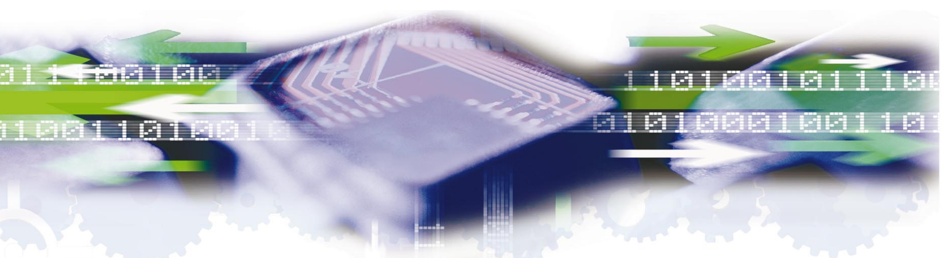
Ultra-Wideband and GPS: Can They Co-exist?

Dennis Akos, Ming Luo, Sam Pullen, and Per Enge Stanford University

Modern society uses radio signals for all kinds of applications. But whether they are used for communications, location-determination, remote sensing, or some other purpose, they are almost all generated by modulating a sinusoidal carrier wave, and the signal energy produced is concentrated in a fairly narrow band permitting a large number of signals to share the frequency real estate. Ultra-Wideband (UWB) signals are different. Instead of using a carrier, UWB signals are generated as a sequence of very short pulses which results in the signal energy being spread over a large part of the radio spectrum. Recent advances in UWB technology may lead to devices which can image objects buried underground or behind walls; permit short-range, high-speed data transmissions for broadband access to the Internet; locate assets with ranging signals; or provide covert, secure communications. Some argue that these low-power devices will be able to operate in the radio spectrum already occupied by existing radio services without causing them interference. But is this true in the case of GPS? GPS signals are very weak, as anyone who has tried to use a standard GPS receiver indoors can attest. A relatively small amount of interference can disable a receiver. To see if UWB and GPS signals actually can share the same part of the radio spectrum, several government and university research laboratories are conducting compatibility tests. One such set of tests was undertaken by researchers at Stanford University and in this month's column they report their findings. Our authors are Dennis Akos, Ming Luo, Sam Pullen, and Per Enge.



Ultra-Wideband (UWB) technology has received increasing attention as a result of the Federal Communications Commission's (FCC) Notice of Inquiry and more recently Notice of Proposed Rulemaking suggesting revisions to Part 15 of the Commission's rules regarding ultra-wideband transmissions. In other words, the FCC has been soliciting input on its proposal to regulate UWB devices within the existing Part 15 category. Part 15 regulates the operation of low-power radio frequency devices without a license from the FCC or the need for frequency coordination and includes devices such as cordless telephones, garage and car door radio remote controls, and many wireless local area computer networks. Part 15 has many aspects, but a key component is that existing rules do not permit intentional radiation in certain sensitive or safety-related bands that are designated as restricted.

A change to the existing regulation is now under consideration by the FCC to permit UWB devices to operate as intentional radiators across protected bands, such as those occupied by GPS. Since GPS is a weak signal with specified received power levels of –130 dBm, some have voiced concern as to what impact such a change may have on GPS performance. Preliminary field trials conducted by a UWB manufacturer in cooperation with Stanford University showed a potential for interference between the two systems. As a result, the U.S. Department of Transportation has funded a controlled study at Stanford University to investigate the potential interference of UWB devices with GPS. This article summarizes the findings of this effort.

A number of other groups have also undertaken similar investigations. After reporting the results of the Stanford University effort, we will also compare and contrast these findings to those of the other reports submitted on the topic.

It is clear from all of the tests that some UWB signals could degrade GPS positioning and navigation to the point where GPS would be unusable.

UWB Signal Structure

Just what is UWB? The definition of UWB adopted by the FCC originates from the Office of the Secretary of Defense/Defense Advanced Research Projects Agency. It states that a UWB device is one which has a –20 dB fractional bandwidth of at least 0.25, which implies that UWB signals have relatively wide bandwidths when compared with traditional modulation methods. For example, consider a transmission centered at 2.0 GHz. In order to meet the established criterion, the output power of this transmission at 1.5 GHz and 2.5 GHz would need to be no less than 20 dB down from that measured at the 2.0 GHz center frequency. Although it is possible to achieve this in different ways, the current focus is on transmission systems that employ series of distinct pulses as opposed to the more traditional modulated sinusoidal carrier wave.

The core of a UWB transmitter is a pulser. This is simply an electronic component that, when triggered, generates a very short pulse of energy. We obtained a prototype pulser, suggested by a UWB manufacturer, for the testing at Stanford. **Figure 1** shows the pulse in the time domain. Note the extremely rapid

Dr. Dennis Akos *is a research associate with the GPS Lab at Stanford University and a visiting faculty member with the Computer Engineering Department at Luleå University of Technology in Sweden. His research interests are computer architecture, RF design, and applied signal processing.*

Ming Luo *is a research engineer in the Stanford University GPS Lab. She has been working on the research and validation of the Stanford Local Area Augmentation System (LAAS) Integrity Monitor Testbed (IMT) for the past three years. Since late 1999, she has been investigating the interference from UWB to GPS receivers. She holds an MSEE degree and previously worked for the NASA Gravity Probe-B (GP-B) satellite program for five years before starting with LAAS-related research.*

Dr. Sam Pullen *is technical manager for GNSS research at Stanford University. He has supported the Federal Aviation Administration in developing LAAS architectures, requirements, and integrity algorithms since receiving his Ph.D. from Stanford in Aeronautics and Astronautics in 1996. He has developed the LAAS IMT which utilizes innovative algorithms for detection, exclusion, and recovery of system failures. He has also developed performance assessment and optimization methods for LAAS and for the Wide Area Augmentation System (WAAS) and supported the Johns Hopkins University Applied Physics Laboratory GPS Risk Assessment study of early 1999. He was awarded the ION Early Achievement Award in June 1999.*

Dr. Per Enge *is an associate professor of Aeronautics and Astronautics at Stanford University where he conducts research on GPS and its augmentation. He co-authored an article on network-assisted GPS in the July issue of GPS World where additional biographical details may be found.*

rise and fall time of the pulse with little ringing effects. **Figure 2** shows a spectrum of a continuous series of pulses generated at a rate of 20 megapulses per second.

