575.365, which is 105 KHz away from the UWB spectral line. This is shown in Figure 5.4. 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. Thus the results presented here should not be considered worst case.

In practice, UWB lines will frequently find the 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 generates such lines.

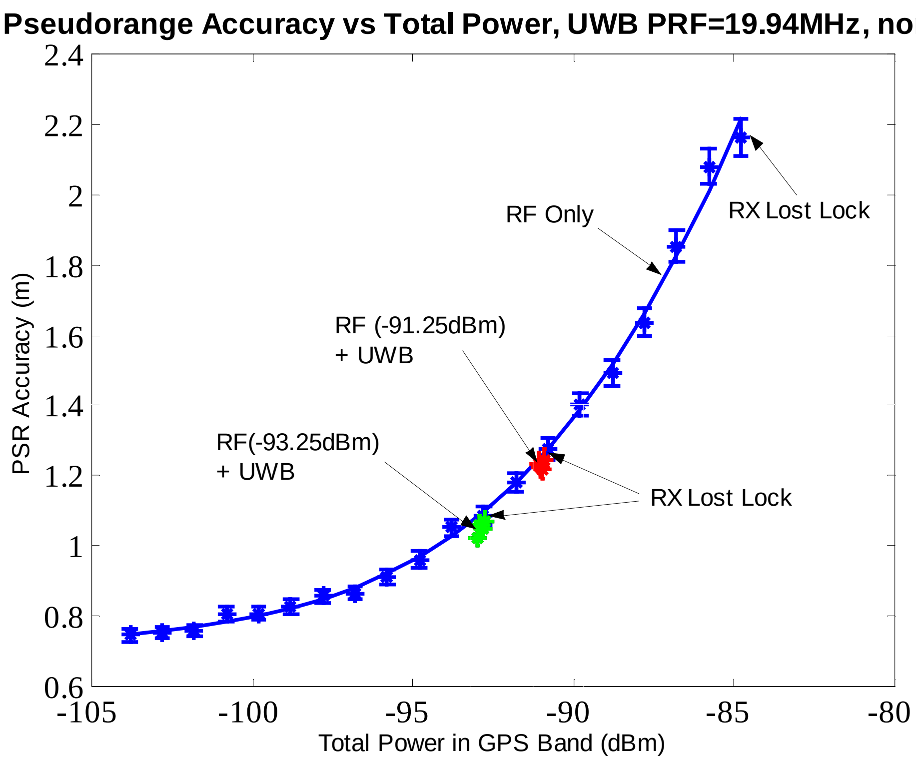


Figure 5.3. Multiple Back-Off Points with a 19.94 MHz Constant PRF UWB Waveform

The next case of interest is the 100 kHz constant PRF UWB waveform. For this signal, the discrete spectral lines appear at 100 kHz. These lines are so close together that they appear more like broadband noise than any of the previous cases tested. More importantly, at this low PRF 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 cases repeats this assertion and are shown in Figure 5.5.

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.

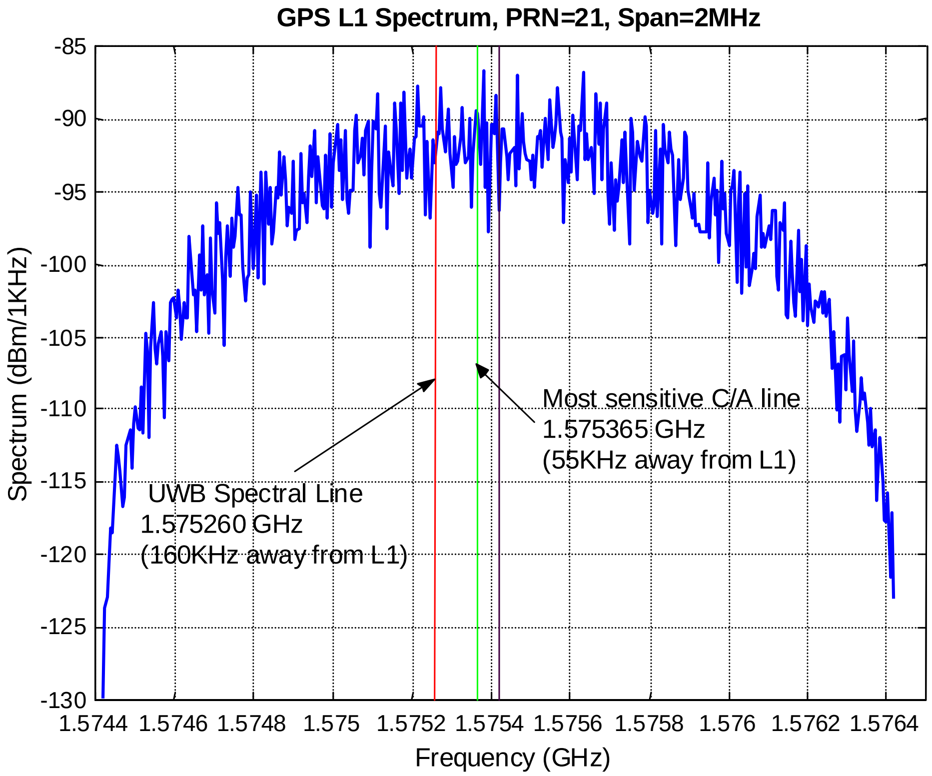


Figure 5.4. PRN 21 C/A Code Spectral Line Investigation

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. One class of such methods is to modulate the UWB pulses to remove the periodic nature of the waveform and thus reduce the spectral line component of the UWB spectrum into a less damaging broadband noise component. Two such modulation methods were discussed and tested for the Phase I report. They are 2-position pulse position modulation and 10-position pulse position modulation. The basis behind these modulation methods is shown in Figures 5.6 and 5.7.

