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Discussions on RF Signal Propagation and Multipath

Radio frequency (RF) signal multipathing is a phenomenon common to virtually all types of radio communications and navigation systems. It affects the complete radio spectrum ranging from low frequency (LF) channels in the kiloHertz range up to and beyond microwave channels in the gigaHertz range. This document provides a brief overview of multipath and why it is an important consideration in radio wave propagation, followed by solutions provided by NovAtel Inc. as related to GPS positioning systems.

Radio Wave Propagation

It is generally the objective of a radio service to relay information from one location to another by the use of a radio transmitter at the origin and one or more receivers at the remote destination points. The link between these points includes the origin transmitting antenna, propagation medium (free space or the earth's atmosphere), and the destination receiving antenna.

Radio waves (electromagnetic radiation) propagate from the transmitting antenna to the receiving antenna utilizing the propagation medium between them. We will assume that the earth's atmosphere (ionosphere and troposphere) is the primary propagation medium. To understand multipath, it is helpful to understand the nature of these waves and their behavior in the propagation medium. As the subject of radio wave propagation is a field of study in its own right, only enough subject matter is covered here to provide some background for multipath discussions.

Radio waves, also called radio frequencies, (or, the RF signal), propagate through free space (vacuum) at the speed of light (299,792,458 metres/second). The frequency of the RF signal is expressed as the number of complete polarity reversal cycles that occur during a period of one second. Thus a frequency of 10 MHz indicates that the signal experiences 10,000,000 polarity reversal cycles every second.

Wavelength is the distance the RF signal travels during the period of one RF cycle. Thus wavelength = c/f, where c is velocity of electromagnetic waves expressed in metres per second and f is frequency expressed in cycles per second. A frequency of 1575.42 MHz will have a wavelength of approximately 19 cm whereas a frequency of 1 MHz will have a wavelength of approximately 300 metres. Wavelength plays an important role in RF signal propagation and reflection characteristics.

The rate of signal propagation changes if the signal passes through different mediums of different dielectric constants, such as the various layers of the earth's atmosphere and differing temperature zones. When this occurs, the velocity of propagation as well as the direction are altered somewhat. The degree of alteration depends on the degree of change in medium dielectric constants as the signal passes from medium to medium. This is the same phenomenon that causes light to reflect off mirrors and why objects immersed in water appear distorted when viewed from above the waterline. Just as light waves are subject to refraction and reflection phenomena, so are RF signals (both are electromagnetic waves).

RF signals generally propagate between the transmitting antenna and the receiving antenna in one of the following most common methods: line of sight (space waves), refraction, or reflection. Dominant propagation characteristics vary with the frequency (or wavelength) of the transmitted signal involved. As well, these characteristics are also variable depending on changing conditions in the earth's atmosphere (primarily the ionosphere and troposphere) which cause varying degrees of signal refraction and even reflection. Natural and man-made objects can influence wave propagation as well. Metals and fluids tend to be highly reflective surfaces for electromagnetic waves and thus influence the path of propagation.

Low and medium frequencies (LF or long waves, and MF or medium waves) ranging from about 30 kilohertz up to a few megahertz propagate primarily by surface waves. Surface waves tend to follow the earth's surface and are capable of dependable non-line-of-sight propagation of up to about 150 kilometres. Surface wave propagation distances are greater over the ocean than over land and may extend up to a few hundred kilometres. Because of the long wavelengths involved in the

LF/MF range, radio signal reflections are of little consequence. (Periodically conditions may exist which cause some atmospheric refraction.)

High frequencies (HF or short wave) range from about 3 MHz up to about 30 MHz and propagate by combinations of line of sight, refraction, and reflection. Propagation characteristics tend to vary from day to night, summer to winter. This is because the dominant propagation of short waves is dependent upon the earth's ionosphere, and as the ionosphere's characteristics change through day, night, summer, and winter, so do its propagation characteristics. Because of susceptibility to changing conditions, HF radio navigation and communications reliability can be highly variable. Propagation ranges thus can vary from line of sight (50 km) during poor conditions or up to thousands of kilometres during optimal conditions. These long distance propagations are possible because of ionized particles in the ionosphere causing the RF signals to refract or reflect back down to the earth's surface. And when the earth's surface is highly reflective (such as over water bodies) multiple reflections between the earth and ionosphere occur allowing long distance propagation (multi-hop).

Very high frequencies (VHF) range from about 30 MHz up to about 300 MHz and propagate primarily by line of sight. For most applications this limits reliable propagations to about 30 - 50 km. However, these distances can be increased by raising the transmitter and receiver antennas as high as possible above the terrain. Obviously, aircraft may have line of sight capabilities of 200 km or more. VHF occasionally experiences special atmospheric conditions known as tropospheric ducting where temperature inversions in the atmospheric layers cause signal refraction due to sudden changes in the air mass dielectric constants, thus causing the signal to follow the inversion duct. Ducting can extend the propagation distance to hundreds of kilometres. At VHF frequencies, many natural and man-made objects become fairly good RF signal reflectors.

For ultra high frequencies (UHF) ranging from 300 MHz up to about 3000 MHz (3 GHz) where the signal wavelengths are submetre, line of sight is the primary mode of propagation. Thus, signal propagation distances on the earth are generally limited to 50 km. Aircraft can achieve hundreds of kilometres depending on their altitude above the earth's surface. Natural terrain as well as man-made objects can have great influence on the signal as it travels along the propagation route. Because of the small wavelengths in this frequency range, reflections occur off almost any metal structure larger than a few centimetres in size. This frequency range is the primary segment used for satellite communications and navigation systems including TRANSIT and GPS.

The GPS RF Signal

The GPS satellite constellation maintains precise orbit patterns at approximately 10,898 nautical miles above the earth's surface. Each of the 24 orbiting satellites (exact number may vary) broadcast continuous PRN code as well as precise orbit data on the GPS L1 channel (1575.42 MHz carrier) and L2 channel (1227.60 MHz carrier). Each satellite transmits these signals using a right hand circular polarized (RHCP) antenna.

As the GPS signal must travel approximately 10,898 nmi, some refraction and delay of the signal does occur as it travels through the changing propagation mediums (ionospheric layers and troposphere). Some GPS receivers, such as the NovAtel GPSCard, model out much of the ionospheric and tropospheric delays. However, the most successful method for cancelling the effects of atmospheric refraction and delays is to use a dual frequency GPS receiver (L1/L2). These two frequencies have a special ralationship which, when combined with special down-conversion and mixing techniques, allows them to be combined in such a way as the effects of atmospheric delay are almost completely cancelled.

Because GPS is a radio ranging and positioning system, it is imperative that ground station signal reception from each satellite be of direct line of sight. This is critical to the accuracy of the ranging measurements. Obviously anything other than direct line of sight will skew and bias the range measurements and thus the positioning triangulation (or more correctly, trilateration).