Coding. Several different parameters are used to encode information onto a series of pulses. Pulse repetition frequency (PRF) is simply the number of pulses a transmitter generates per second. A strong correlation exists between the PRF and the information capacity of the transmission. Information transmission via UWB comes from modulating the individual pulses or blocks of pulses. There are at least two primary modulation methods. Consider an on/off modulation scheme to encode binary data in which pulses are generated at a constant PRF. If a "1" is to be transmitted, the pulse is generated, while if a "0" is desired, no pulse is generated. This provides a binary data rate equal to the PRF.

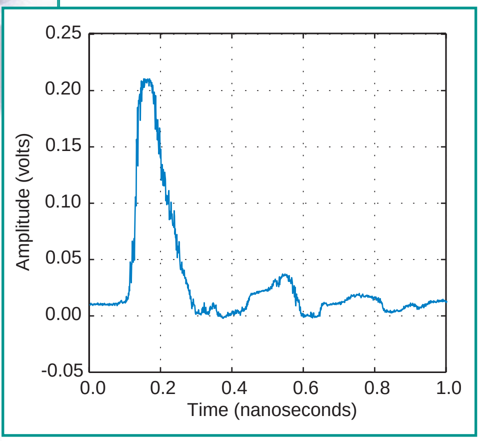


FIGURE 1 A single UWB pulse depicted in the time domain

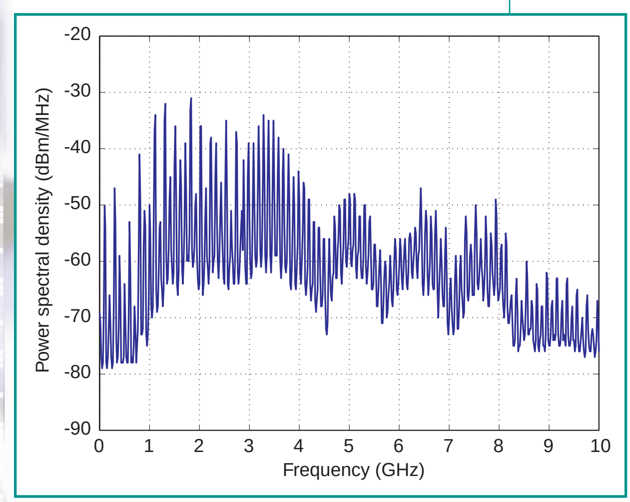


FIGURE 2 Resulting frequency spectrum of a UWB signal (UWB pulse train)

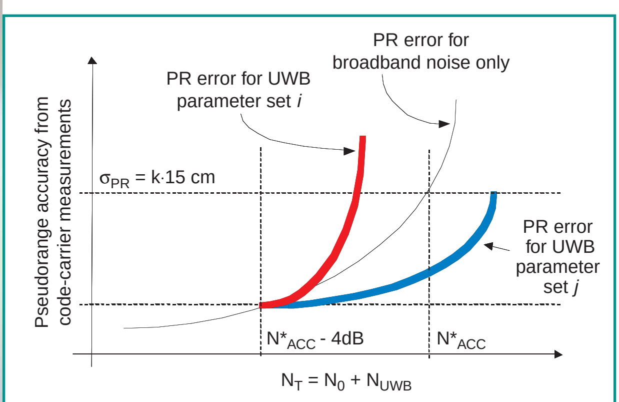


FIGURE 3 Pseudorange accuracy as UWB power is added to increase the total noise

A second possible modulation scheme is one in which the position of the pulses is offset from nominal. A pulse could be slightly advanced or delayed in time to encode information. The "slots" in which a pulse is shifted define the possible states for that particular PRF and thus specify the possible data rate. In working with series of pulses, it is possible to employ various duty cycles for bursts of pulses to encode information. Finally, note that individual PRF modulation methods can be combined in numerous ways, which results in a large degree of variation in UWB signals.

It is important to recognize how UWB differs from traditional communication systems. No longer is information being transmitted using a modulated continuous sinusoid of a particular frequency. Rather, UWB uses distinct pulses to convey information. Thus, many traditional analysis techniques need to be revised in order to study UWB signals.

Note also that the pulse shape depicted in Figure 1 is produced directly at the output of the pulser. Any signal conditioning, such as amplification or filtering, may distort this basic pulse shape based on the response of the individual components. Such a change will result in a spectral change as well. For example, an amplifier increasing the signal power in the vicinity of 1.6 GHz will result in a pulse shaping that will have a greater impact on GPS, while passing the pulse through a notch filter at 1.6 GHz will likely produce a pulse, and subsequent spectrum, with less of an impact on GPS. Our test procedures take into account the special characteristics of UWB signals.

