ClearTrak ™ GPS Receiver Technology

Optimized L2 Tracking

True Multipath Mitigation

Interference Protection

Future Signal Compatibility

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Leica

MADE TO MEASURE

Biographies

Tom Stansell is a Vice President of Leica Geosystems in Torrance, California, where he is involved in technology development and strategic relationships. Tom received his BEE degree in 1957 and his MEE degree in 1964, both from the University of Virginia. At the Johns Hopkins Applied Physics Laboratory he participated in development of the Transit Satellite Navigation System. At Magnavox, he led the development of many Transit and GPS products and their underlying technology. He is the author of many technical papers, received the ION Weems Award in 1996 for continuing contributions to the art and science of navigation, and became a Fellow of the ION in 1999.

Jon Maenpa is a product development Project Leader at Leica Geosystems in Torrance, California, where he has worked since 1995. Prior to Leica Geosystems, Jon was with Magnavox Advanced Products and Systems Company, where he worked on development of a variety of satellite navigation and satellite communication products since 1977. Jon holds a Bachelor of Science degree in Electrical Engineering from the University of California at Los Angeles, and he recently completed a graduate program at the Anderson School of Business, also at UCLA. He has authored eleven papers in the field of navigation.

ClearTrak™ Technology

ClearTrak™ is the term Leica Geosystems uses to signify our suite of technologies which assures the best possible GPS receiver performance. The System 500 Receiver, illustrated in Figure 1, is the first to employ the entire suite of ClearTrak™ technologies. Because we want ClearTrak™ to be more than just a mysterious buzzword, this paper clearly defines the issues and the solutions provided by this industry-leading technology.

There are four key issues which affect GPS survey performance and user value:

1. Anti-Spoofing (AS), which is encryption of a satellite's P code into a Y code.
2. Multipath, which corrupts measurements of the signal received directly from each satellite.
3. Interfering signals.
4. Planned changes in the satellite signal.

The following sections of this report define each of the challenges and show how ClearTrak™ technology provides the industry-leading solution.

Figure 1 - System 500 Receiver

ClearTrak™ Anti-Spoofing Solutions

Although the earliest GPS survey receivers employed only the L1 signal, the industry soon recognized the productivity advantages of using both the L1 and the L2 signals. GPS was designed with two signals in order to eliminate the refraction effects caused when signals pass through the earth's ionosphere. However, the survey community realized that two signals can be used not only to correct for the ionosphere but also to greatly accelerate the process of ambiguity resolution, which is required to achieve centimeter accuracy. (The phase of the L1 signal repeats, i.e., is ambiguous, every 19 cm. It is difficult to select which of these is the correct cycle. However, the phase of the L1 minus the L2 signal has 86cm ambiguities, which are much easier to resolve, and having been resolved allow quick resolution of the L1 ambiguities). Resolving L1-only ambiguities may require 10 to 30 minutes of data collection, whereas resolving dual-frequency ambiguities typically requires only 30 seconds. This productivity difference is why access to both L1 and L2 is vital for GPS surveying. (Reference 1 provides additional information on state-of-the-art ambiguity resolution techniques.)

About the time that GPS manufacturers were beginning to produce dual frequency survey receivers, the Government decided to implement Anti-Spoofing (AS). The intent was to prevent an enemy from transmitting false GPS signals which could confuse or misdirect friendly GPS users. The AS technique encrypts the P code, transmitted on both L1 and L2, into a Y code. Since the Y code is known only to friendly forces, it is impossible for an enemy to transmit a signal capable of confusing a friendly receiver. Because civilians have access to the C/A code on the L1 signal, AS does not cause an L1 problem. However, currently there is no C/A code on the L2 signal, so AS could have denied civilian use of the L2 signal altogether.

The Jet Propulsion Laboratory developed a technique to alleviate this L2 access problem. By time shifting and cross-multiplying (cross correlating) the received L1 and L2 signals, it was possible to create a very weak, L1 minus L2, 86 cm difference frequency signal. Thus, in conjunction with the standard C/A code L1 signal, both GPS frequencies continued to be available for civilian use, and this technique was adopted by at least two GPS receiver manufacturers. The problem, however, is that the resulting L1 minus L2 signal is so weak that it is impossible to reliably collect data from low elevation satellites or from signals which pass through even light foliage. Also, even extremely low levels of interfering signals can prevent dual frequency operation.