The Role of Receiving Antennas

The role of a receiving antenna is to intercept electromagnetic waves as they propagate through space (or the earth's atmosphere). In order for an antenna to efficiently intercept a desired frequency or band of frequencies, it must be "tuned" to the frequency band where optimal reception is desired. Tuning helps reject out-of-band signals as well. Once intercepted, the electromagnetic wave induces alternating currents in the receiving antenna that accurately duplicate the RF signal as transmitted from the transmitting antenna. Once intercepted, the signal can be further amplified, filtered, downconverted, and demodulated or decorrelated by the receiver circuitry.

Radio waves exhibit polarity characteristics based on the transmitting antenna design. For example, vertical (or whip) antennae are considered as vertically polarized, whereas dipole and other horizontally oriented antennae are considered horizontally polarized. Space radio systems such as GPS tend to use antennae that are circular polarized. For optimum signal transfer, radio links require that the receiving antennae polarization match that of the transmitting antenna. If cross polarization occurs between the two systems, the receiving system may lose anywhere from 10 to 30 dB of the available signal. GPS earth stations require RHCP polarization to match the polarization of the satellite transmitted signal for optimal signal reception.

GPS earth stations require that the receiving antenna radiation pattern possesses omnidirectional characteristics. An omnidirectional antenna is required to provide optimal reception of all GPS signals within the antenna's reception hemisphere (from horizon to horizon at all bearings and elevations).

As the signal wavelength of L1/L2 signals is quite short (about 19 cm L1/24.4 cm L2), this allows for the small and efficient antenna design. Further to this, antenna designs in general tend to be most efficient and practical using quarter wavelength and half wavelength construction. This means that practical GPS antenna construction dimensions can be as small as 4 to 5 centimetres in size.

The two most commonly used GPS antennae use quadrifilar and microstrip construction techniques. Both types are optimized for RHCP polarization.

Due to the physical characteristics of a quadrifilar antenna (relatively high profile vertical structure), they generally have very good low angle reception. As GPS signals tend to be weaker at low angles (the horizon), this can be an asset for early signal acquisition for rising satellites. Low angle antenna radiation patterns can also be an asset for craft that are subject to pitch and roll conditions. On the negative side, undesired multipath reflections off water bodies are also strongest at low angles.

Microstrip (or patch) antennae, on the other hand, are generally very low profile structures (essentially a tuned flat plate separated by dielectric material from the ground plane). This type of antenna, by nature, tends to favor high elevation reception over low angles. Thus, low angle multipath reception off water bodies is less of a problem than for quadrifilar antennae. However, on the other hand, flat-plate patch antennae perform less favorably at the horizon when the craft is subject to pitch and roll conditions. In recent years, microstrip antenna construction techniques have evolved such that dome shapes are possible that enhance the low angle reception capabilities. The NovAtel GPSAntenna model 501 is an example where special construction techniques are used to enhance the low angle performance over traditional flat plate patch antennae.

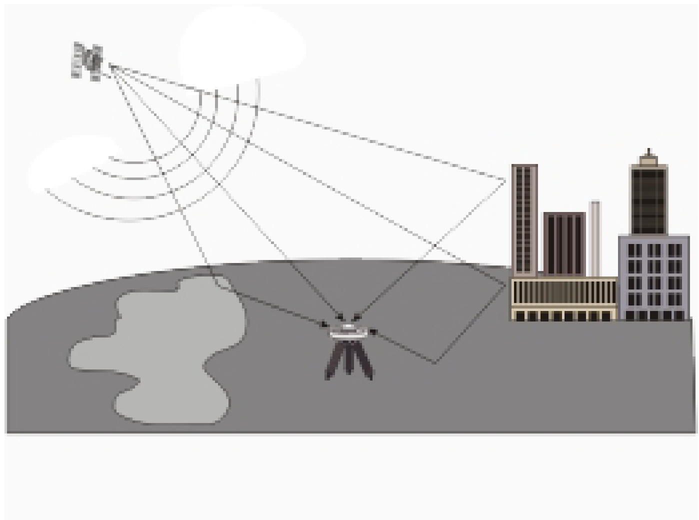
Each type of antenna has its advantages and disadvantages. Whatever type of antenna is chosen for the GPS receiver, multipath reception will still have to be dealt with as a common problem.

In most radio systems, the shortest direct propagation route is generally the preferred route (with the exception of short-wave multihop used to achieve long distance radio communications on the earth). However, in practice, the RF signals may arrive at the receiving antenna from more than one propagation route. This is where problems may arise at the receiving antenna and leads us into the important topic of multipath reception and its associated problems and solutions.

What Is Multipath?

Multipath occurs when an RF signal arrives at the receiving antenna from more than one propagation route (multiple propagation paths - thus multipath).

Figure 1 Illustration of GPS Signal Multipath



What Causes Multipath?

When radio waves (electromagnetic radiation) are emitted from a radio transmitter antenna, the RF signal propagates in all directions from the antenna. Because the RF signal is emitted in many directions simultaneously and is travelling different paths, these signals encounter various and differing natural and man-made objects along the various propagation routes. Whenever a change in medium is encountered, the signal is either absorbed, attenuated, refracted, or reflected.

Refraction and reflection cause the signals to change direction of propagation. This change in path directions often results in a convergence of the direct path signal with one or more of the reflected signals. When the receiving antenna is the point of convergence for these multipath signals, the consequences are generally not favorable.

Whenever a signal is refracted, some signal polarity shifting takes place. And when full reflection occurs, full polarity reversal results in the propagating wave. The consequences of signal polarity shifting and reversal at the receiving antenna vary from minor to significant. As well, refracted and reflected signals generally sustain some degree of signal amplitude attenuation.

Take, for example, some common occurrences we are all familiar with, such as commercial AM radio and television. Especially at night, it can be observed that AM radio signals "fade" in and out resulting in momentary loss of reception. Or in the case of television reception we see "ghost" images on the screen, or "flutter" when aircraft fly overhead. These are all effects of signal multipath. In the case of radio ranging systems, such as GPS, multipath reception can cause serious errors in the range measurements and thus position accuracy.

It is generally understood that, in multipath conditions, both the direct and reflected signals are present at the antenna. However, in some situations, the direct signal may be obstructed or greatly attenuated to a level well below that of the received multipath signal. Obstruction of direct path signals is very common in city environments where many tall buildings block the line of sight to the satellites. As buildings generally contain an abundance of metallic materials, GPS signal reflections are abundant (if not overwhelming) in these settings. Obstruction of direct path signals can occur in wilderness settings as well. If the GPS receiver is in a valley with nearby hills, mountains and heavy vegetation, signal obstruction and attenuation is also very common.