Test Procedures

It is possible to classify UWB emissions into three types: noise-like, pulse-like, or continuous wave (CW)-like. We developed a radiofrequency interference (RFI) equivalence concept in order to relate the interference impact of UWB signals on GPS (over a range of UWB emission parameter values) to that of a well-understood RFI source, namely broadband (white) noise. Relative performance is critical when working with receivers designed to meet a minimum set of performance standards such as those set for aviation GPS receivers. If not using relative performance, 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 which does not meet the minimum performance requirements.

We chose pseudorange (PR) "accuracy" as the primary measurement for testing aviation receivers. Since carrier-smoothed pseudoranges are used in aviation applications, degradations in both code delay (pseudorange) and carrier-phase tracking influence PR accuracy. Current standards for the Wide Area and Local Area Augmentation Systems (WAAS and LAAS) GPS-based aircraft approach, define the PR accuracy requirement as a PR measurement with an error standard deviation of 15 centimeters or less. This sensitive metric protects the safety of aviation applications.

Methodology. The test methodology consists of inserting broadband noise into the GPS aviation receiver and increasing its level until 15 centimeters 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 15 centimeters 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 between UWB and broadband noise.

Figure 3 depicts this process, with one curve representing what would be expected from broadband noise, and the other two UWB parameter sets *i* and *j*, which were introduced with a 4 dB back-off. In the figure, cases *i* and *j* indicate UWB results that would be worse than and better than, respectively, the broadband noise measurement. If the UWB waveform is particularly damaging, the receiver may lose lock shortly after its introduction with minimal power being added; thus no curve will be traced out for that particular harmful UWB waveform. This test procedure allows determination of a ratio of broadband noise to UWB power. This ratio, in turn, allows us to evaluate UWB interference to GPS using standard link-budget techniques that typically assume that the incoming interference has white-noise characteristics.

Test Setup. As **Figure 4** shows, we combined the GPS signal, broadband noise, and the UWB signal before injecting them into the GPS receiver. A single-channel GPS simulator generates the GPS signal. The GPS receiver operated with the minimum received satellite signal level specified for GPS satellites. We applied compensation as needed to adjust for room temperature, satellite simulator noise output, and the effects of a remote antenna preamplifier. A noise generator and a low-noise amplifier generated broadband noise, and an adjustable attenuator varied the RF noise power. A pattern (arbitrary waveform) generator, which triggers the UWB pulse generator, produced the desired UWB pattern. We swept UWB power within the desired range by means of a programmable attenuator and monitored the spectrum analyzer in real time with a power meter. A personal computer with GPIB (General Purpose Interface Bus) and RS-232 buses automated the testing.

Note the insertion of a GPS L1 filter (with bandwidth of 24 MHz) between the combiner and the GPS receiver. We measured all power (broadband RF and UWB) in the GPS band so as to be able to combine both measurements and compare them later. This filter also controls the bandwidth of the interference. Therefore, the test results will not depend as much on the front end of each individual receiver.

Test Procedure. We adapted our test procedure from Section 2.5.8 of the RTCA WAAS Minimum Operational Performance Standards (MOPS). Tests used unsmoothed pseudorange accuracy instead of smoothed to shorten the testing period and estimated the one-sigma pseudorange error by computing the standard deviation of the code-minus-carrier test statistic after removing a second-order polynomial fit of the mean. Note 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. For the receiver under test, we found the unsmoothed accuracy requirement ($k \cdot 15$ centimeters) to be about 1.4 meters, implying a k-value of 9.3.

The detailed test procedure can be found in our report *Potential Interference to GPS from UWB Transmitters; Test Results Phase 1A.*

Each trial began by setting the GPS power to –131 dBm and the broadband noise power to –103.5 dBm spread over 24 MHz and then allowing the GPS receiver to track the simulated satellite and reach steady state. Software measures the unsmoothed pseudorange minus carrier phase to estimate the one-sigma pseudorange error. We then increased the broadband noise power in 1

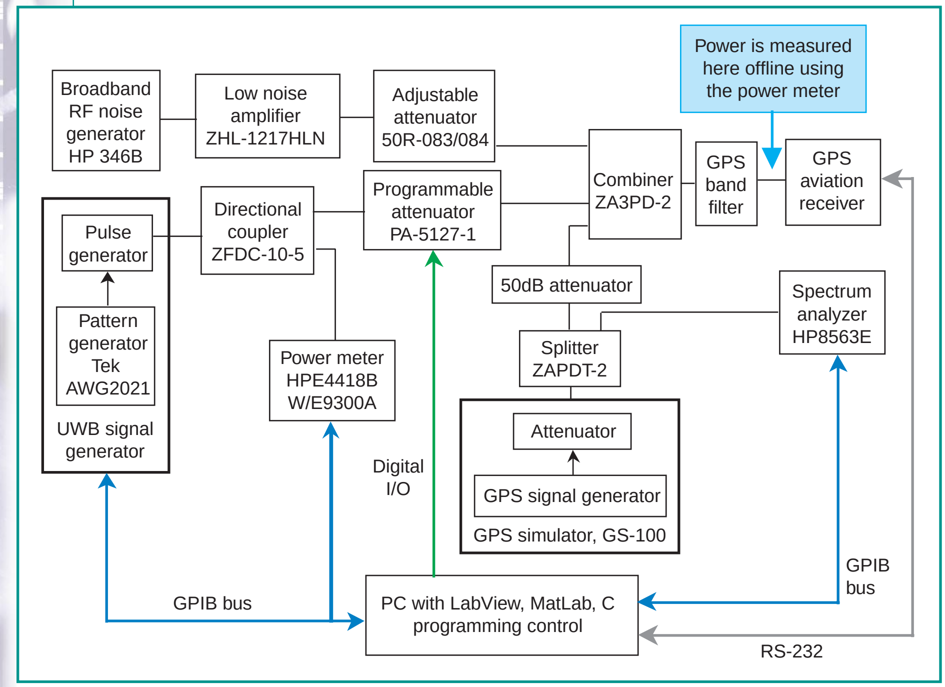


FIGURE 4 UWB interference test setup

Further Reading

For a description of the FCC's Part 15 regulations, see

⊕ *Code of Federal Regulations (CFR), Title 47 – Telecommunications, Part 15 – Radio Frequency Devices*, Federal Communications Commission, Washinton, D.C.,October 1, 2000. An on-line version is available at <http://www.access.gpo.gov/nara/cfr/waisidx_00/47cfr15_00.html>.