Leica Geosystems was the first company to develop a more robust solution, called code aiding. By tracking satellite signals with a large dish antenna, we discovered that the Y code was the product of the known P code times a much slower encryption code. Therefore, by correlating the Y code signal with the known P code before further processing, the result is a signal which is 20 times stronger (+13 dB)! This gives an enormous boost to performance, and, in addition, Leica Geosystems GPS receivers actually track the P code.

This concept (U.S. Patent No. 4,972,431, issued on 20 November 1990) was first implemented in the WILD WM 102 dual frequency survey receiver, which was introduced in 1988. The concept also was used in Leica Geosystem's second-generation survey product, System 200, which was introduced in 1991. The technique was further improved to give full wavelength phase measurements (U.S. Patent No. 5,535,278, issued on 9 July 1996) and was implemented in LEICA System 300, which was introduced in 1995.

This mature, fully proven, and industry-leading Code Aided Cross Correlation process provides the best L2 signal quality in the industry. It is a key part of Leica Geosystem's ClearTrak™ technology suite, and it is one important reason for the outstanding performance of the new System 500 family of GPS survey products.

Multipath Mitigation Technology

In most applications of high precision GPS, multipath is the most significant source of error. Figure 2 illustrates what is meant by multipath. In addition to the direct

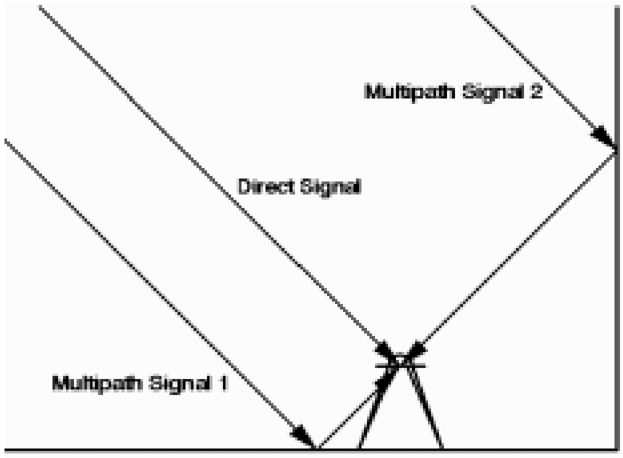

Figure 2 - Multipath Defined

signal path from a GPS satellite to the receiving antenna, there are many indirect paths, thus the name multi-path. Note that in a typical environment there may be hundreds of multipath reflectors. Therefore, the GPS receiver is required to process the combination of the direct signal plus all of the indirect signals. The error due to multipath is defined as the difference between real-world measurements, where multipath abounds, and the measurements which would be obtained if there were no multipath. Both code (pseudorange) and carrier phase measurements are affected by multipath. The distinguishing characteristic of multipath signals is that they arrive at the receiving antenna later than the direct signal, simply because they travel a longer path. As you will see later, the delay in time of arrival directly affects the impact of each multipath signal.

There are four primary multipath mitigation techniques in current use by GPS manufacturers:

1. Antenna characteristics,
2. Multipath estimation with multiple correlators,
3. Filtering by carrier aided code smoothing, and
4. Use of reduced width correlators (RWC).

<u>Antenna characteristics</u> which tend to minimize reception of multipath signals are: a high front-to-back gain ratio, excellent circular polarization, and minimum response at very low elevation angles. Leica Geosystems provides state-of-the-art antennas designed for this purpose.

Multipath estimation with multiple correlators significantly increases the cost and complexity of a GPS receiver. This is because many correlators must be used for each satellite in order to model a limited number of the most significant multipath signals. Leica Geosystems does not use this technique, not only because of its cost and complexity but also because we have simple and inexpensive ways to achieve equal or better results without depending on an inexact modeling process.

Filtering code measurements with carrier aided smoothing is a widely used technique invented by Leica Geosystems(unfortunately not patented by Leica Geosystems). The basic idea is to use the very precise measure of pseudorange change provided by carrier phase measurements to remove the effects on the code tracking function of satellite motion, user motion, and oscillator drift. As a result, the code loop and/or subsequent code filtering can employ very long time constants to remove much of the multipath noise. The amount of smoothing in single frequency receivers is limited by the need to track ionospheric refraction, which affects code and carrier measurements equally but in opposite directions. There is no upper limit to smoothing for dual frequency receivers. Reference 2, dated February 1982, is the earliest document to describe this technique.