Consequences Of Multipath Reception

When a GPS multipath signal converges at the GPS antenna, there are two primary problems that occur:

1) a multiple signal with amplitude and phase shifting

2) a multiple signal with differing ranges.

1) Earlier it was mentioned that receiving antennae need to be polarized to match that of the transmitted signal – in the case of GPS, right hand circular polarization (RHCP). The problem arises that when the multipath signal reverses polarity (to left hand or LHCP), the direct and reflected signals will cancel each other when induced at the receiving antenna. The amount of signal cancellation varies with the degree of signal polarity shift and relative amplitude of the direct vs. multipath signal. On the other hand, if the multipath signal converges at the antenna inphase (through multiple reflections), the induced direct and multipath signals will actually sum together causing the receiver signal to significantly increase in amplitude. This inphase and out-of-phase signal reception can play havoc with the receiver automatic gain control circuitry (AGC) as it struggles to maintain constant signal levels for the receiver correlator.

2) Because a multipath signal travels a greater distance to arrive at the GPS antenna, the two C/A code correlations are, by varying degrees, displaced in time, which in turn causes distortion in the correlation peak and thus ambiguity errors in the range measurements.

As mentioned in the previous subsection, it is possible that the received multipath signal has greater amplitude than the direct path signal. In such a situation the multipath signal becomes the dominant signal and receiver pseudorange errors become significant due to multipath biases and may exceed 150 metres.

In single point positioning, the biases caused by multipath are not generally of great concern. Largely, this is because single point nominal positioning accuracies are influenced by a wide range of systematic biases that limit repeatable accuracies to about 100 metres CEP. The sources of these biases can be attributed to:

- Satellite orbit prediction
- Satellite clock drift
- Selective Availability (SA)
- Ionospheric delay
- Tropospheric delay
- Receiver clock offset
- Signal multipath

The majority of the above biases can be cancelled if pseudorange differential techniques are incorporated. When real-time differencing techniques are used, nominal accuracies of about 5 metres CEP (standard correlators) and about 0.75 metre CEP with NovAtel's Narrow Correlator tracking technology are easily achievable. (These figures assume a relatively low multipath environment and using a multipath reduction antenna choke ring).

However, multipath is one bias that is normally uncorrelated between the monitor and remote differential stations antennas (especially under kinematic situations) due to unknown or complex signal multipath occurrences. Now, with pseudorange C/A code differential accuracies achievable in the one to five metre range, multipath becomes a major concern, and may significantly bias users' position accuracy expectations.

Further to this discussion, when pseudorange and carrier phase double differencing techniques are used, biases are further reduced to achieve accuracies below 20 cm CEP range (such as with NovAtel's RT-20 technology). But once again, multipath is a major obstacle in maintaining these accuracies with certainty.

If a differential monitor station is subject to significant multipath conditions, this in turn will bias the range corrections transmitted to the differential remote receivers. And in turn, if the remote receivers also experience a high level of multipath, the remote receiver position solutions will be significantly biased by multipath from both stations.

Some Hardware Solutions For Multipath Reduction

A few options exist by which GPS users may reduce the level of multipath reception. Among these include: antenna site selection, special antenna design, and ground plane options.

Antenna Site Selection

Multipath reception is basically a condition caused by environmental circumstances. Some of these conditions you may have a choice about and some you may not.

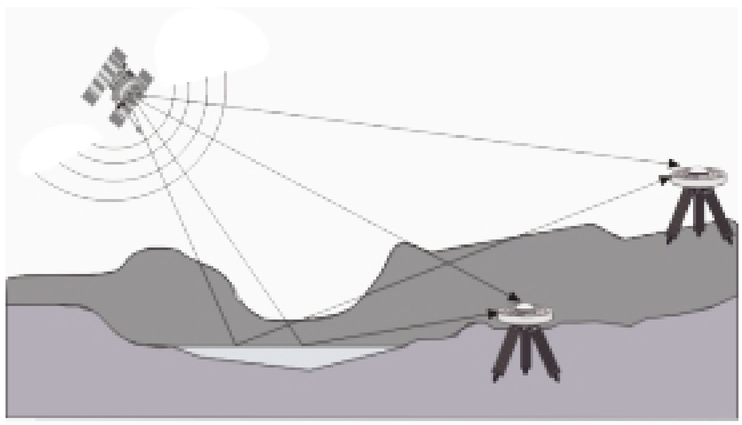
Many GPS reception problems can be reduced to some degree by careful antenna site selection. Of primary importance is to place the antenna so that unobstructed line-of-sight reception is possible from horizon to horizon and at all bearings and elevation angles from the antenna. This is, of course, the ideal situation, which may not be possible under actual operating conditions.

Try to place the antenna as far as possible from obvious reflective objects, especially reflective objects that are above the antenna's radiation pattern horizon. Close-in reflections will be stronger, and typically have a shorter propagation delay allowing for autocorrelation of signals with a propagation delay of less than one C/A code chip (300 m).

When the antenna is in an environment with obstructions and reflective surfaces in the vicinity, it is advantageous to mount the antenna as high as possible to reduce the obstructions and should be placed above reflective surfaces as much as possible.

Water bodies are extremely good reflectors of RF signals and are most troublesome for reception of low angle satellites. The best solution here is to avoid these locations. However, for marine vessels, that is not a viable solution, and the water reflections are a source of constant multipath errors.

Figure 2 Illustration of GPS Signal Multipath vs. Increased Antenna Height



Antenna Designs

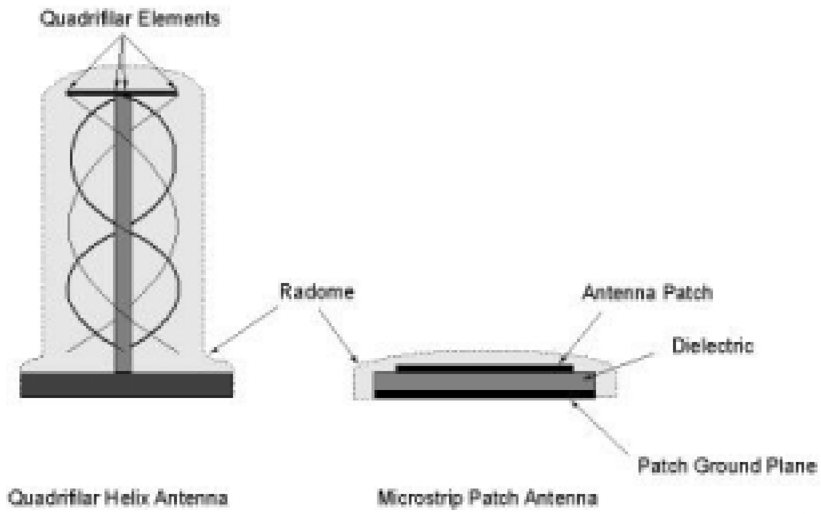
Low angle reflections, such as from water bodies, can be reduced by careful selection of the antenna design. For example, flat plate microstrip patch antennas have relatively poor reception properties at low elevation angles near their radiation pattern horizon.