For the FCC's announcement of proposed Part 15 changes to accommodate UWB, see

⊕ *Federal Communications Commission Notice of Proposed Rule Making, In the Matter of Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems*, FCC 00-163,ET Docket No. 98-153, Released May 11, 2000.

For a description of the minimum acceptable interference effects on GPS, see

⊕ *Minimum Operational Performance Standards (MOPS) for Global Positioning System/Wide Area Augmentation System Airborne Equipment*, DO-229B, SC-159, RTCA, Inc., Washington, D.C., October 6, 1999.

For a discussion of Stanford's initial testing of UWB interference effects, see

⊕ "Preliminary Assessment of Interference Between Ultra-Wideband Transmitters and the Global Positioning System: A Cooperative Study," by G. Aiello, G. Rogerson, and P. Enge published in the *Proceedings of the 2000 Institute of Navigation National Technical Meeting*, Anaheim, California, January 26-28, 2000, pp. 28-35.

For further information on the comprehensive Stanford UWB interference tests, see

⊕ *Potential Interference to GPS from UWB Transmitters; Test Results Phase 1A: Accuracy and Loss-of-Lock Testing for Aviation Receivers*, by M. Luo, D. Akos, S. Pullen, and P. Enge, Stanford University, Version 2.1, October 28, 2000.

⊕ *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*, Stanford University, Version 3.0, March 16, 2001.

For the report on NTIA testing of UWB effects on GPS, see

⊕ *Assessment of Compatibility Between Ultrawideband (UWB) Systems and Global Positioning System Receivers*, NTIA Special Publication 01-45 by the National Telecommunications and Information Administration, U.S. Department of Commerce, Washington, D.C., February 2001. An on-line version is available as

<http://www.ntia.doc.gov/osmhome/reports/UwbGps/NTIASP_01_45.pdf>.

For information on the University of Texas Applied Research Laboratory and Johns Hopkins University Applied Physics Laboratory UWB tests as well as comments by Time Domain Corporation, the U.S. GPS Industry Council, and ARINC and the Air Transport Association, see

⊕ FCC Comments Database on Proceeding 98-153 which may be searched on-line at <http://gullfoss2.fcc.gov/cgi-bin/ws.exe/prod/ecfs/comsrch_v2.hts>.

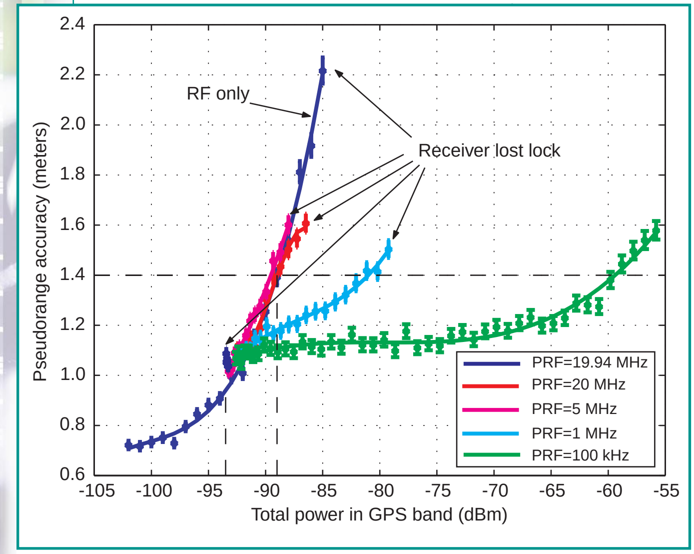


FIGURE 5 Comparison of UWB for different PRFs

dB steps until the receiver lost lock, and recorded the noise power setting (N^*_{ACC} in Figure 3) where the error just exceeded the $k \cdot 15$ centimeters (1.4 meters) requirement. Once we determined the receiver sensitivity to broadband noise, UWB testing began. We set the noise attenuator to approximately 4 dB below the value of N^*_{ACC}, and chose one set of UWB signal parameter values from the test matrix and the UWB noise power (N_{UWB}) 10 dB below the broadband random noise power (N_0). We then increased the UWB power in 1 dB steps until the receiver lost lock, and recorded the power setting where the pseudorange error of $k \cdot 15$ centimeters (1.4 meters) was exceeded. This completed one trial. The process repeated with the next UWB signal permutation of interest until all the desired combinations of UWB signal parameter values had been tested.

Test Results

Our tests examined the impact of particular PRFs, receiver sensitivity to UWB spectral lines, the type of UWB signal modulation, and receiver loss of lock and acquisition under different UWB signal scenarios.

