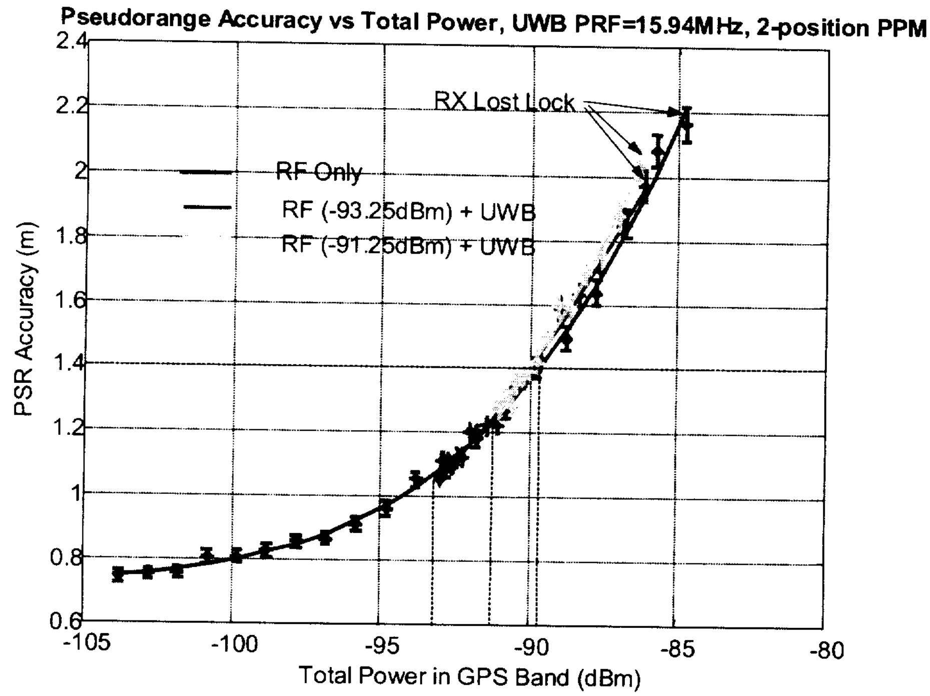

Figure 5.9. Multiple Back-Off Points with a 15.94 MHz 2-Position Pulse Position Modulation PRF UWB Waveform

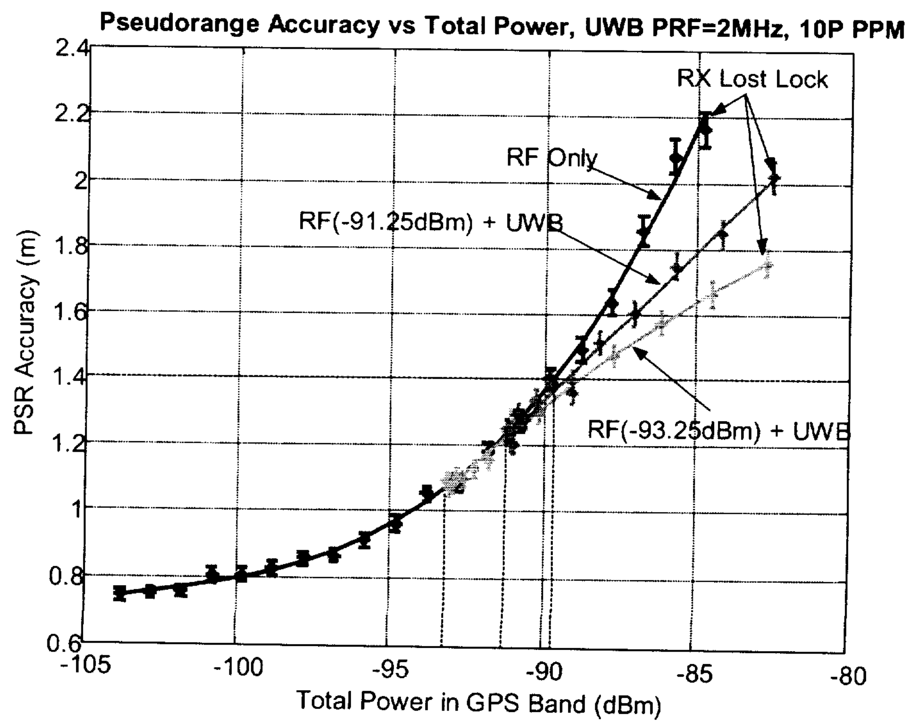

Figure 5.10. Multiple Back-Off Points with a 2 MHz 10-Position Pulse Position Modulation PRF UWB Waveform