Quadrifilar helix antennas and other similar vertically high profile antennas tend to have high radiation gain patterns at the horizon. These antennas, in general, are more susceptible to the problems resulting from low angle multipath reception. So, for marine vessels, this type of antenna encourages multipath reception. However, the advantages of good low angle reception also means that satellites can be acquired more easily while rising in the horizon. As well, vessels subject to pitch and roll conditions will experience fewer occurrences of satellite loss of lock.

A good antenna design will also incorporate some form of left hand circular polarization (LHCP) rejection. Multipath signals change polarization during the refraction and reflection process. This means that generally, multipath signals may be LHCP oriented. This property can be used to advantage by GPS antenna designers. If a GPS antenna is well designed for RHCP polarization, then LHCP multipath signals will automatically be attenuated somewhat during the induction into the antenna. To further enhance performance, antennas can be designed to increase the rejection of LHCP signals. NovAtel's GPSAntenna model 501 is an example of an antenna optimized to further reject LHCP signals by more than 10 dB.

The Model 600 GPSAntenna is an active antenna designed to operate at the GPS L1 and L2 frequencies, 1575.42 and 1227.60 MHz. The microstrip receiving elements are coupled to filters and a low-noise amplifier (LNA). The unit is optimized to receive right-hand-circularly-polarized signals, and its radiation pattern is shaped to reduce signals arriving at low elevation angles; these features decrease the errors associated with electromagnetic interference and multipath. Also, the model 600 roll-off compares well to a patch antenna roll-off mounted on a large choke ring ground plane. This antenna has a major advantage above the choke ring ground plane antenna - it is lighter by several pounds and much smaller.

Figure 3 Illustration Of Quadrifilar vs. Microstrip Patch Antennae



<u>Antenna Ground Planes</u>

Nearby objects can influence the radiation pattern of an antenna. Thus, one of the roles of the antenna ground plane is to create a stabilizing artificial environment on which the antenna rests and which becomes a part of the antenna structure and its resultant radiation pattern.

A small ground plane (relative to one wavelength at the operating frequency) may have minimal stabilizing effect, whereas a large ground plane (multiple wavelengths in size) will have a highly stabilizing effect.

Large ground planes also exhibit a shielding effect against RF signal reflections originating below the antenna's radiation pattern horizon. This can be a very effective low angle shield when the antenna is elevated on a hill or other structure above other reflecting surfaces such as vehicles, railway tracks, soil with high moisture content, water bodies, etc.

One of the drawbacks of a "flat plate" ground plane is that it gives a "hard boundary condition", ie. allowing electromagnetic waves to propagate along the ground plane and diffract strongly from its edge. The "soft boundary" condition, on the other hand, will prevent the wave from propagating along the surface of the ground plane and thereby reducing the edge diffraction effects. As a result the antenna will exhibit a completely different radiation pattern. The "soft boundary" condition is typically achieved by a quarter wavelength deep, transversely corrugated ground plane surface (denoted as "choke ring ground plane"). When the depth of the corrugation (choke rings) is equal to a quarter wavelength, the surface wave vanishes, and the surface impedance becomes infinite and hence provides the "soft boundary" condition for the electromagnetic field. This results in modifications to the antenna radiation pattern that is characterized by low back lobe levels, no ripples in the main lobe, sharper amplitude, roll-off near the horizon and better phase center stability (there are smaller variations in 2 axes). This is what makes NovAtel's GPS antennas so successful when used with the NovAtel GPSAntenna choke ring ground plane.

NovAtel's Internal Receiver Solutions For Multipath Reduction

The multipath antenna hardware solutions described in the previous paragraphs are capable of achieving varying degrees of multipath reception reduction. These options, however, require specific conscious efforts on the part of the GPS user. In many situations, especially kinematic, few if any of the above solutions may be effective or even possible to incorporate. By far, the best solutions are those which require little or no special efforts in the field on the part of the GPS user. This is what makes internal receiver solutions so desirable and practical.

NovAtel has placed long term concerted effort into the development of internal receiver solutions and techniques that achieve multipath reduction, all of which are transparent to the GPSCard user. These achievements have led to three patented technologies:

- Narrow Correlator® tracking technology
- MET
- MEDLL

Each of the above listed solutions utilizes innovative correlator delay lock loop techniques. As the correlator is the heart of the GPS receiver C/A code tracking loop, further discussions on the correlator are provided to give just enough background to grasp the basic concepts of NovAtel's Narrow Correlator tracking technology, MET, and MEDLL multipath reduction technologies.

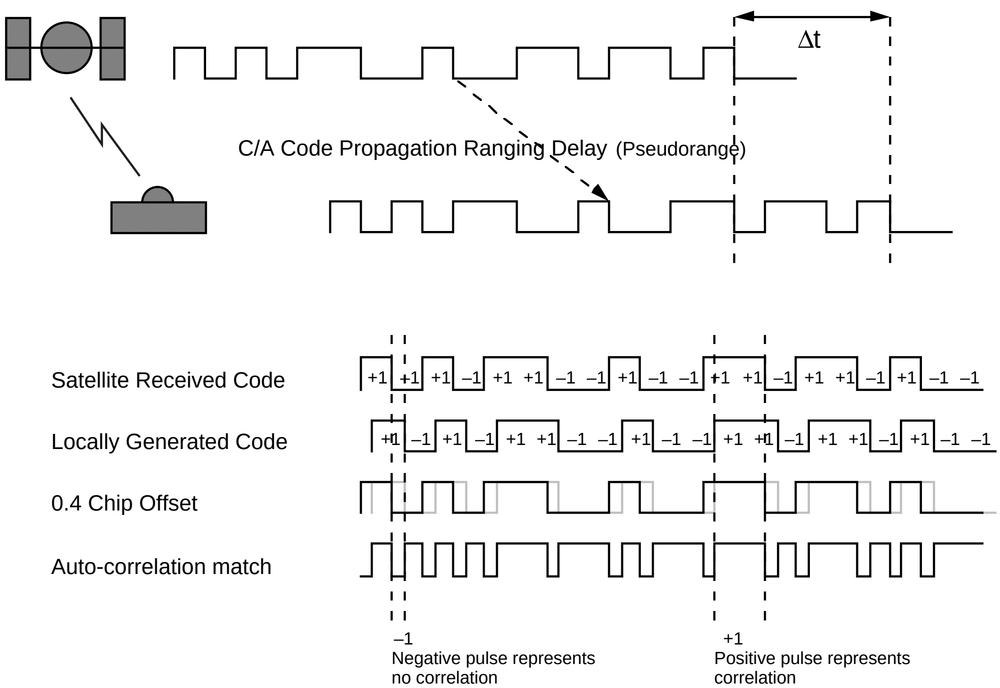
The Role of the GPS Receiver Correlator

Each GPS satellite transmits a unique pseudorandom noise (PRN) C/A code (coarse/acquisition) and P code (precision). As the P code is generally for military and special authorized use only, it is denied general access by means of "anti-spoofing" (A-S), which is an encryption of the P code and referred to as the Y code. (As commercial GPS users are generally restricted to C/A code use, this discussion is limited to C/A code.)

