Range Biases on the WAAS Geostationary Satellites

R. Eric Phelts, Todd Walter, Per Enge, *Stanford University*
Dennis M. Akos, *University of Colorado*
Karl Shallberg, Tom Morrissey, *Zeta Associates, Inc.*

ABSTRACT

Due to limited receiver bandwidth and tracking configuration differences, measurements made on a narrowband geostationary satellite signal may differ significantly from those made on GPS signals and result in relatively large range bias errors for users. Modeling and analysis of this net effect is complicated by several parameters including a wide range of allowed GEO signal correlator spacings (relative to GPS for both the reference and user receivers). Further, the differential group delays of the reference receivers, user receivers, and GEO signal itself play a significant role in the magnitude of this effect. The result is that a narrowband GEO signal appears distorted relative to wideband GPS signals.

This paper describes the history and identification of the GEO bias problem in WAAS and its current remedy. The paper models several filters and identifies the differential group delay as the key cause of this distortion. It then analyzes the effects of differential group delay on correlation functions and provides supporting analysis using actual filter models and live signal data processed in real GPS receivers. Finally, this paper provides estimates on ranging performance for future (wideband) GEOs and offers recommendations on receiver configurations designed to minimize this bias error.

INTRODUCTION

The Wide Area Augmentation System (WAAS) was declared operational in July of 2003. It uses a network of 25 reference stations at known locations to correct for errors in GPS satellite ranging. It then broadcasts the corrections to WAAS users via two Inmarsat geostationary satellites (GEOs). In addition to using the GEOs as datalinks, WAAS also uses them as additional ranging sources. Despite this dual intention, the GEOs have proven less accurate than GPS satellites as ranging sources.

There are several differences between GPS and GEO signals. First, the civilian GPS signal is approximately 20MHz (or more) wide while the current GEO signals are only 2.2MHz. Second, the GEO signals are at relatively low elevation angles (between 9° and 30°) to most users in CONUS and are effectively stationary. Both of these factors make multipath mitigation significantly more challenging for GEO signals.

Biases noted on GEO signals are often attributed to multipath. The "unobservable bias," measured on GEO range residuals from receiver to receiver (at WAAS reference stations) was attributed to standing-wave multipath. As a result, WAAS currently adds a penalty of 5m to every GEO range measurement. This penalty increases the GEO UDRE and reduces availability for certain geometries where an additional satellite would be most useful.

Further investigation of this WAAS "unobservable bias" along with Signal Quality Monitoring (SQM) research has instructed that differences in the structure of the GEO signal relative to GPS must also cause a bias for some users[2]. Any additional ranging source not identical to the GPS signals will appear as a deformed signal and can potentially create a bias in the receiver. The size of the bias will depend on the specifics of a receiver's pre-correlation filter and tracking loops. This bias will not be a common mode; it will not be removed by (i.e., included with) the clock term in the navigation solution.

BACKGROUND

Figure 1 shows the power spectra for both a GPS signal (PRN03) and a GEO signal. They are appreciably different, and they cause different distortions of correlation peaks as a result of the filtering differences in their respective transmission paths. As a result, both user and reference receivers are susceptible to biases that differ as a function of their receiver configurations.

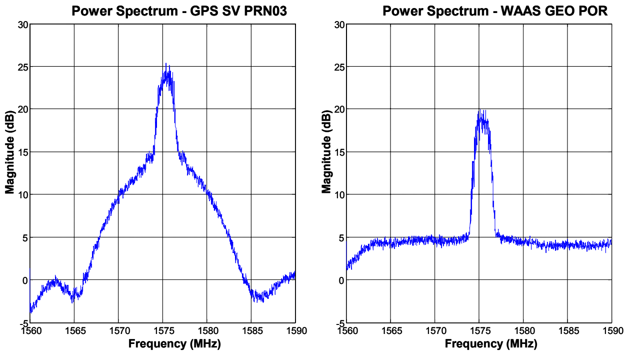

FIGURE 1. The power spectrum of GPS PRN03 and an Inmarsat GEO signal. The GPS signal bandwidth exceeds 20MHz while the GEO signal is bandlimited to 2.2MHz. (Note that since no AGC was used, differences in noise floor levels result from GPS/GEO signal power differences.)