Reduced width correlators (RWCs) have been used for many years to mitigate multipath effects on code measurements. The earliest GPS receivers employed what we now call a "wide correlator" to track and measure the transmitted C/A and P codes. The wide correlator choice was simple, natural, and effective. Later, however, it was recognized that by switching to a "reduced width correlator" after initial signal acquisition, the amount of code measurement noise is significantly reduced, primarily because some of the multipath error is eliminated.

Figure 3 is the classic way to illustrate the effect of multipath on various tracking techniques. It shows the error caused by one unusually strong multipath signal as a function of its arrival delay relative to the direct signal. (The measurement used both for the error and for the delay is in terms of C/A code "chips", where one C/A code chip is about 293 meters long.) The assumed multipath signal has one-half the voltage amplitude of the direct signal, i.e., one quarter of the direct signal power. The plot shows the envelope of maximum positive and negative code tracking error as the phase of the multipath signal changes relative to the direct signal. In other words, the code error moves up and down, positive and negative, to the maximum values defined by the envelope at that particular delay. The outer envelope shows the maximum error when tracking a GPS C/A code with a wide correlator. The maximum error is ¼ of a C/A code chip, or ±73.3 meters. The error is present for any multipath code delay greater than zero and less than 1.5 chips, or 440 meters.

Well inside the wide correlator envelope is an RWC error envelope. Illustrated is the envelope for a correlator with 10% the width of the wide correlator, which is a typical value in the industry. Compared with the wide correlator, Figure 3 shows that the maximum error with the 10% RWC is 10% as large, and the error ends for multipath delays greater than 1.05 chips, or 308 meters. It is evident that the RWC is a very effective multipath mitigation technique, and Leica Geosystems is licensed to practice the most advanced, patented, variable width, RWC technology.

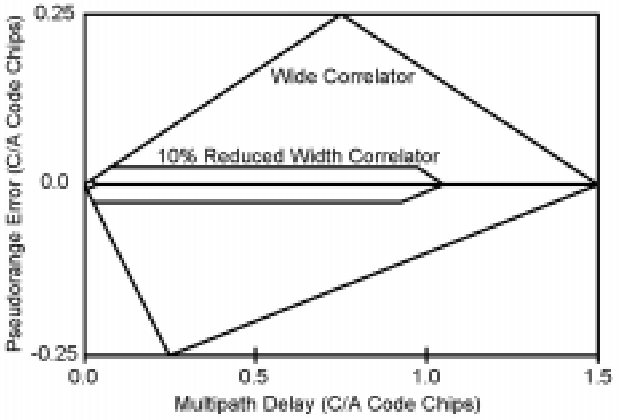

Figure 3 - Code Multipath Error Envelopes

ClearTrak™ Code Multipath Mitigation

Of the four code multipath mitigation techniques reviewed above, Leica Geosystem's ClearTrak™ technology uses two optimized antenna characteristics and filtering with carrier aided code smoothing. As explained above, estimation with multiple correlators is not used because we have simpler methods which perform better.

Although our previous products did use reduced width correlators, ClearTrak™ now employs a new and more effective technique which we call the Multipath Mitigation Correlator (MM Correlator) (patents applied for). The error response of the MM Correlator also is shown in Figure 3, but the scale of the graph makes it almost impossible to see. Therefore, in order to see the MM Correlator response, Figure 4 is a magnified view of the front tip of the curves in Figure 3. The envelope of the MM Correlator has a maximum error which is one-quarter that of the 10% RWC. Equally important, the error response returns to zero for any multipath delay greater than 0.05 of a chip, or 14.7 meters. Both of these characteristics greatly reduce the impact of multipath signals.

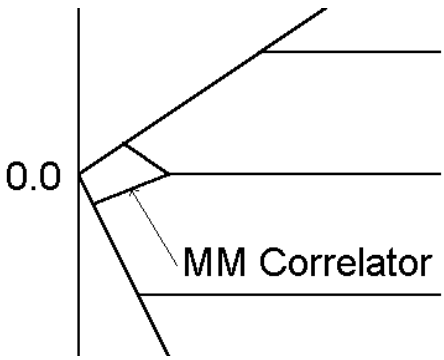

Figure 4 - Multipath Mitigation Correlator Envelope

Naturally we are very proud of this new technology. The performance improvement promised by Figure 4 is very dramatic indeed. However, the proof of a pudding is in the eating. Other companies have claimed significant technical improvements which, in practice, gave little or no real-world performance improvement. Also, because the largest and most troublesome multipath signals are reflected near the antenna, they have very little path delay. Therefore, the proof of performance is only with real-world data.