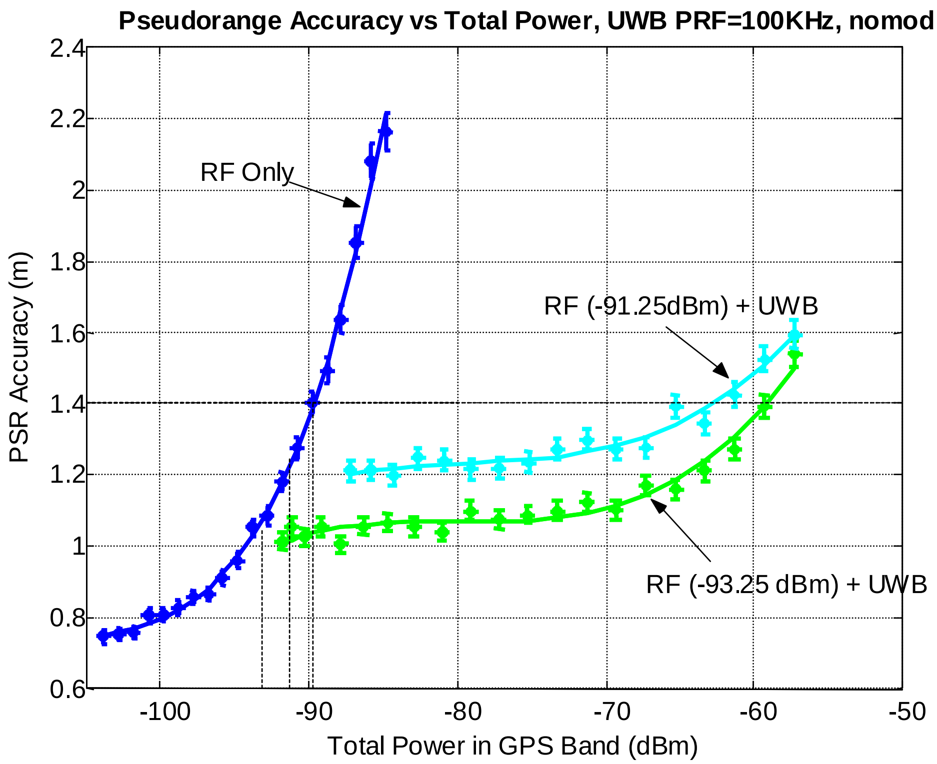
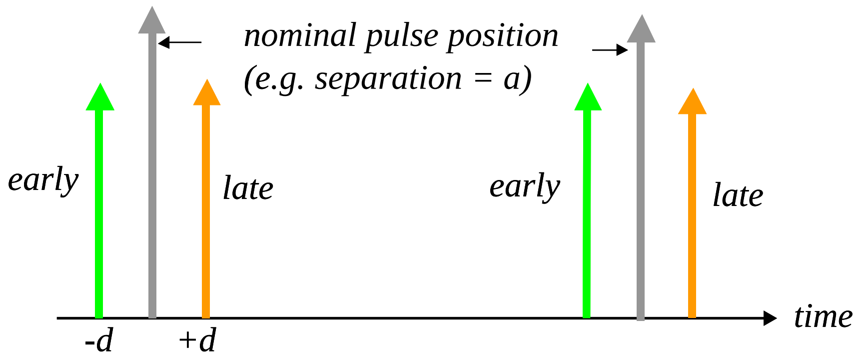


Figure 5.5. Multiple Back-Off Points with a 100 kHz Constant PRF UWB Waveform

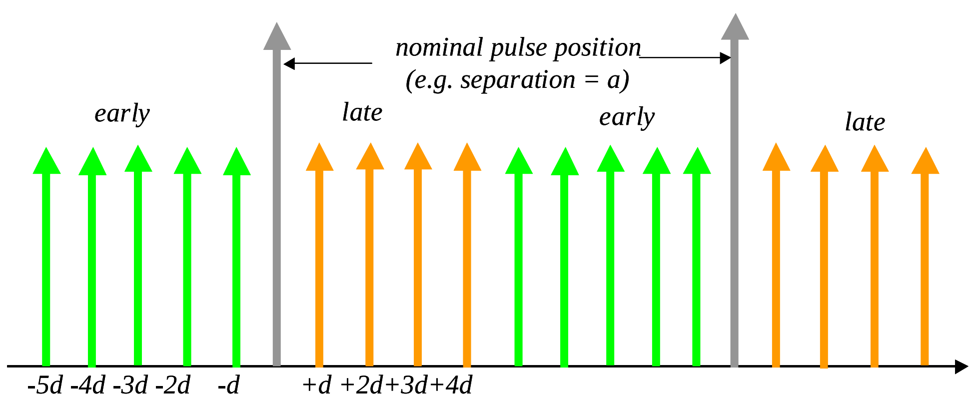
The goal behind both of these modulations is to make the appearance of the pulses more random in nature, removing the periodicity and as a result and minimizing the undesired spectral lines. The more random the appearance of the pulses can be made, the greater the reduction in the height of the spectral lines. In all of the modulation cases tested in Phase I, none were able to completely remove the visible spectral lines but all did result in some reduction in their magnitude. Of the two cases considered in Phase II testing the 10-position pulse position modulation did a slightly better in achieving the smaller spectral lines than did the 2-position pulse position modulation. Also it is important to recognize that with the position modulation methods, the base PRF needed to be scaled downward to ensure the required 50ns 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.