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

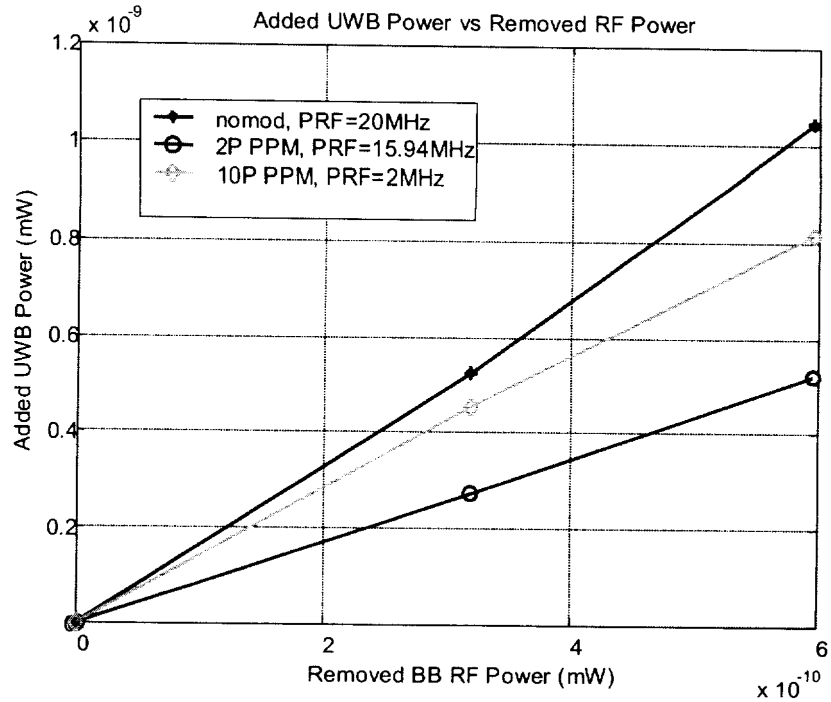

Figure 5.11. Broadband Noise/UWB Equivalency Plot

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.