The C/A code has a clocking rate (chipping rate) of approximately 1.023 MHz. This chipping rate causes the GPS RF signal to have a main lobe (90% power) spread spectrum of approximately 2.046 MHz. As each satellite transmits on the same L1 carrier frequency, they are differentiated only by their respective PRN codes.

To receive each GPS satellite PRN signal, the earth station receivers have C/A code generators that can match each of the satellite PRN codes. As well, the internal code generator must be clocked at a chipping rate that is as close as practical to that of the satellite's clock. It is in the "matching" of the individual received C/A codes against those generated by the local receiver code generator that the ***correlator*** becomes of crucial importance. As the name "correlator" implies, it must be able to "correlate" a match between two PRN codes. Unless correlation can be achieved, the received signals only appear as random noise.

Figure 5 Example of C/A Code Correlation

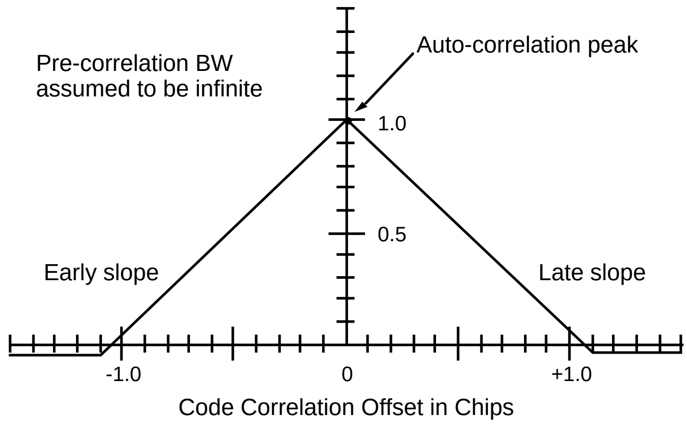


The GPS receiver measures its distance from each satellite by measuring the time it takes the GPS signal to propagate from the satellite to the receiver antenna. The GPS receiver determines its position by means of trilateration of the range measurements of at least four measured satellite ranges. The receiver's ability to accurately correlate and phase lock on each PRN code directly influences the accuracy of the receiver's range measurements accuracy, which in turn affects the accuracy of the computed position. NovAtel's GPSCard has twelve parallel channels that can simultaneously correlate and track up to 12 satellites.

<u>The Autocorrelation Function</u>

The ideal GPS receiver would have an infinitely wide receiver BW which would allow the receiver to capture 100% of the GPS spread spectrum signal. The normalized autocorrelation function for an infinately wide BW is generally illustrated as shown in Figure 6 below.

Figure 6 Theoretical Normalized Auto-correlation Function



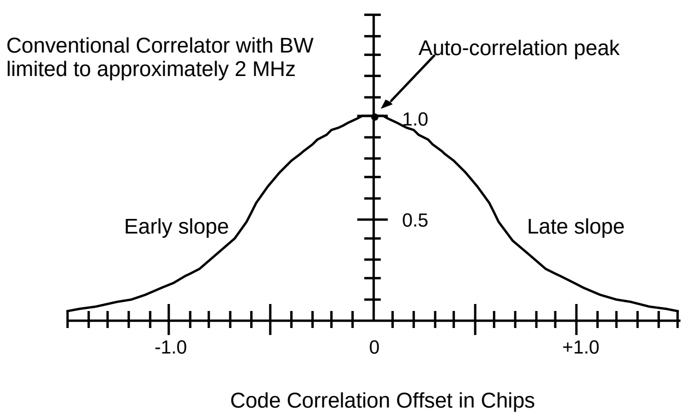
The auto-correlation peak is maintained by continually adjusting the locally generated code for peak correlator output. The unlimited BW provides a sharp correlation peak and steep early/late slope which facilitates accurate error correction for the code-lock-loop (also called Delay Lock Loop).

In reality, a GPS receiver would need a brick wall bandpass filter with a BW of at least ten times the code C/A code chipping rate to be capable of capturing > 99% of the GPS spread spectrum signal. For most GPS receivers this is generally not practical to achieve.

<u>The Standard Correlator</u>

For most general purpose GPS receivers a 2.046 MHz BW is easier to achieve and is typically adequate to capture approximately 90% of the GPS C/A code spread spectrum RF signal. However, this BW limiting has its tradeoffs which causes rounding of the autocorrelation function. The narrower the receiver BW, the greater will be the rounding of the correlation function. Figure 7 below illustrates the degree of autocorrelation rounding and flattening at the peak caused by 2 MHz BW limiting.

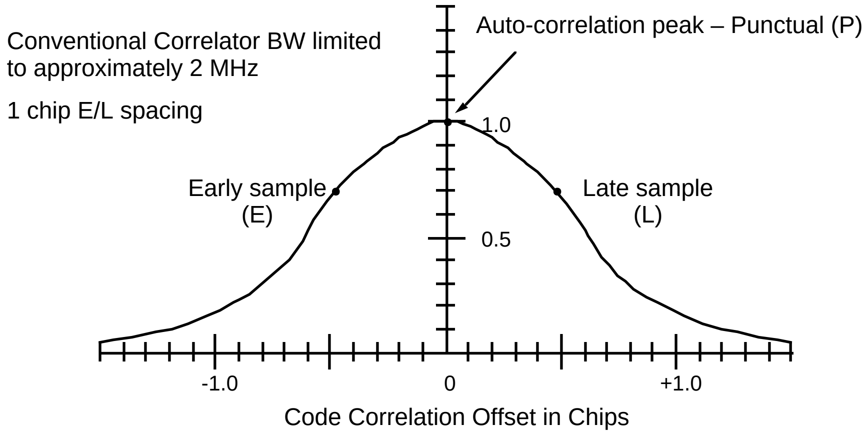
Figure 7 Typical Bandwidth Limited Correlation Function



There are various problems associated with single correlator sampling, especially for a 2 MHz BW limited receiver as illustrated in Figure 7 above. As can be seen, the BW limited correlation function is almost flat at the peak. This creates "wandering" at the peak resulting in significant ambiguity in determining the actual correlation peak as well as sensing the early/late slope for error correction. This correlation ambiguity directly translates into range measurement ambiguity.