It is important to stress that all of the accuracy plots were made with what we call „raw code measurements", meaning that we did not use carrier aided code smoothing. The objective is to see what improvement is made by the MM Correlator. If carrier aided code smoothing were used, the solution scatter would be much smaller.

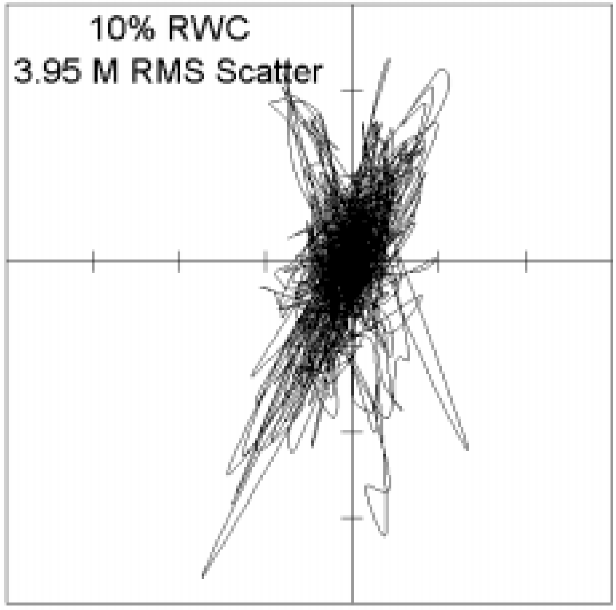

Figure 5 - Under Foliage with 10% Reduced Width Correlator

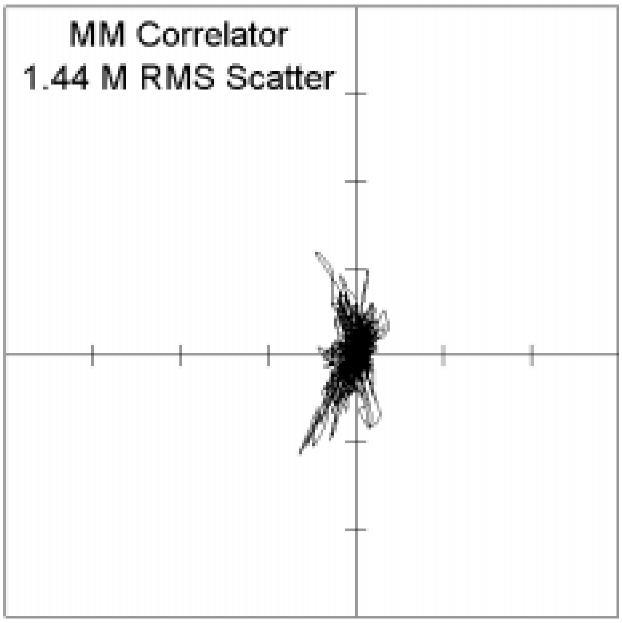

Figure 6 - Under Foliage with Multipath Mitigation

Figures 5 and 6 present raw differential code navigation solutions with the reference receiver in the open but with the rover receiver under foliage. This is a difficult multipath environment because direct signals are attenuated through the foliage whereas a multipath signal, depending on its path, may avoid the foliage attenuation and thus appear stronger relative to the direct signal. One antenna was used at each location with two receivers connected to each antenna. Therefore, the two receivers connected to each antenna „saw" identically the same signals. One SR9500 receiver pair (reference and rover) used a 10% RWC and the System 500 receiver pair used the MM Correlator. The plots, which have the same ±17.5 meters per axis scale, show the north and east differential navigation error every 15 seconds for 4 hours and 26 minutes. The difference is dramatic, illustrating the real-world advantage of ClearTrak™ with the MM Correlator. Statistically, the horizontal scatter with the 10% RWC is 3.95 meters rms, and with the MM Correlator it is 1.44 meters rms. ClearTrak™ with the MM Correlator is 2.7 times better in this very difficult, under foliage, real-world test