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 test case of 15.91 MHz PRF with 2-position pulse position modulation places a spectral line at 1575.09 MHz, again in the primary spectral lobe of the GPS signal. As a result, the GPS receiver loses lock quite early for both back-off points as is shown in Figure 5.8.



The pulse will take either an early position (nominal - d) or late position (nominal + d). The minimum separation of two pulses is 50 ns (limitation of the pulsar). We constructed a sequence of 252K points with d = 2 ns and a = 56 ns when clock=250 MHz. The ratio of position dithering (d/a) was 1/28 (3.57%). The relation of PRF/clock is 1/14.

Figure 5.6. Basis for 2-Position Pulse Position Modulation



The pulse will randomly take the early positions (nominal -d to -5d), the nominal position, or the late positions (nominal+d to +4d). The minimum separation of two pulses is 50 ns (pulsar limitation). We constructed a sequence of 250k points with d = 50 ns when clock = 40 MHz. The ratio of position dithering was up to -50% to +40%.

Figure 5.7. Basis for 10-Position Pulse Position Modulation

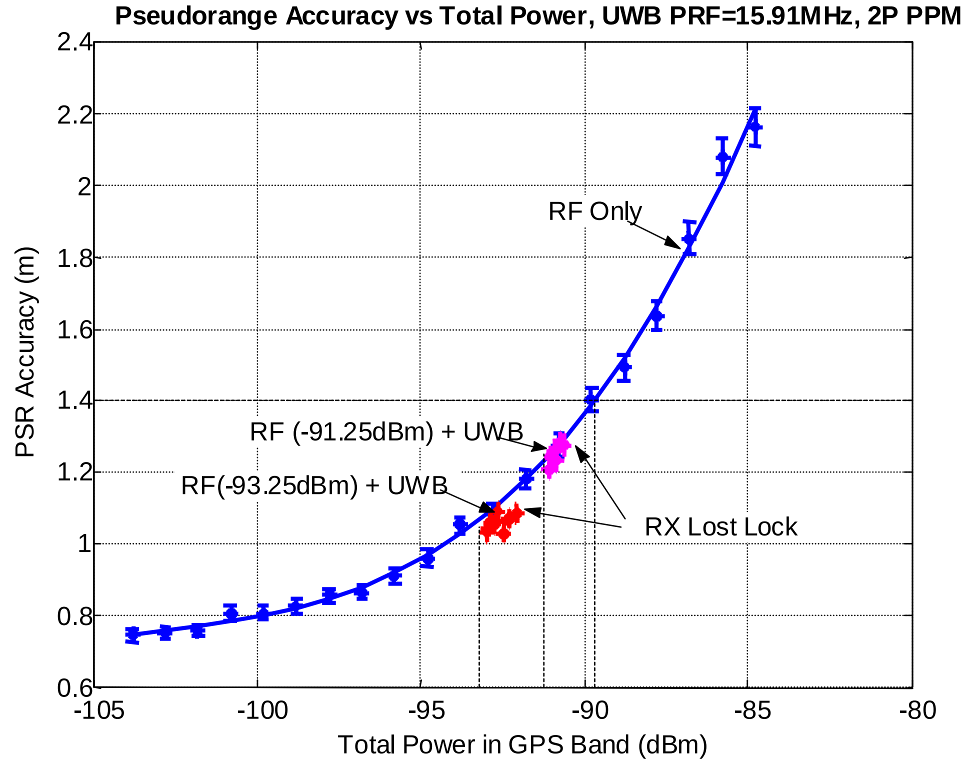


Figure 5.8. Multiple Back-Off Points with a 15.91 MHz 2-Position Pulse Position Modulation PRF UWB Waveform

At a slightly different PRF, 15.94 MHz, the spectral lines adjacent to the GPS lobe fall at 1562.12 and 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 as is shown in Figure 5.9.

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 significantly different performance variations from the GPS receiver. The specific impact all depends on the exact oscillator, PRN code, and UWB PRF.

Lastly, the 10-position pulse position modulation UWB waveform is tested with both back-off points. The results of which are presented in Figure 5.10. Note that the performance is improved over all of the waveforms tested thus far with the exception of the low 100 kHz PRF UWB signal. Again, this is a combination of the lower PRF combined with a modulation method that is fairly effective is reducing the magnitude of the resulting discrete spectral lines.

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, a “2” dB back-off point was also tested in order to attempt to construct a noise equivalency factor.