PRF Comparisons. Figure 5 shows the results of unmodulated UWB tests for various PRFs between 100 kHz and 20 MHz, as well as the receiver normalization curve. When the PRF is 100 kHz, the receiver accuracy degrades slowly as UWB power increases. By comparison with the normalization curve, the UWB interference is about 30 dB less severe to the receiver than white noise. This is not surprising: when the PRF is low (compared to the bandwidth of the front end of the GPS receiver), each UWB pulse has sufficient separation from the others so that the interference to GPS is “pulse-like” and the impact is small. When the PRF is high (5–20 MHz), the receiver accuracy degrades much faster when UWB power increases. The impact of UWB is similar to that of broadband white noise.

The results suggest that the impact of UWB strongly depends on PRF. Higher PRF tends to have more severe impact on GPS receivers. In addition to this general trend, we also found that when the PRF is 19.94 MHz, the receiver loses lock at relatively low UWB power (the testing data points are all clustered together in the plot). This is much worse than the 20 MHz case. We investigated this issue further, as described in the next section.

Spectral Line Sensitivity. Figure 6 compares three cases with constant PRFs of 19.94, 19.95, and 20 MHz. Although these PRFs are very similar, the spectral line locations of these three cases are quite different with respect to the GPS spectrum (Figure 7). There is a large spectral spike that hits the peak of the GPS L1 main lobe when the UWB PRF is 19.94 MHz. This spike hits the side of the main lobe when the PRF is 19.95 MHz and hits at about the fifth side lobe when the PRF is 20 MHz. This explains why a PRF of 19.94 MHz does the most severe damage to GPS, the 19.95 MHz PRF is less threatening, and the 20 MHz PRF has the smallest impact among these three cases. This indicates that these higher PRFs do not impact the receiver solely as increased thermal noise but rather as a combination of thermal noise and discrete line spectra.

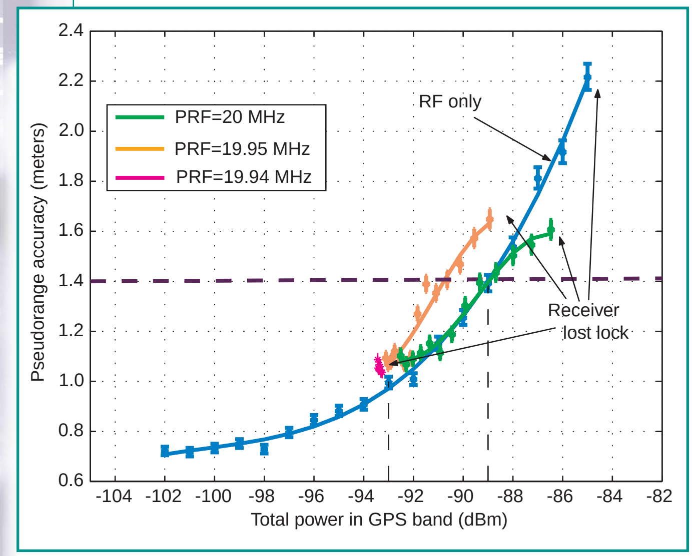


FIGURE 6 Accuracy comparison for different PRFs

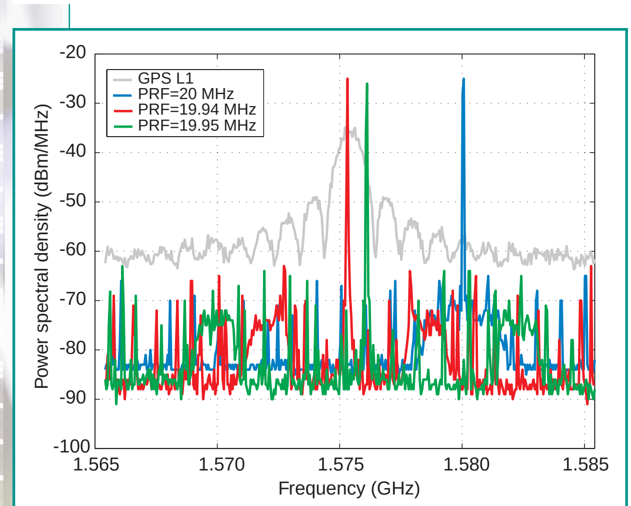


FIGURE 7 Spectrum comparison among PRFs of 20 MHz, 19.94 MHz, and 19.95 MHz

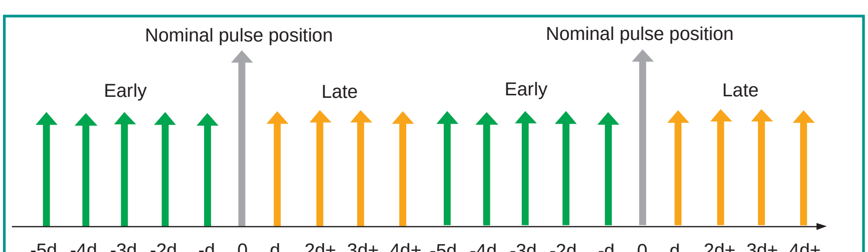


FIGURE 8 Ten-position random PPM

When the PRF is 19.94 MHz, the UWB spectrum results in a distinct CW line or "tone" that falls at an integer multiple (79) times the PRF, or 1575.26 MHz, which is within the main spectral lobe of the GPS signal. Thus, GPS performance is significantly worse — the receiver loses lock with only an additional −101.27 dBm of UWB energy and cannot achieve the desired accuracy point. By comparison, UWB is as much as 17 dB more damaging than broadband noise (in the 24 MHz band around L1). If the broadband noise power is measured at the output of a 1 MHz band-pass filter (as in other GPS interference studies), then equal damage results from a UWB signal that is approximately 3.2 dB weaker. We found this degradation without making any effort to place the UWB signals on the more sensitive GPS spectral lines. A detailed examination shows that the C/A-code line at 1575.26 MHz (that line 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 (1575.365 MHz for PRN 21). The total penalty is 9.7 dB (3.2 dB + 6.5 dB) for CW-like UWB interference with the spectral line at the most sensitive location. This result matches closely with the well-understood performance difference between broadband and CW interference. According to the MOPS for aviation receivers, CW interference masks are 10 dB more restrictive than those for broadband interference.