The WAAS Minimum Operational Performance Standards (MOPS) attempt to ensure user receivers do not experience large biases on GEO (and GPS) pseudoranges, however, it does so in the absence of specific knowledge of these effects. Specifically, the MOPS accuracy specification (Section 2.1.4.1.3) states that the RMS of GEO residuals must be below 1 meter at maximum signal power. Since simulators may be used during testing and validation, however, biases caused by filter effects may be discounted as ordinary interchannel biases. (Refer to Section 2.5.8.2.1 of the WAAS MOPS. [1]) Alternatively, one test receiver may give satisfactory performance while another (untested) receiver of the same type, may have substantially different group delay characteristics, due to manufacturing tolerances, and fail to meet the specification.

ANALYSIS

The group delay is the negative derivative of the phase response of a filter. (See Equation 1.) It is measured in units of time (e.g., nanoseconds) and indicates the amount of time delay or shift of a signal as a function of the frequency component of that signal. Differential group delay (sometimes referred to as peak-to-peak group delay ripple), refers to the variation of the group delay response over the 3dB passband (or bandwidth, *BW*) of a filter. (See Equation 2.) Note that these definitions utilize both time domain and frequency domain references. As a result, it is sometimes difficult to visualize the effects that a filter's group delay response may have on GPS signal tracking and, more specifically, correlation peaks. However, a non-zero differential group delay response generally creates correlation peak distortion since it causes the peak to become non-symmetric.

$$\mathrm{T}_{\mathrm{Gd}}(\omega) = \mathrm{grd}\left[H_{pre}\left(e^{j\omega}\right)\right] = -\frac{d}{d\omega}\left\{\arg\left[H_{pre}\left(e^{j\omega}\right)\right]\right\} \qquad (1)$$

$$d\mathrm{T}_{\mathrm{Gd}}(\omega) = \mathrm{T}_{\mathrm{Gd}}(\omega) - \mathrm{T}_{\mathrm{Gd}}(\omega_c), \quad \omega_c - \pi(BW) \le \omega \le \omega_c + \pi(BW) \qquad (2)$$

In the above equations, $\omega = 2\pi f$, ω_c is the filter center frequency in radians per second, and BW is the filter 3dB-bandwidth in Hertz.

A better intuition for group delay effects may be gained by forming a signal approximation that directly relates both frequency and time domain components. Accordingly, the correlation function for a GPS signal may be approximated by an appropriately-weighted sum of sine and cosine functions using a Fourier series expansion. The form of this expansion is well-known and is given by Equation 3 below.

$$F(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left[a_n \cos\left(\frac{n\pi x}{L}\right) + b_n \sin\left(\frac{n\pi x}{L}\right)\right] \qquad (3)$$

where

$$a_n = \frac{1}{L}\int_{-L}^{L} F(x)\cos\left(\frac{n\pi x}{L}\right)dx, \quad n = 0, 1, 2, 3, \ldots;$$

$$b_n = \frac{1}{L}\int_{-L}^{L} F(x)\sin\left(\frac{n\pi x}{L}\right)dx, \quad n = 1, 2, 3, \ldots$$

In the above equation, $2L$ is the waveform period, x is the incremental time step (fractional period) and n is the index number of the Fourier coefficients.