The second test was conducted in a moving vehicle as it circled in a parking lot. As shown by Figures 7 and 8, two AT502 survey antennas were mounted on the van. Each antenna fed two receivers: one was the SR9500 with a 10% RWC and the other was a System 500 with the ClearTrak™ MM Correlator. A reference station antenna was mounted on a nearby rooftop, and it also was connected to an SR9500 and a System 500. Using KOF

Figure 7 - Van with Two Antennas

Figure 8 - Van Antenna Mounts

(Kinematic On the Fly) calculations, we then computed the position of each van-mounted antenna relative to the reference antenna, with centimeter accuracy, at one-second intervals, for just over 44 minutes. We also computed the differential code navigation results for each van-mounted antenna during the same interval. In this way, the second-by-second code navigation error was determined by subtracting the KOF position from the corresponding code navigation solution. Figures 9 and 10 compare the results for the van's left antenna and Figures 11 and 12 compare results for the van's right antenna. Again, the real-world differences are dramatic, with the MM Correlator being about two times better than the 10% RWC while moving.

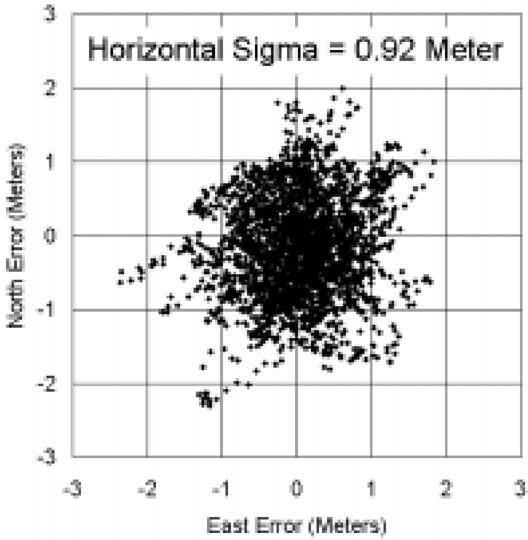

Figure 9 - Left Antenna with Reduced Width Correlator

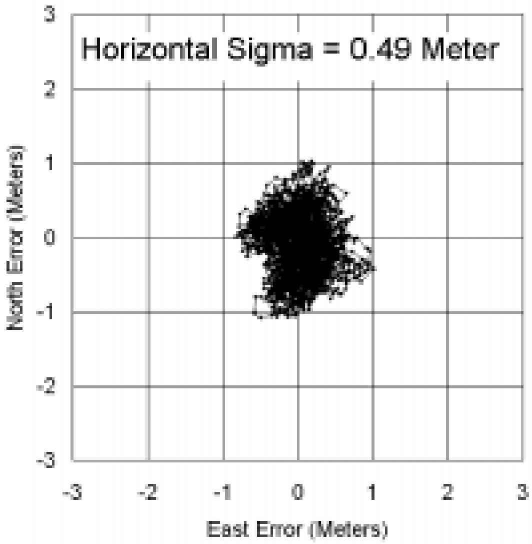

Figure 10 - Left Antenna with ClearTrak™

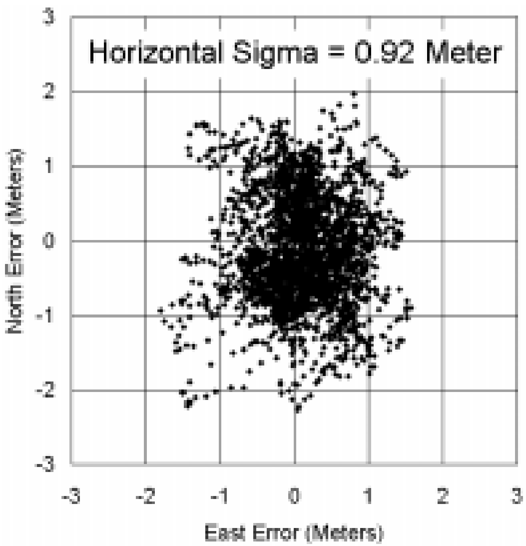

Figure 11 - Right Antenna with Reduced Width Correlator

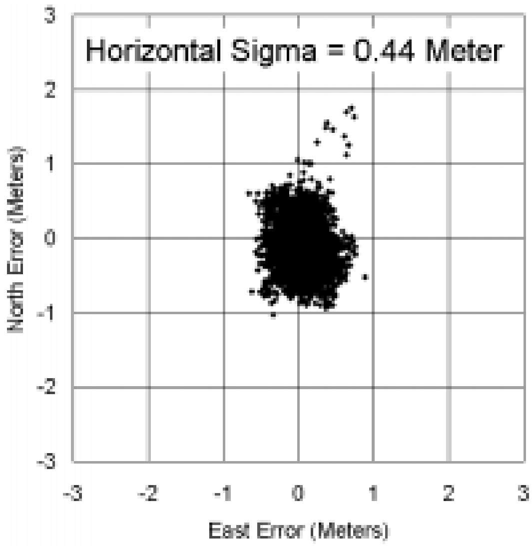

Figure 12 - Right Antenna with ClearTrak™

Leica Geosystem's ClearTrak™ code multipath mitigation technology is not advertising fluff, it is real, and it provides users with significant advantages. Better code navigation accuracy not only is useful on its own, but it also leads to faster and more reliable ambiguity resolution for survey applications.

ClearTrak™ Interference Protection

By the time GPS satellite signals reach the earth from a distance of more than 20,200 kilometers, they are very weak indeed. In fact, the GPS C/A code signal has the strength of a 2.5 milliwatt (0.0025 watt) transmitter from a hill 50 kilometers (30 miles) away! This is far less than a child's walkie-talkie at that distance.

With such a weak signal, there are only three ways to avoid trouble from interfering signals. The first is a characteristic of the GPS signal design, called spread spectrum modulation. Due to spread spectrum modulation, the GPS C/A signal appears to be up to 1,000 times more powerful than an interfering signal. Thus, compared with an interfering signal, the GPS signal appears to be a 2.5 watt transmitter 50 kilometers away.