To help reduce the correlation peak ambiguity, one commonly adopted solution is to utilize three correlation samples per satellite channel (called Punctual, Early, and Late). The Early (E) and Late (L) correlators are generally spaced 1 chip apart from each other, while the Punctual (P) is centred between them (P - 0.5 chip = Early, and P + 0.5 chip = Late).

Figure 8 Standard Correlator with Punctual, Early and Late Correlator Sampling (PEL)



As the E and L correlator samples are spaced 1 chip apart, this places them on the steepest part of the autocorrelation E and L slopes. This placement provides greater sensitivity to changes in the correlation delay-lock-loop (DLL). The E and L samples are differenced to create the appropriate DLL loop feedback for maintaining code lock. Thus, when the E-L difference is zero, the P correlation will be at its peak.

This correlator technique is generally referred to as a "Standard Correlator" and is the most common method in use (especially with low-cost general accuracy receivers). Because of its relatively flat correlation peak combined with the wide E-L sample width, Standard Correlators tend to be highly susceptible to multipath correlation distortion which may significantly skew the correlation function, thus resulting in skewed position solutions.

Standard Correlator spacing can typically achieve C/A code range measurement accuracies of 100 cm RMS (not including multipath bias). A high multipath environment can potentially skew the ranges by as much as 80 metres.

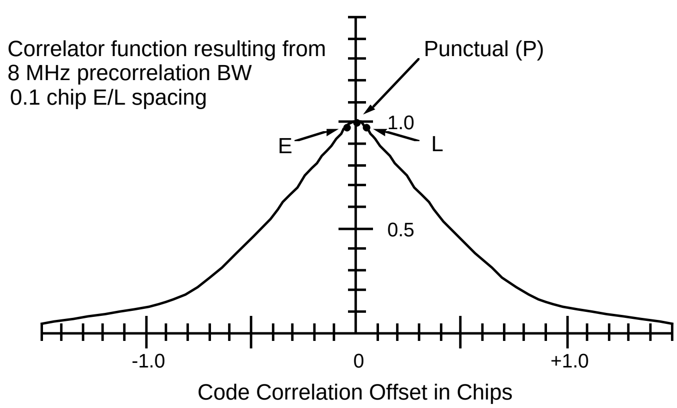
When used in differential mode, the Standard Correlator receiver can achieve nominal position accuracies of two to five metres CEP (low multipath environment) while using a multipath reduction antenna choke ring ground plane. However, once again, in a high multipath environment, this level of position accuracy may be significantly degraded.

The Narrow Correlator Tracking Technology

NovAtel has patented a correlation technique, which sharpens the autocorrelation peak and narrows the Early and Late spacing from 1 chip to 0.1 chip.

A sharper correlation peak is achieved by broadening the receiver BW while using a filter with flat response over the pass-band and sharp cutoff rejection for out-of-band signals. The broader BW allows the receiver to capture a greater portion of the GPS signal spread spectrum. This increased BW reduces the amount of receiver-induced distortion on the GPS C/A code, which in turn allows for more accurate correlation. As well, a high sampling frequency of approximately 20 MHz contributes to the narrow correlator's performance.

Figure 9 Example of Narrow Correlator Sampling (PEL)



NovAtel's Narrow Correlator tracking technology is "dynamically adjustable". This means that the correlator spacing is initially wide for fast acquisition and reacquisition purposes (1 chip spacing), followed by a narrowing down to 0.1 chip spacing for higher accuracy tracking and multipath rejection.

The advantages of Narrow Correlator tracking technology are substantial over the Standard Correlator. Because of the narrower correlation peak and narrower correlator spacing, there is less floating or ambiguity about the correlation peak resulting in greater code correlation accuracy and stability. This directly translates into less noisy and more accurate range measurements. As well, the Narrow Correlator tracking technology achieves less susceptibility to multipath signals that arrive with delays of greater than the 0.1 chip E-L spacing.

Because of the sharper correlator peak combined with the smaller 0.1 chip E-L spacing, the Narrow Correlator tracking technology can achieve C/A code range measurement accuracies of 10 cm rms. This is a ten fold gain over the Standard Correlator. However, multipath can still bias these measurements by as much as 10 metres.

The benefits of operating NovAtel's Narrow Correlator tracking technology receiver in single differencing DGPS mode results in position accuracies of 0.75 metre CEP (low multipath environment) while using a multipath reduction antenna choke ring ground plane. This yields significant accuracy improvement over the Standard Correlator.

Narrow Correlator vs. Multipath

The Narrow Correlator tracking technology is inherently less susceptible to multipath correlation biases than the Standard Correlator, by virtue of the 0.1 chip E-L sampling. This does achieve improvements in the C/A code pseudorange measurements, but does little for the reduction of carrier phase multipath biases.

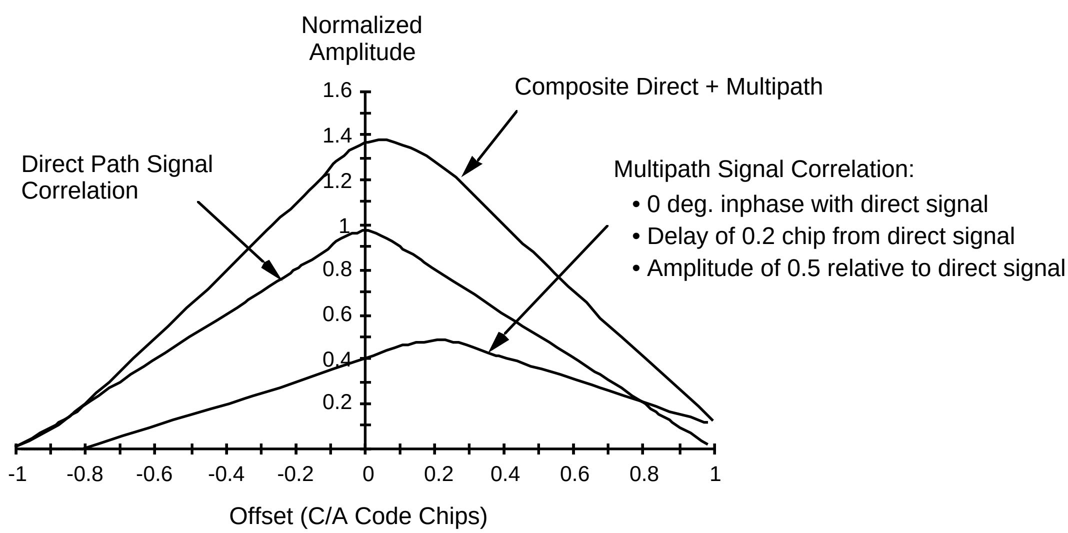
Under high multipath conditions, Narrow Correlator tracking technology range measurements can be skewed by as much as 10 metres. This is why the GPSAntenna model 501 and choke ring ground plane are still recommended for maximum Narrow Correlator performance.