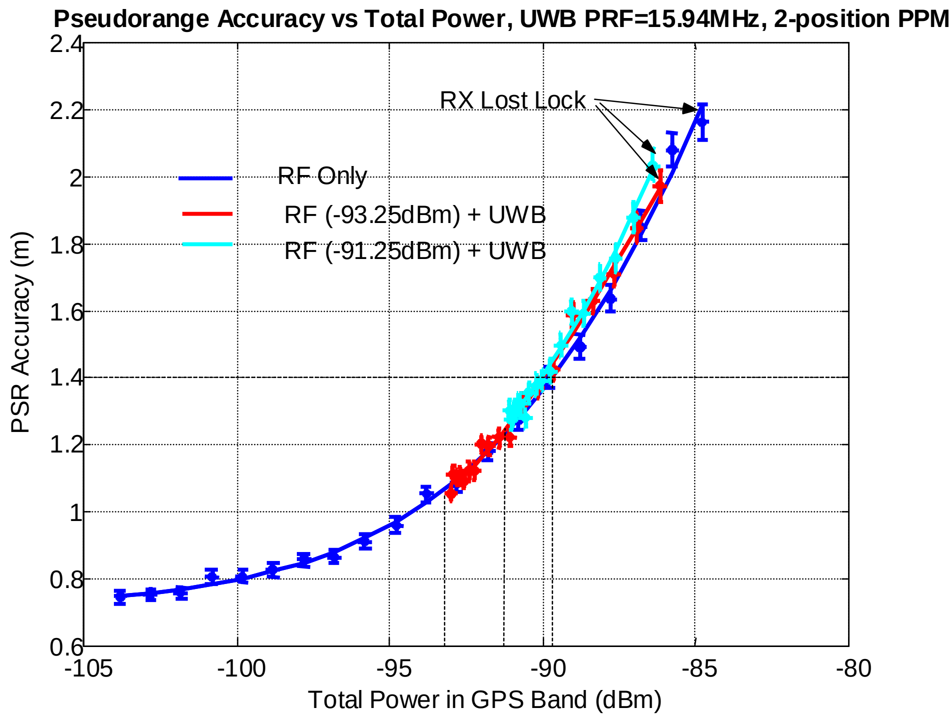


Figure 5.9. Multiple Back-Off Points with a 15.94 MHz 2-Position Pulse Position Modulation PRF UWB Waveform

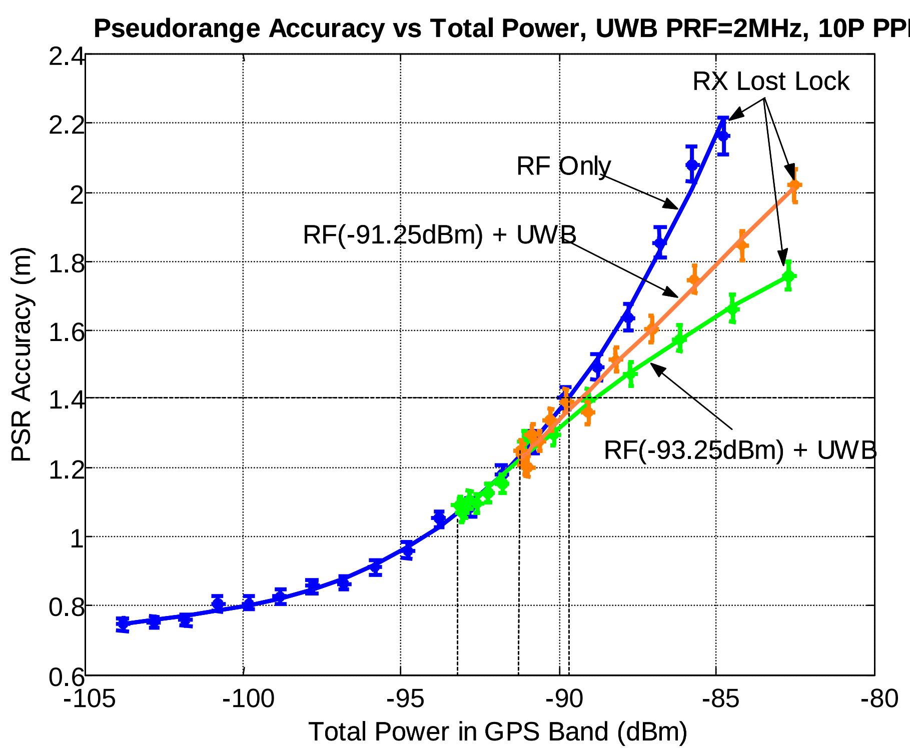


Figure 5.10. Multiple Back-Off Points with a 2 MHz 10-Position Pulse Position Modulation PRF UWB Waveform

Table 5.1 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.

Using the tabulated values, it is possible to construct a plot of the noise equivalency factor for the UWB waveforms based on these results. This equivalency plot, in Figure 5.11, show the amount of removed broadband noise power in 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 budgets and allowable margins in the future.

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

GPS Power = –131.3 dBm,
RF Noise Power at 1.54 dB back-off = -93.25 dBm,
RF Noise Power at 3.54 dB back-off = -91.25 dBm,
RF Noise Power at Accuracy Threshold = -89.71 dBm,