The second defense against interference is spectrum allocation. Governments of the world have defined the GPS L1 frequency as protected for navigation. Unfortunately, the L2 frequency is not as well protected (which is why eventually there will be a third civilian frequency). Because satellite communication companies want to encroach on GPS frequencies, it is important to remind your national government how vital GPS is to your business. If you suffer GPS interference, complain to the appropriate government agency, such as the FCC in the United States. A website to report large-scale GPS interference is:

www.navcen.uscg.mil/userinput/GPSUserInput/GPSOutageUserInput.htm

The third technique is to design the GPS receiver to be as immune to interference as possible. Leica's ClearTrak™ technology includes two important and effective techniques:

- Sharp cutoff „SAW" filters to eliminate out-of-band interference, and
- Adaptive, multi-level signal sampling to minimize the effect of in-band interference.

The spread spectrum bandwidth of the GPS signal is ±10 MHz around the L1 center frequency of 1,575.42 MHz and the L2 center frequency of 1,227.6 MHz. Therefore, it is desirable to eliminate any signal received outside of these bands. For this purpose, there is no more effective device than a Surface Acoustic Wave (SAW) filter. Figure 13 shows the bandpass characteristic of the ClearTrak™ SAW filter for the GPS L2 signal. The L1 SAW filter has a similar characteristic. The filter passes the GPS signals, but just outside the signal bandwidth the filter cuts off the response to all other signals very suddenly. Outside the center band, interfering signals are reduced by a factor of between 100,000 (50 dB) and 1,000,000 (60 dB). Engineers call this a "brick wall" filter.

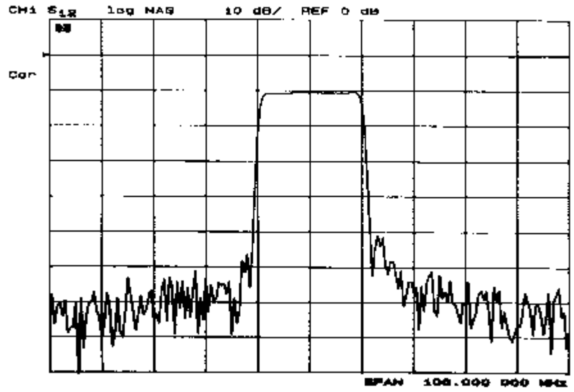

Figure 13 - Brick Wall L2 SAW Filter Response

Field test results have verified the effectiveness of the ClearTrak™ SAW filters. For example, an older generation of GPS receivers without ClearTrak™ SAW filters often suffered interference from the network of „Digipeaters", which provide digital data relay services for amateur radio operators over a wide area of central Europe. Near Stuttgart, Germany, a number of survey sites directly in the beam of the local Digipeaters were occupied with both the older receivers and receivers equipped with ClearTrak™ SAW filters. Whenever Digipeater traffic increased, the older receivers would lose satellite signals, whereas receivers with the ClearTrak™ SAW filters continued to provide excellent survey results with no signal loss.