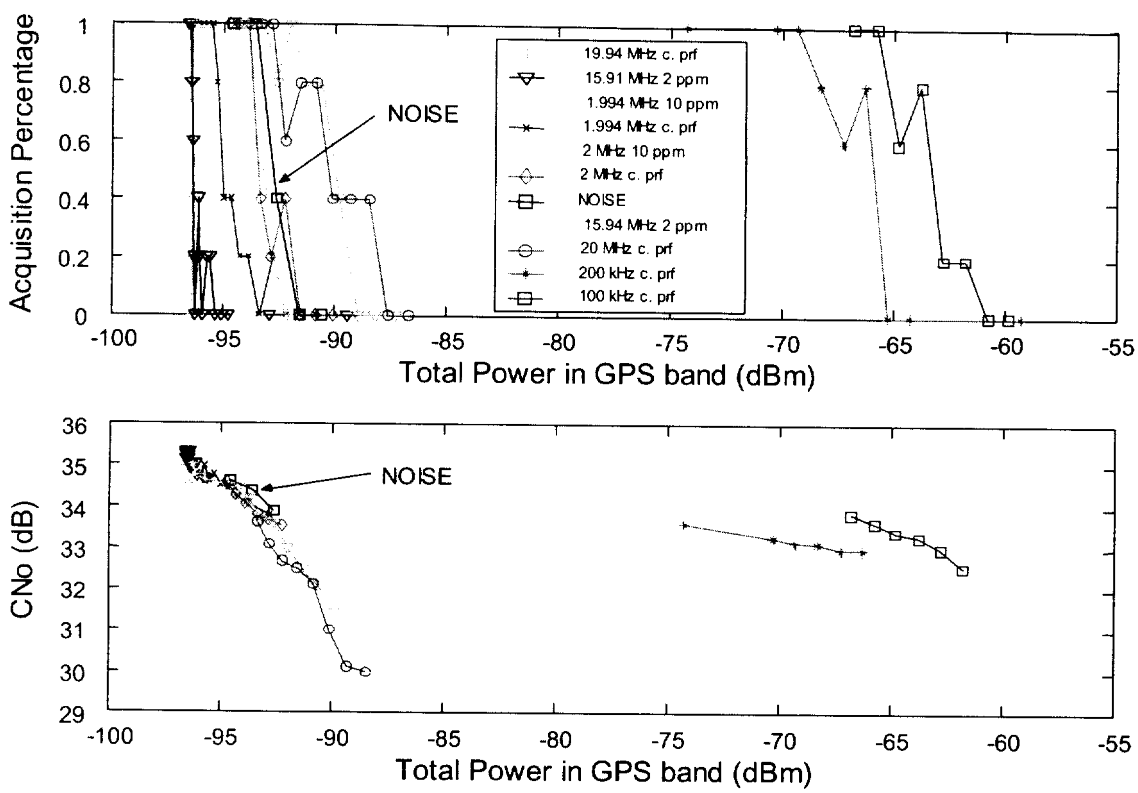

Figure 7.1. Acquisition Results with Corresponding Measured C/No Values

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

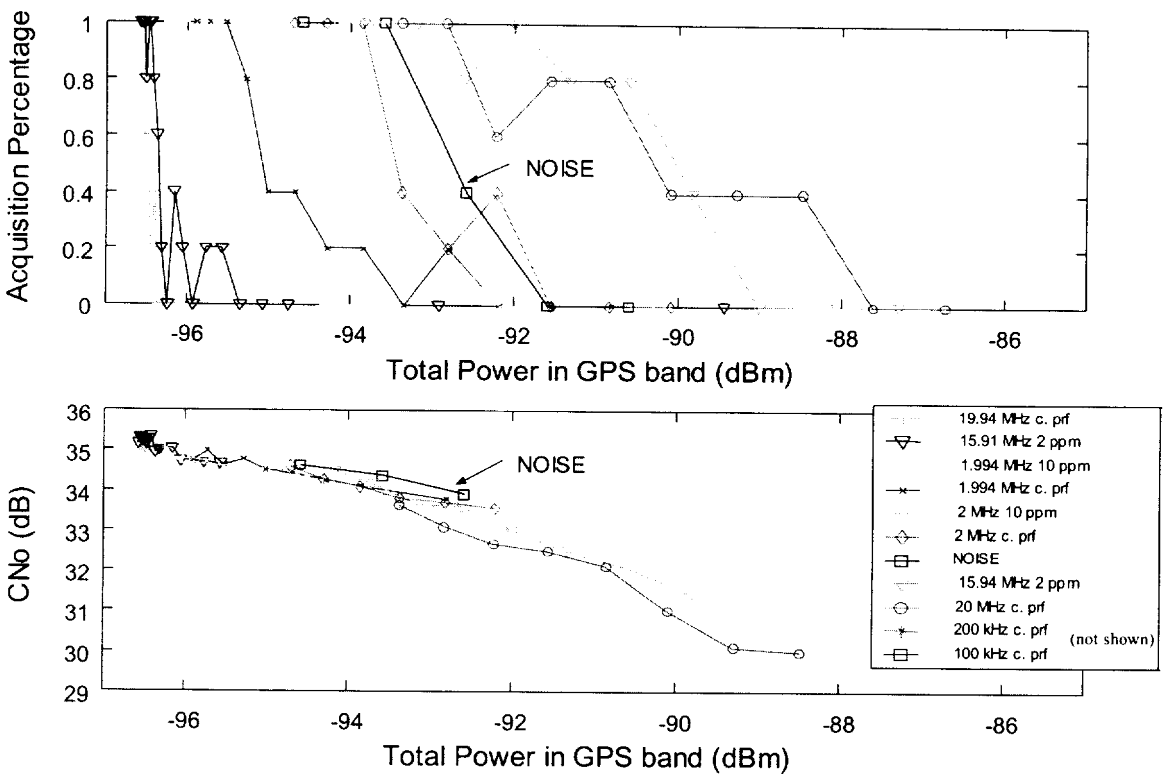

Figure 7.2. Acquisition Results with Corresponding C/No Values – Zoomed View

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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