Table 5.1. Summary of Power Measurements from Phase II Accuracy Testing

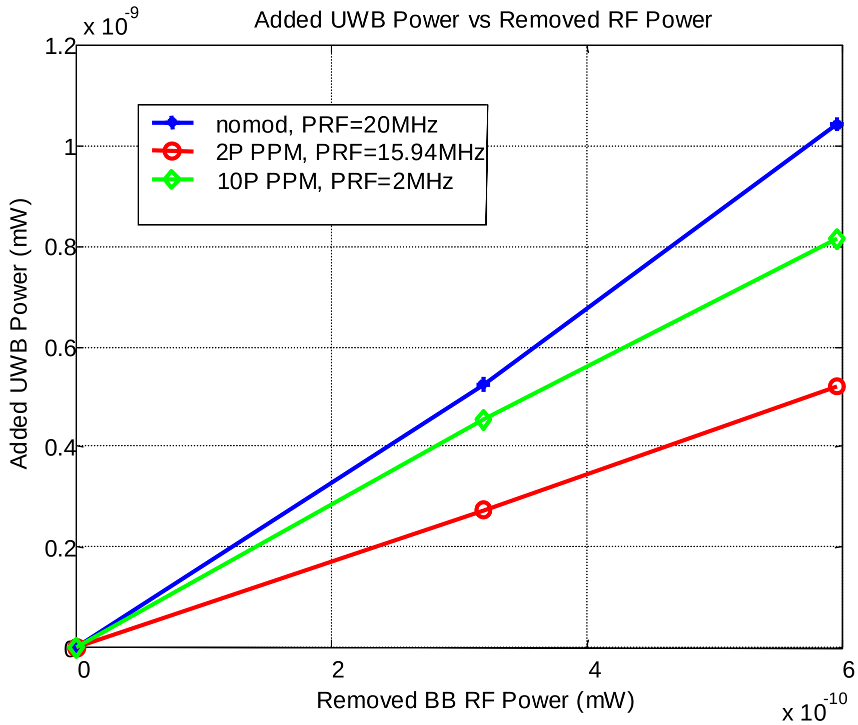


Figure 5.11. Broadband Noise/UWB Equivalency Plot

6.0 Loss of Lock Test Procedure and Results for Aviation and OEM GPS Receivers

The platform/experiment used to test accuracy for the aviation receiver can be easily extended to also check the loss of 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 a useful measure 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 a worst case acceptable criteria, but it is likely accuracy on these receiver will be impacted as well.

Recall the test configuration from Figure 3.5. 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.

As a result, 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 in the accuracy test procedure step 6) the threshold is replaced with loss of lock as opposed to the original *k*15 cm pseudorange accuracy. Although not stated explicitly in the accuracy testing, the loss of lock point is included on all the results presented in that section – which is often well above the accuracy threshold. This is true for all UWB waveforms under investigation in Phase II testing with the exception of the 100 kHz constant PRF. Even with maximum possible output power (–57.3 dBm) of the UWB device, this waveform did not result in a loss of lock for the GPS receiver.

The loss of lock metric is best presented in tabular format and is shown in Table 6.1. 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, that 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 6.1. Summary of Loss of Lock Power Measurements from Phase II Testing

This is the first set of data presented for a second GPS receiver. These results show it 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. Further receivers should be tested and quantified to determine their specific functionality in the presence of UWB signals.

7.0 Acquisition Testing

All testing at Stanford University prior to this Phase II investigation had been done assuming the UWB signal is introduced into the receiver once it is already tracking the GPS signal. The first process required of any GPS receiver when it is initially powered on is signal acquisition, as it must first determine which GPS satellites are in view and the fundamental parameters (code phase & carrier frequency) for each. It is well understood that GPS signal acquisition is a more sensitive process and requires higher C/No values than does tracking [14]. Stated another way, assume the GPS receiver is tracking a signal down to within 1-2 dB of its C/No loss of lock threshold, then that tracking process is interrupted and the GPS signal must be re-acquired. Before tracking can continue, a sufficient increase in C/No, typically on the order of 3-5 dB, must occur for acquisition to take place so the receiver can be return to tracking state. As a result, it is advantageous to do an initial investigation into GPS acquisition performance in the presence of UWB. In order to be consistent with the overall goals of the testing philosophy thus far, this performance evaluation should be relative to white noise performance. Thus an experiment was developed to test acquisition results for a high-performance general-purpose GPS receiver in the presence of UWB relative to acquisition results in the presence of white noise.

Initially a re-acquisition test, where the GPS signal is lost for a brief period and then returns, had been proposed for use with an OEM receiver. However, further investigation determined the acquisition process to be heavily dependent on the specific receiver's firmware and the logic implemented for the acquisition process. As a result, a number of receivers were considered for such an experiment and none contained all the desired characteristics necessary. Therefore, it was decided a re-acquisition test was impractical at this stage and focus turned toward developing a more general acquisition experiment. Further complicating matter, the OEM receiver under consideration did not allow for any control of the general acquisition process. As a result a high-performance general-purpose GPS receiver was utilized in order to implement the developed test procedure.

7.1 Acquisition Test Procedure

The acquisition test procedure has been developed through experimental work with various receivers in order to determine a meaningful performance metric given the available timeframe. Although the test may not be considered all-inclusive, it will most definitely provide an initial set of useful performance data.

7.1.1 Broadband Noise Normalization

1) Set up the test equipment as shown in Figure 3.5 replacing the GPS aviation receiver firmware with firmware designed for a high-performance general-purpose (the second OEM receiver is not utilized in the acquisition testing).

2) The GPS receiver is operated with a minimum received satellite signal level. Compensation is applied to adjust for room temperature, satellite simulator noise output, or the effects of a remote antenna preamplifier as needed. In other words, set the GPS power (C) to –131 dBm+G_{LNA} where G_{LNA} is the gain of any equipment that might nominally appear between the antenna and the receiver under test.

3) Broadband random noise is added to the simulated GPS satellite signal at the receiver input. Set the center frequency of the broadband noise to 1575.42 MHz.

4) Introduce the GPS signal in the test configuration and allow the receiver one minute to attempt to acquire the GPS signal. Perform five 1-minute trials at this specific noise power level. Each time the receiver can successfully acquire the signal, record the resulting C/No value reported and average across any of the five trials that were successful.

5) If more than one trial resulted in a successful acquisition, increase the noise power by 1 dB and repeat step 4). However, if none of the trials resulted in a successful acquisition, reduce the noise power by 1 dB and repeat step 4).