In practice, UWB lines will frequently find more sensitive lines than those hit in this example because: (1) many GPS satellites will be in view; and (2) the Doppler frequency for each satellite will change as the satellite moves across the sky, causing the frequency of the more sensitive lines to shift. Eventually, sensitive lines from one satellite or another will fall on the spectral lines from any nearby UWB transmitter that has such lines. Also, for any practical UWB transmitter, some variation around the nominal UWB PRF is unavoidable due to imperfect clock components. For example, a transmitter designed with a 20 MHz PRF may wander over to 19.94 MHz (a difference of only 0.3 percent) and cause loss of GPS satellite tracking.

Effect of Modulation. We tested three modulation schemes at Stanford: random on-off keying (OOK), two-position random pulse position modulation (2P PPM), and ten-position random pulse position modulation (10P PPM). In general, modulation tends to "whiten" the UWB spectrum. Therefore the impact on GPS becomes more white-noise-like compared with the non-modulation cases.

Figure 8 illustrates an example of 10P PPM. The pulse will randomly take one of ten positions: one of the early positions (−d to −5d), the nominal position, or one of the late positions (+d to +4d). We constructed a sequence of 250,000 points with minimum pulse separations of 50 nanoseconds (limited by the UWB pulser), and show the results in Figure 9. Since there are ten evenly spaced positions for each nominal pulse location, when the PRF is set to 2 MHz, the actual spectral lines would look as if the PRF were 20 MHz in the no-modulation case. But each pulse position only has one chance in ten to actually occur; thus the spectral spikes are much smaller, and the noise floor is higher, as Figure 10 shows. Though the spectral spike of the 1.994 MHz PRF case hits the GPS main lobe, its strength is much smaller than for a PRF of 19.94 MHz in the no-modulation case; thus the impact to GPS is much less severe. The lower magnitude of these spikes makes the exact location of the spikes less important, which explains why the 2 MHz PRF and 1.994 MHz PRF cases yield similar results.

It is important to notice that modulation does not guarantee the disappearance

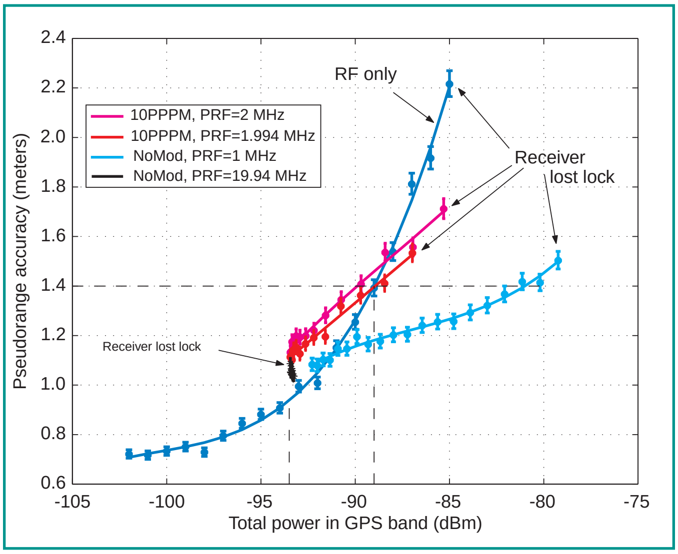


FIGURE 9 Test results for ten-position PPM

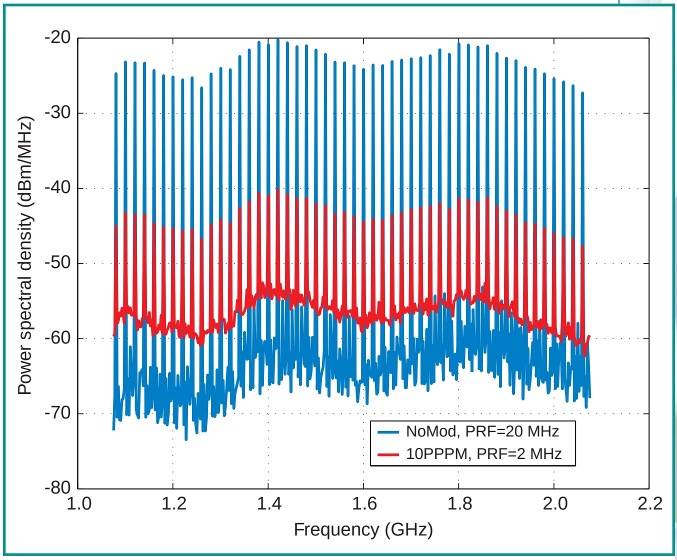


FIGURE 10 Spectrum comparison between 10-position PPM and no modulation

of the spectral lines. A carefully-designed modulation scheme is necessary to make sure that the spectrum is whitened. If that is the case, the UWB interference appears as white noise, and the dependence on the location of the spectral line (and the component variation, clock stability, and so on) disappears. We have found that, with high PRFs, the best possible outcome is that the effect of UWB approaches that of white noise (the equivalence factor approaches 0 dB). It is important to recognize that if the spectrum can be made completely white, the result will still be an impact relative to the increase in the noise floor from the additional signal.