For the remainder of the discussions in this document about multipath, assumptions will be made concerning the characteristics of the received GPS signals and the GPS receiver being used:

- that the direct path and multipath signals are both being received;
- that the multipath signal is assumed to be weaker than the direct path signal;
- multipath signal delays of less than 1 code chip are of greatest concern, and delays greater than 1 code chip are of little or no consequence.

If the autocorrelation graph of the direct path and multipath signals are simultaneously represented and then combined, the results can be illustrated in Figure 10 below.

Figure 10 Direct Path, Multipath (InPhase), and Resultant Correlation Function

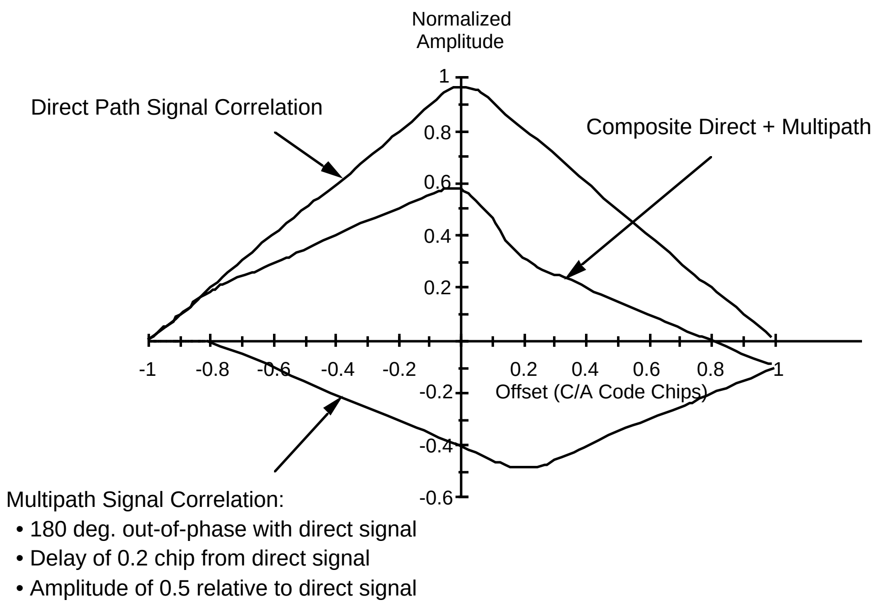


In this example, the multipath signal has a delay of 0.2 chips, an amplitude of 0.5 relative to the direct path signal, and is inphase with the direct path signal. As can be seen by the composite correlation, signal magnitude increases, and more importantly, distortion of the autocorrelation curve results. The distortion of the autocorrelation curve skews the E-L sampling and thus the Punctual resolution, resulting in tracking errors.

It should be noted that inphase multipath signals typically result from an even number of reflections. If we recall that any time a signal is reflected, it will experience polarity reversal. Therefore, the GPS multipath signal must undergo two reflections to arrive at the antenna inphase with the direct path signal. (It is assumed that 180 degree phase shift results from each reflection; however, lower angles of incidence will result in something less than 180 degrees.)

Figure 11 below illustrates the effects on autocorrelation when the multipath signal is 180 degrees out-of-phase with the direct path signal.

Figure 11 Direct Path, Multipath (Out-of-Phase), and Resultant Correlation Function

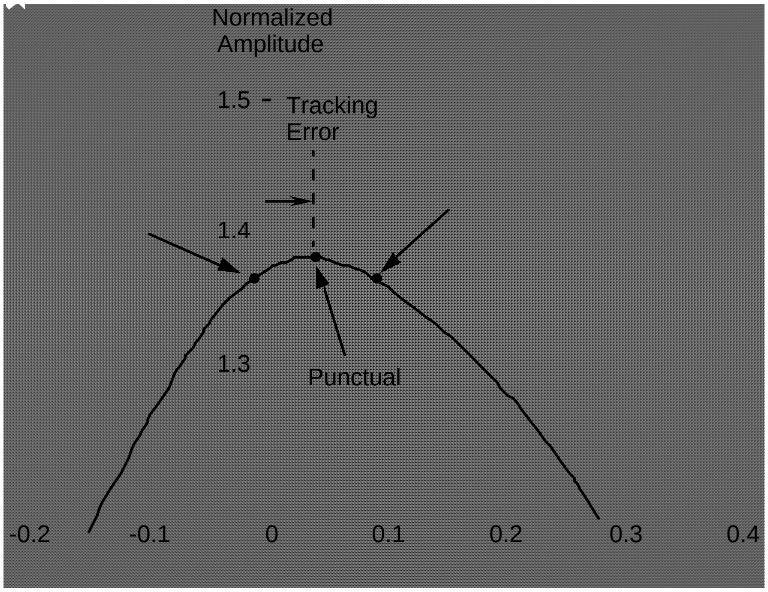


For signals arriving 180 degrees out-of-phase, distortion of the autocorrelation function can be even more substantial than for inphase multipath signals. It should also be noted that multipath signals arriving at the antenna 180 degrees out-of-phase are generally the result of a single reflection or odd multiple of reflections. Obviously, single reflections are of greatest concern because these will generally have greater amplitude and less propagation delay than multiple reflection signals (recalling that delays of less than one chip are of greatest concern).

Another problem with 180º out-of-phase multipath signals is that they directly cancel out the direct path signal. This can cause substantial reduction and distortion to the autocorrelation function, or even cause loss of lock in the receiver tracking loops.

Figure 12 below further illustrates the effects of multipath to the autocorrelation function on a normal dot-product or early minus late delay-lock-loop (DLL). As a normal DLL is designed to feedback to the hardware in such a way as to keep the power of the early and late correlators equal, a distorted correlation function will bias this process.

Figure 12 Tracking Error Due to Multipath



The above paragraphs have briefly covered the performance gains of the Narrow Correlator tracking technology referenced against Standard Correlator code tracking techniques. It has been discussed and illustrated that NovAtel's Narrow Correlator tracking technology is capable of significant performance improvement over the Standard Correlator. However, multipath continues to be the dominant limiting factor in the accuracy performance of the Narrow Correlator tracking technology when used in single-differencing DGPS modes of operation. Maximum performance of the Narrow Correlator receiver can be achieved when combined with NovAtel's model 501 GPSAntenna mounted on the NovAtel choke ring ground plane.