6) Continue the testing until the results span a successful acquisition on all five attempt to no success on all five attempts, recording the associated noise power levels and receiver reported C/No as available.

7.1.2 Procedure for Testing Potential UWB Impact on GPS Acquisition

1) Set up the test equipment as shown in Figure 3.5 replacing the GPS aviation receiver firmware with firmware designed for a high-performance general-purpose (the second OEM receiver is not utilized in the acquisition testing).

2) The GPS receiver is operated with a minimum received satellite signal level. Compensation is applied to adjust for room temperature, satellite simulator noise output, or the effects of a remote antenna preamplifier as needed. In other words, set the GPS power (C) to –131 dBm+G_{LNA} where G_{LNA} is the gain of any equipment that might nominally appear between the antenna and the receiver under test.

3) Broadband random noise is added to the simulated GPS satellite signal at the receiver input. Set the center frequency of the broadband noise to 1575.42 MHz. The power level of the broadband noise should be set 4 dB lower that the maximum level at which all five trials in the broadband noise normalization testing resulting in a successful acquisition.

4) Introduce a specific UWB signal at a minimal power level.

5) Introduce the GPS signal in the test configuration and allow the receiver one minute to attempt to acquire the GPS signal in the presence of the noise and UWB waveform. Perform five 1-minute trials at this specific UWB power level. Each time the receiver can successfully acquire the signal, record the C/No value reported and average across any of the five trials that were successful.

6) If any of the five trials were successful, increase the UWB power by 1 dB and perform the testing again. Repeat steps 5) & 6) until all five trials fail to provide any successful acquisition attempts. Record UWB power levels and receiver reported C/No as available.

7.2 Acquisition Test Results

The acquisition test has been performed over the subset of waveforms specified in this report plus four additional cases of interest. Results from all UWB signals as well as the broadband noise cases have been plotted in Figure 7.1. The top plot in Figure 7.1 shows the percentage of the trials that resulted in a successful acquisition attempt as a function of total power (broadband noise only or the combination of broadband noise and UWB). The lower plot indicates the resulting average C/No value reported by the receiver after a successful acquisition attempt at a specific measured power level within the GPS band.

The majority of the results are clustered within a single region, thus Figure 7.1 is expanded in Figure 7.2 for a more detailed examination. Also the tabulated power values are shown in Table 7.1 for all cases. The table shows the power levels at the two extreme cases for all waveforms tested: 1) all five 1-minute trials results in a successful acquisition; and 2) none of the five 1-minutes trials results in a successful acquisition.

The results show a definite correlation with those obtained in the accuracy testing. The UWB waveform which has the least impact is the 100 kHz constant PRF. Again, it is likely this signal appears as less damaging pulsed interference even after the GPS L1 filter. In the acquisition testing, a second low constant PRF case of 200 kHz was also utilized. Although not quite as benign as the 100 kHz case, it too is less damaging than many of the high, even modulated cases. This goes to confirm the supposition that lower PRFs should be less damaging to GPS performance that was indicated in the previous testing by a single case. 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 the distinct spectral lines resulting from the UWB signals will also be a 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 observed are not isolated to one mode of receiver operation – rather the presence of UWB signals will impact all phases of GPS signal processing.