Loss of Lock and Acquisition Test. Although PR accuracy has been our primary test metric, we conducted additional tests, including tests of loss of lock and of acquisition. These tested loss of lock by extending the accuracy test, that is, by increasing the level of the interference, until the receiver lost lock on the signal. In addition to the aviation receiver used for the accuracy test, we included in the loss-of-lock test an OEM GPS module designed to target the high-volume lower-cost market segment. Across all UWB waveforms tested, the OEM receiver provides somewhat poorer performance than that offered by the aviation receiver. The OEM receiver shows the similar general trend under UWB interference and experiences the same sensitivities to the UWB signal (PRF and the location of discrete spectral lines) as does the aviation receiver. The detailed test procedure and results can be found in the Stanford Phase II test report.

It is well understood that GPS signal acquisition is a more sensitive process than GPS signal tracking. Accordingly, it is critical to consider the impact UWB transmissions will have on the more sensitive acquisition process. We conducted these tests with a high-end general purpose GPS receiver, beginning by generating a broadband noise calibration curve to maintain the equivalence-measurement concept in the testing. We introduced the GPS signal along with a specific broadband noise power, and gave the GPS receiver five one-minute attempts to acquire the signal, recording an "acquired" or "not acquired" result. This process occurred over a range of noise values that allowed zero to five attempts to be successful in acquiring the signal. Once the noise curve was completed, we reduced by 4 dB the highest noise power that resulted in five successful acquisition attempts, and introduced a specific UWB signal. We increased UWB signal power to the point at which all five one-minute attempts failed to acquire the GPS satellite. This enabled comparison of acquisition performance in the presence of the various UWB signal parameter values with performance in the presence of broadband noise.

Figure 11 shows a plot of the results from all UWB signals as well as the broadband noise cases. The top plot shows the percentage of the trials that resulted in a successful acquisition attempt as a function of total power. The lower plot indicates the resulting average C/N_0 value reported by the receiver after a successful acquisition attempt at a specific measured power level within the GPS band. The results show a definite correlation with those obtained in the accuracy testing. The UWB waveform that has the least impact is the 100 kHz constant PRF. At the opposite extreme, the most damaging UWB waveform was the same as that which was most damaging in the accuracy testing — the 19.94 MHz constant PRF. This indicates that the distinct spectral lines resulting from the UWB signals will also be the primary issue impacting GPS acquisition performance. Lastly, the strong correlation between the most and least damaging cases for both acquisition and accuracy testing gives evidence that the performances observed are not isolated to one mode of receiver operation. Rather, the presence of UWB signals will impact all phases of GPS signal processing.

Other Compatibility Studies

In addition to the Stanford study, several other UWB assessments have recently been released. The largest and most comprehensive are the two studies conducted by the National Telecommunications and Information Administration (NTIA), which is responsible for spectrum management in the United States. One of these studies focuses on UWB-GPS compatibility, and the other investigates the impacts of UWB on other federal radio systems. The NTIA GPS compatibility study includes interference bench tests similar to those described above incorporating a variety of UWB signal characteristics and GPS receiver types. In addition, it develops a set of operational scenarios that specify the location of the UWB transmitter and GPS receiver, assumed path loss, and other factors. These scenarios vary widely in terms of numbers of UWB transmitters, proximity of transmitters to GPS receivers, and GPS receiver performance requirements. Applying the results of UWB-GPS bench testing, NTIA determined the maximum tolerable UWB transmission levels under each scenario. RTCA, the body charged with developing U.S. civil aviation standards, followed similar procedures and extended the set of scenarios to include aircraft precision landing.

Time Domain. Two studies funded by Time Domain Corporation, one of the key UWB proponents, took a somewhat different approach. Time Domain funded the Applied Research Laboratory at the University of Texas (ARL:UT) to perform tests of two of its own UWB transmitters and several GPS receivers. These tests included bench tests and outdoor tests with "typical" sets of GPS satellites in view. The data from these tests were passed along to the Johns Hopkins University Applied Physics Laboratory (JHU/APL), which Time Domain contracted to analyze segments of the data and draw conclusions from it. JHU/APL in its report avoids focusing on specific scenarios or performance metrics. Instead, it plots a variety of GPS metrics as a function of UWB-GPS separation distance.

To the degree that the test activities of the UWB-GPS studies are similar, all three studies obtained approximately the same results. UWB transmissions with PRFs well below the minimum GPS receiver front-end bandwidth of 2 MHz appear as low-duty-cycle pulsed interference to GPS receivers and generally have limited impact, although they offer little communications utility. Higher-PRF UWB transmissions that are modulated so that no significant spectral lines fall into the primary spectral lobe of the GPS L1 C/A-code have approximately the same impact on GPS as an equivalent amount of white noise. If UWB spectral lines do exist in this band, the impact can be "tone-like" or as much as 10 dB worse than white noise. All sides of the UWB rulemaking debate (including Time

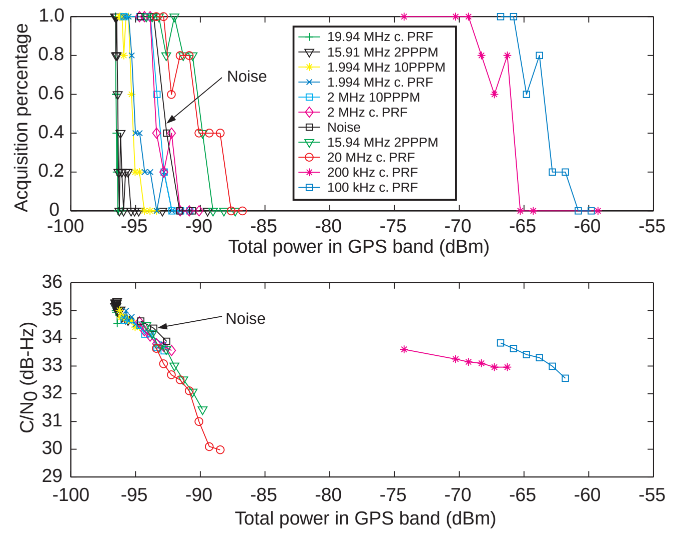


FIGURE 11 Acquisition results with corresponding measured C/N_0 values

Domain) appear to agree on these basic points.