MET™ Overview

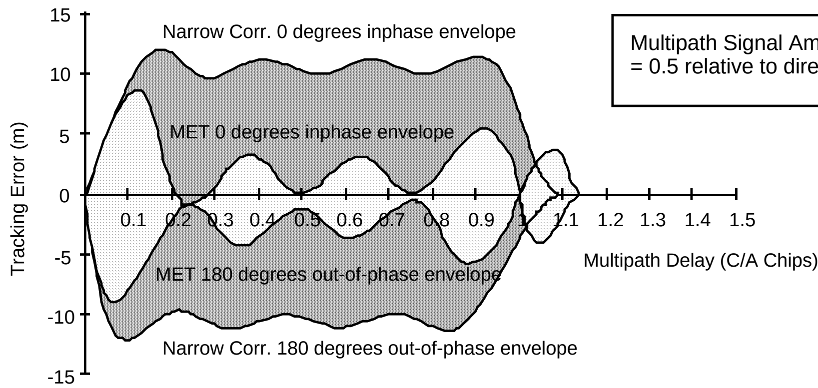
It has been recognized that the use of a choke ring ground plane is highly effective in reducing reception of low angle multipath signals However, installation and usage of the choke ring is not always practical (or desirable) for many types of installations such as on aircraft and other high dynamics types of installations. To alleviate the necessity of a choke ring ground plane, NovAtel has developed a new technology called MET (Multipath Elimination Technology). MET is currently available as the "M" option to the GPSCard Series.

MET is a further enhancement of NovAtel's Narrow Correlator tracking technology whereby multiple correlators are spaced symmetrically, as closely as possible, at the top of the correlation peak. By means of software manipulation, the multiple correlator samples are used to model the shape and slope (Early and Late slopes) near the peak of the direct path correlation function, and thus model out the multipath distortions.

In practice, a GPSCard utilizing MET technology can typically achieve multipath error reductions of up to 50% and does not require the use of a GPSAntenna choke ring ground plane. This 50% multipath error reduction will provide significant confidence improvement and flexibility when used at both the monitor and remote DGPS stations.

Refer to Figure 13 for an illustration of comparisons between multipath error envelopes between NovAtel's Narrow Correlator tracking technology and MET.

Figure 13 ***Multipath Error Envelopes for Narrow Correlator vs. MET***



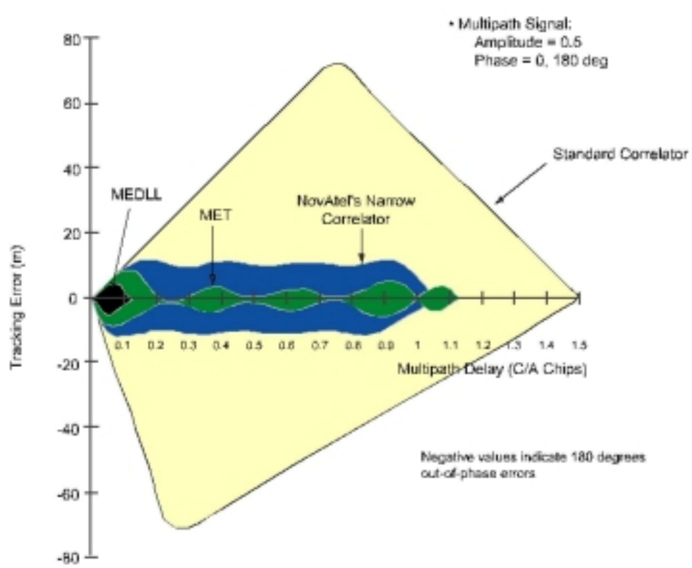
MEDLL™ Overview

NovAtel has developed a multipath reduction technology that approaches the theoretical limits of multipath-free GPS signal reception. This new patented technology, called "Multipath Estimation Delay-Lock-Loop" (MEDLL), utilizes a combination of hardware and software techniques that are capable of reducing the combined effects of pseudorange multipath errors by as much as 90% compared to a system using a Narrow Correlator. As well, MEDLL does all this *without* the need to mount the antenna on a choke ring ground plane.

The MEDLL technology takes further advantage of NovAtel's parallel channel Narrow Correlator sampling techniques. It is unique in that it utilizes an "array" of narrowly-spaced correlators distributed about the autocorrelation function whereby each satellite tracking channel is sampled by a dedicated correlator array. Currently, MEDLL is a 12 channel receiver (configuring for more channels is possible). This array distribution of correlator sampling allows the receiver to measure the shape of the received correlation function. Using a "maximum likelihood estimation" technique, MEDLL deconvolves the received signals into their direct path and multipath components by determining the amplitude, delay, and phase angle of each of the composite signals. Once the composite signal has been broken down into its components, the signal with the least delay is determined to be the direct signal, and all other signals with greater delay are considered to be the multipath components (assuming the direct path signal is available and unobstructed).

MEDLL can effectively remove all multipath signals that have a propagation delay of greater than 0.1 chip relative to the direct path signal. The remaining multipath effect on the C/A code pseudorange measurements is now in the same order of magnitude as a P code GPS receiver.

Figure 14 ***Multipath Error Envelopes for Narrow Correlator vs. MET vs. MEDLL***



Conclusion

It has been discussed in this paper that the influences on radio wave propagation depend on the frequency and propagation mediums through which the RF signal travels. UHF signals such as GPS are highly susceptible to reflections because of the short wavelengths at the L1 channel. As GPS is a radio navigation ranging system, the direct path signal is of primary interest. Any propagation delays or multipath reception causes biases to the ranging measurements that cannot be differenced by traditional DGPS single differencing techniques. Multipath is the greatest source of errors to a system operating in single differencing mode. It has been concluded that careful site selection and the GPSAntenna model 600, or good antenna design combined with a choke ring ground plane are very effective in reducing multipath reception.

The role of correlators was discussed to provide some insight into how multipath influences the correlation function required for satellite tracking and ranging. This led to the advantages of using a Narrow Correlator™ tracking technology versus the Standard Correlator and how this relates to reductions in pseudorange multipath biases. It was then discussed how MET™ technology is an enhancement of the Narrow Correlator tracking technique used by the GPSCard that provides up to 50% multipath reduction without the need of an antenna choke ring ground plane.

Finally, the topic of MEDLL™ was discussed to describe a multi-correlator array technology whereby a multi-card system is used to sample the multipath signals as well as the direct path signals, recognizing the difference between them, then rejecting the multipath signals, leaving only the desired direct path signal. MEDLL is the most effective receiver technology available that reduces the combined effects of GPS L1 C/A code and carrier phase multipath by as much as 90% (without the need for a choke ring ground plane).

References

- "Theory and Performance of Narrow Correlator Spacing in a GPS Receiver" – by A.J. Van Dierendonck, Pat Fenton, and Tom Ford
- "A Practical Approach to the Reduction of Pseudorange Multipath Errors in a L1 GPS Receiver" – by Bryan Townsend and Patrick Fenton
- "A Multipath Estimating Delay Lock Loop: Approaching Theoretical Accuracy Limits", – by Richard D.J. van Nee, Jaap Siereveld, Patrick C. Fenton, and Bryan R. Townsend.

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