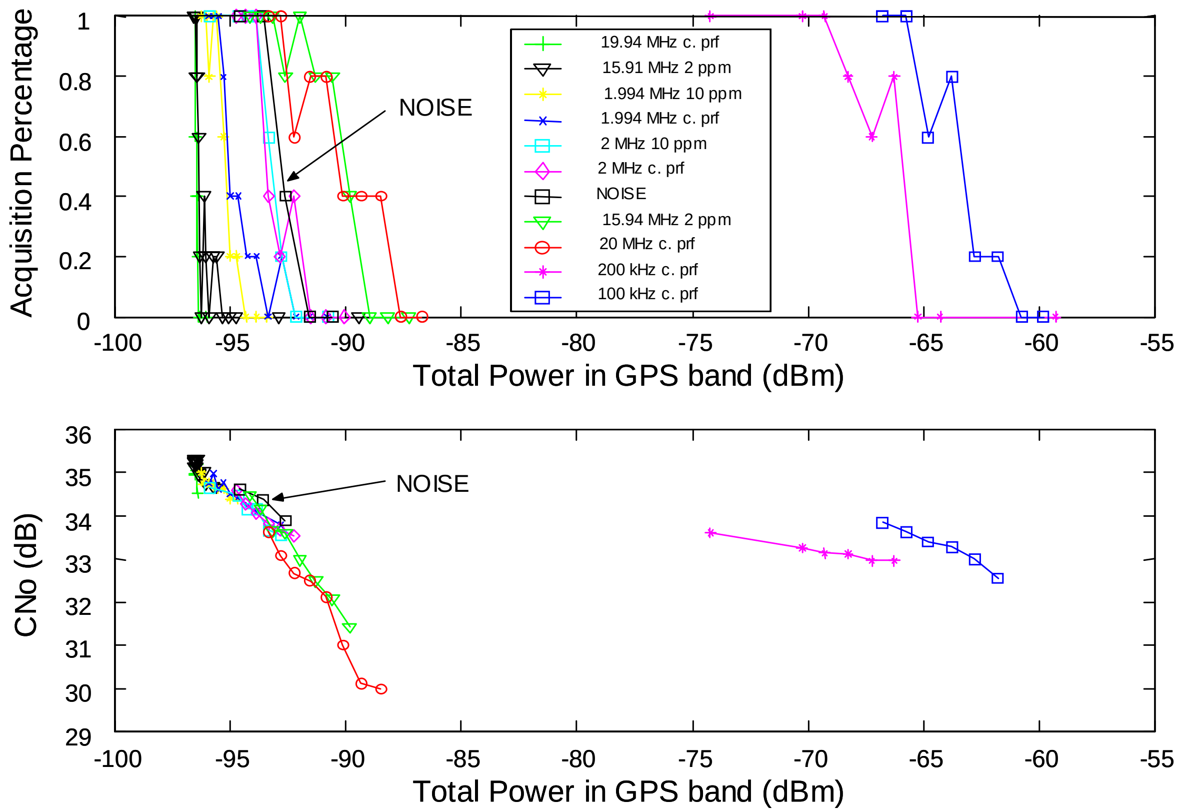


Figure 7.1. Acquisition Results with Corresponding Measured C/No Values

Waveform	*Modulation*	*All Acq Power*	*No Acq Power*
19.94 MHz	***const. prf***	***-96.5 dBm***	***-96.4 dBm***
15.91 MHz	***2 ppm***	***-96.5 dBm***	***-95.3 dBm***
1.994 MHz	***10 ppm***	***-96.0 dBm***	***-94.3 dBm***
1.994 MHz	***const. prf***	***-95.5 dBm***	***-92.2 dBm***
2 MHz	***10 ppm***	***-93.9 dBm***	***-91.6 dBm***
2 MHz	***const. prf***	***-93.8 dBm***	***-92.2 dBm***
NOISE		***-93.6 dBm***	***-91.6 dBm***
15.94 MHz	***2 ppm***	***-93.2 dBm***	***-89.0 dBm***
20 MHz	***const. prf***	***-92.8 dBm***	***-88.5 dBm***
200 kHz	***const. prf***	***-69.3 dBm***	***-65.3 dBm***
100 kHz	***const. prf***	***-65.8 dBm***	***-60.8 dBm***

- ***Base GPS signal power = -131.3 dBm***
- ***Base noise power (after 4 dB back-off) = -97.6 dBm***
- ***Chart depicts total power measured in band (after GPS L1 filter)***

Table 7.1. Summary of Acquisition Results with Specific Power Levels

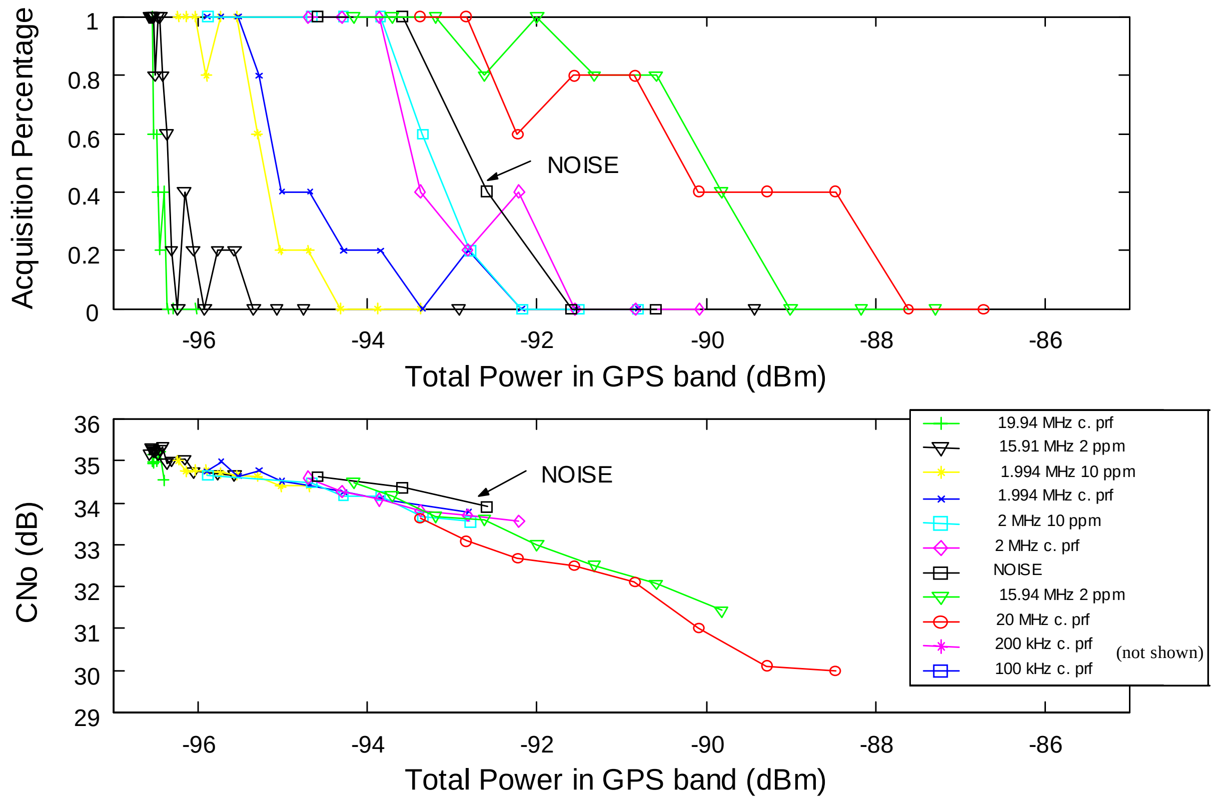


Figure 7.2. Acquisition Results with Corresponding C/No Values – Zoomed View

8.0 Summary and Conclusions

A second phase of investigations into the impact UWB signals will have on GPS receivers has been completed at Stanford University. The test philosophy has remained consistent with the previous (Phase I) testing. The primary goal here is to compare the impact on GPS receivers of various UWB waveforms and broadband noise.