On the other hand, if interfering signals fall inside the GPS band, the last line of defense is the adaptive multi-level signal sampling technique first defined by Reference 3. Except for rejection of interfering signals, there is very little performance loss from using a simple one-bit (binary) signal sampling process. However, to obtain every possible advantage against interfering signals, Leica Geosystem's ClearTrak™ technology employs the more advanced technique. It involves use of an Automatic Gain Control (AGC) function to make sure the signal sample levels are placed optimally for the signals actually being received and multi-level quantification of the signal amplitude. In this way, a receiver with ClearTrak™ has about five times more signal power (7 dB) relative to an interfering signal than a receiver without this technology.

Figure 14 shows laboratory test results which compare ClearTrak™ technology to an older generation of receivers without SAW filters and without multi-level signal sampling (Prior_Tech). The plot shows, as a function of frequency, the amount of interfering (jamming) signal power required to adversely affect GPS signal tracking in terms of jam-to-signal (J/S) ratio. It is clear that the bandwidth within which interfering signals can affect GPS tracking has been dramatically reduced widthed around the two GPS frequencies of 1575.42 MHz and 1227.6 MHz. The plot also shows the in-band improvement due to multi-level signal sampling. (More detail on these interference protection technologies can be found in Reference 4.)

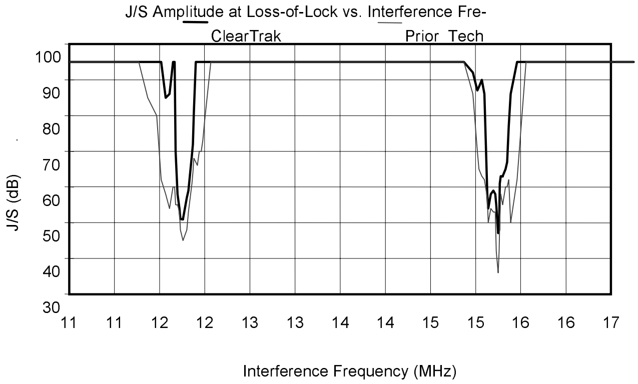

Figure 14 - Interference Rejection Comparison

To summarize, Leica Geosystem's ClearTrak™ technology provides two state-of-the-art methods to protect against interference. „Brick wall" SAW filters are the best way to avoid „out-of-band" interference, and adaptive multi-level signal sampling is the best way to minimize „in-band" interference. Protection from interference is another important way ClearTrak™ helps assure successful field measurements.

ClearTrak™ Provides Future GPS Signal Compatibility

Today, GPS satellites transmit both a C/A code signal and a Y code signal on the L1 frequency, but they transmit only a Y code signal on the L2 frequency. The U.S. Government has announced that in a few years new satellites will be modified to also transmit a C/A code on the L2 frequency (at this time an exact schedule has not been decided). Leica Geosystems GPS receiver hardware already is compatible with this new C/A code signal and will be able to take full advantage of its substantially greater signal strength. All of the ClearTrak advantages also will apply to the new signals. Thus, Leica Geosystems GPS receivers also have an important built-in protection from obsolescence.

Conclusion

The purpose of this paper has been to clearly define the signal processing issues which most affect precision GPS applications, such as survey, and to clearly explain the solutions provided by Leica Geosystem's ClearTrak™ technology. The System 500 GPS Survey products, pictured in Figure 1, are the first to employ the entire suite of ClearTrak™ technologies.

We have addressed the four key issues which affect high precision GPS performance, which are:

1. Anti-Spoofing (AS), which is encryption of a satellite's P code into a Y code.
2. Multipath, which corrupts measurements of the signal received directly from each satellite.
3. Interfering signals.
4. Planned changes in the satellite signal.

Each of these challenges was described, and the ClearTrak™ solution to each was explained. These technologies are one reason why Leica Geosystems GPS products with ClearTrak™ provide such outstanding productivity in real-world environments.

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