Stanford and NTIA. The Stanford and NTIA studies identify specific measures of performance for each GPS application (such as pseudorange accuracy and loss-of-lock probability for civil aviation) and apply these to determine the impact of UWB. Based on the pre-existing requirements for GPS operations, NTIA used its scenarios and link budgets to derive the maximum tolerable UWB transmission power that would just meet these requirements. **Table 1** briefly summarizes the exhaustive NTIA results. We have used color coding (from best to worst: blue, green, yellow, and red) to indicate the comparison between the maximum tolerable UWB power levels (under both best-case and worst-case conditions) and the proposed Part 15 limit of −71 dBW/MHz. Note that some GPS users would indeed be protected by the Part 15 limit, but others would not. If UWB in practice will have no less impact than white noise, a limit much lower than −71 dBW/MHz must be set to protect the more-vulnerable GPS applications. The limit would be almost 10 dB lower yet if "tone-like" spectral lines near L1 cannot be prevented (and permanent prevention would be difficult to prove). Since it was not possible to test all permutations in the limited time allowed by the rulemaking process , the safest course is to restrict UWB transmissions to above 3.1 or even 6 GHz until the interactions between UWB and GPS are better understood, as suggested by the comments of the U.S. GPS Industry Council, ARINC/Air Transport Association, and others.

TABLE 1 Maximum Allowable UWB Power Levels from NTIA Study

Class of UWB Interference	Most favorable scenario and UWB modulation	Least favorable scenario and UWB modulation
pulse-like interference	-26.5 dBW/MHz	-73.2 dBW/MHz
noise-like interference	-49.6 dBW/MHz	-98.6 dBW/MHz
tone-like interference	-70.2 dBW/MHz	-106.9 dBW/MHz

Because the JHU/APL study did not apply specific performance measures to particular applications, it made its judgements simply by observing the overall trend of the performance vs. separation plots. The "knee" of most of these curves, when GPS performance became absolutely unacceptable (for example, tracking of several satellites is lost) is at a separation of about 3 meters; thus JHU/APL concluded that 3 meters was the point of "severe" degradation. However, a closer look at the individual plots shows that degradation appears at much greater separations. For example, under minimum-GPS-signal-strength conditions, one GPS satellite is lost at separations of 25 meters or more. This is unacceptable to aviation applications that require use of low-elevation-angle satellites to enhance positioning geometry and require that the probability of losing these satellites unexpectedly be very small.

This discrepancy regarding the amount of degradation that is "harmful" is now a dominant issue in FCC rulemaking. While debate continues regarding the assumptions underlying the various test procedures and scenarios, all UWB-GPS test results published to date show that UWB transmissions overlapping L1 degrade GPS performance to some degree. Time Domain claims that this degradation is only a "nuisance" if four or more satellites remain tracked because some level of GPS positioning is still possible. Time Domain goes so far as to state that GPS operations that require more than this bare minimum are poorly-conceived because GPS is "fragile" and "will not work at all in many places." Indeed, GPS is vulnerable, which is why today's prohibition against other intentional transmissions in the GPS band exists and should be preserved.

Summary and Conclusions

While UWB signals have potential applications in communication, surveillance, and perhaps navigation, they should be designed and regulated so as not to interfere with existing users and spectrum allocations. Bench tests conducted by Stanford University demonstrated that, while low-power and low-data-rate UWB signals can be tolerated by GPS receivers with little degradation, high-PRF UWB signals of use for communications will have at least the same impact as an equivalent amount of white noise. UWB signals with spectral spikes near the GPS L1 frequency make the impact as much as 10 dB worse than white noise, leading to premature loss-of-lock on GPS satellites.

These results, which essentially match those obtained by the NTIA, ARL:UT, and JHU/APL studies, clearly illustrate that restrictions on UWB transmissions beyond those placed on unlicensed Part 15 emissions are required. Since there appears to be a technical consensus on the impacts of UWB, the debate regarding UWB signal restrictions will turn on the definition of harmful interference. Some UWB manufacturers translate this as complete loss of positioning and maintain that interference that increases range errors or causes the loss of one or two satellites is only a nuisance.

For GPS users in the surveying, aviation, and E-911 fields, these nuisances could make their operations infeasible, and if the interference is unexpected, the result could be life-threatening loss of service. The GPS community must make it clear to the FCC and to Congress that it cannot tolerate the degradation of GPS performance and still provide the user benefits that society now takes for granted.

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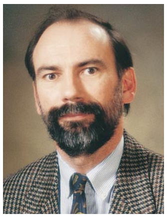
Manufacturers

The Stanford tests used a single-channel **WelNavigate, Inc.** (Oxnard, California) GS-100 GPS simulator to generate the GPS signal; a Hewlett-Packard Company, now **Agilent Technologies** (Palo Alto, California), HP 346B noise generator; and a **Tektronics, Inc.** (Beaverton, Oregon) AWG 2012 arbitrary waveform generator. The tests were automated using LabView software from **National Instruments Corp.** (Austin, Texas).



"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments as well as topic suggestions for future columns. To contact him, see the "Columnists" section on page 4 of this issue.