The first phase of testing investigated the accuracy performance of a GPS aviation receiver in the presence of a wide variety of UWB waveforms. It was found that for relatively high PRFs, i.e. those greater than 2 MHz, the performance impact of UWB on GPS could at best be described as an increase in the broadband noise floor. However, the impact was significantly more damaging when the UWB waveform was periodic in nature and resulted in distinct spectral lines that fell within the GPS band. These spectral lines can be attenuated through modulation of the UWB pulses to remove the periodicity, which produces a spectrum that is more like broadband noise. Multiple techniques for modulation have been tested, with each achieving varying degrees of success. For relatively low PRFs (where the pulses occupy about a 10% duty cycle after the L1-band filter), the UWB signal appeared as pulsed interference to the GPS receiver and is significantly less damaging even at relatively high input power.

In the first phase of testing, all results were based on a single GPS aviation receiver, a single UWB emitter, and an accuracy measure of performance. A number of UWB waveforms were characterized in the testing, resulting in estimates of their impact on the GPS receiver relative to white noise. The model of the UWB spectrum as a combination of discrete spectral lines and broadband noise provided the most reliable predictor of how the UWB signal would impact the GPS receiver. The more predominant in magnitude and close in frequency to the GPS spectral lines that these distinct UWB lines are, the more damaging that waveform will be to the GPS measurements.

As a result, the second phase of testing was designed to accomplish goals set forth by those who had commented on the Phase I report to better understand the relationship between UWB and GPS and also to verify the results from the first phase of testing. Six specific UWB waveforms were chosen as a subset of all possible UWB signals for further investigation. The desire for the second phase of testing has been to focus on accuracy testing once again, but this time to utilize two specific broadband noise back-off points at which the UWB signal is introduced. In addition, two new tests were conducted. The first was a loss-of-lock test. This test looked at the relative levels of broadband noise and UWB power that resulted in a loss-of-lock on a satellite, which is a much more relaxed criteria than the accuracy test since significant accuracy degradation occurs before lock is lost. This experiment was the first conducted at Stanford University to provide data for a second GPS receiver. The second new experiment was developed to test acquisition performance. This is of concern since acquisition is a more sensitive process and had not been investigated in the previous accuracy testing.

The results for accuracy testing were as expected. The problematic cases observed in the Phase I testing were re-tested and again resulted in poor GPS performance. The principal cause for this poor performance was the presence of discrete UWB spectral lines interfering with GPS spectral lines. For the cases investigated where lock was not lost immediately, an equivalency measure was determined from the data taken at both back-off points. This measure provides useful information to those establishing link budgets and allowable margins for the GPS band. The fact that the Phase II tests reconfirmed the Phase I results is reassuring and provides confidence in the new measurements taken in Phase II testing.

Loss-of-lock testing was basically an extension of the accuracy testing. The same problem cases for accuracy testing had problems with maintaining lock. While loss of lock is not by itself an adequate metric because it misses degradation that occurs prior to loss of lock, it allowed the comparison of results for a second OEM GPS receiver to those obtained for the aviation receiver. Most interesting about the OEM receiver results was that they followed the same trends as did the aviation receiver. UWB signals that generated spectral lines continued 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 noticed that the power levels at which the OEM receiver lost lock were consistently lower than the levels where the aviation receiver lost lock, suggesting that the OEM receiver was more susceptible to interferencethan the aviation receiver used in the bulk of the testing to date.

Finally, 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 regardless of the power level, which were the signals with PRFs on the order of 100 kHz, had little impact on acquisition performance as well. 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).

It is possible to provide quantitative values from the testing. Of particular interest are those cases that are as or more damaging than broadband noise for equivalent power levels. This constitutes a majority of those tested with the exception of the low PRF trials. If such a UWB signal includes distinct spectral lines and these lines fall within the GPS band, then UWB can be significantly more damaging than broadband noise. For example, the results show a PRF of 19.94 MHz causes UWB to be 17 dB more damaging than broadband noise, when the broadband noise power is measured across the 24 MHz GPS band. If the broadband noise power is measured at the output of a 1 MHz band pass filter, then equal damage comes from a UWB signal that is approximately 3.2 dB weaker based on the PRN code used for this testing. It is important to recognize that these quantitative values should not be considered worst case as the UWB spectral lines resulting from this testing do not overlap with those most sensitive GPS spectral lines for the specific PRN code utilized.

The impact of UWB on GPS varies considerably with UWB signal characteristics, but it is possible to quantify the difference between UWB interference and broadband noise. Moreover, it is possible to understand how that equivalence depends on the UWB signal parameters. In particular, UWB signals are less damaging than broadband noise when very low UWB PRFs are used and only a single UWB emitter is interfering. On the other hand, UWB signals are significantly more damaging than broadband noise when large UWB spectral spikes fall in the GPS band. The current results include data for two different receivers with multiple test runs for the aviation receiver. In follow-on testing, additional GPS receiver types should be tested, and also it is important to consider the impact of aggregate UWB transmitters. The broadband-noise-equivalence data presented in this report should be of use to standards developers, such as RTCA SC-159 WG-6, that are devising specific UWB-GPS interference scenarios for operational assessment.

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