Using Equation (3) and letting $F(x) = R(x) = R(\tau)$, one may obtain an approximate correlation function ${}^{FS}R(\tau)$ defined for a total of $n = n_{\max}$ cosine and $n_{\max}$-1 sine functions. (Here, without loss of generality, $R(\tau)$ consists only of the in-phase components of the signal.) The frequency domain representation of ${}^{FS}R(\tau)$ is then completely determined by a sum of delta functions (whose amplitudes are given by a_n and b_n). The form of these individual functions is given below [3].

$$\cos(\omega_0 t) \xrightarrow{Fourier} \pi\left[\delta(\omega - \omega_0) + \delta(\omega + \omega_0)\right]$$

$$\sin(\omega_0 t) \xrightarrow{Fourier} j\pi\left[\delta(\omega + \omega_0) - \delta(\omega - \omega_0)\right]$$

Unlike the true correlation function, $R(\tau)$, the approximate correlation function is completely bandlimited; the magnitude of the energy of the spectrum is symmetric about the frequency $\omega = \omega_c$. For $\omega = \omega_c = 0$, Equation (3) implies a summation of positive and negative frequencies. Its maximum frequency can be found using $f_{\max} = f_{3dB} = \frac{n_{\max}}{2L}$ (again, using $f = \frac{\omega}{2\pi}$). To generate an approximate correlation function with a total (double-sided) bandwidth of 2.2MHz, let $n_{\max}$ equal 11 and let $2L$ equal 9.78µs. Then, the single-sided bandwidth, $f_{\max}$, equals 1.1MHz; ,

Now let the group delay response of the approximate correlation function be given by

$$\begin{aligned} \mathrm{T_{Gd}}(f) &= {}_0\mathrm{T_{Gd}}, & |f| \le f_{3dB}; \\ \mathrm{T_{Gd}}(f) &= {}_0\mathrm{T_{Gd}} + {}_0 d\mathrm{T_{Gd}}, & |f| > f_{3dB} \end{aligned} \qquad (4)$$

Then the correlation function is approximated by

$$F(\tau) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left[a_n \cos\left(\frac{n\pi(\tau + \mathrm{T_{Gd}})}{L}\right) + b_n \sin\left(\frac{n\pi(\tau + \mathrm{T_{Gd}})}{L}\right)\right] \qquad (5)$$

where, since no amplitude modifications are modeled, a_n and b_n remain as defined in Equation (3).

Intuitively, since ${}_0\mathrm{T_{Gd}}$ is uniform across all frequencies—and all $n_{\max}$ sinusoidal series approximation terms in Equation (5)—of interest, it will only cause a uniform shift in the peaks—both true and approximate. As a result, without loss of generality, this parameter can be neglected as it will not contribute to correlation peak distortion.

Also, observe that anti-symmetric differential group delay response profiles may also be neglected. Since *sine* is an odd function, Equations (3) and (5) imply that the addition of anti-symmetric sine terms will cancel. For example, when $f_c = 0$, and $|x| = {}_0 d\mathrm{T_{Gd}}$, the sine components of Equation (3) must be equal and opposite—each contributing one-half the total component energy—and only the cosine terms will contribute to the sum. At a center frequency, f_c, the following differential group delay condition would cause zero distortion in the resulting approximate waveform:

$$\begin{aligned} d\mathrm{T_{Gd}}(f) &= {}_0 d\mathrm{T_{Gd}}, & f \le f_c; \\ d\mathrm{T_{Gd}}(f) &= -{}_0 d\mathrm{T_{Gd}}, & f > f_c \end{aligned} \qquad (6)$$

Alternatively, (when $f_c = 0$) Equation (7) would result in an asymmetric correlation peak. Here, if α represents any real number not equal to -1, the net summation of the $n = n_{\max}$ sine components would be non-zero.

$$\begin{aligned} d\mathrm{T_{Gd}}(f) &= {}_0 d\mathrm{T_{Gd}}, & f \le f_c; \\ d\mathrm{T_{Gd}}(f) &= \alpha({}_0 d\mathrm{T_{Gd}}), & f > f_c \end{aligned} \qquad (7)$$

Using the Fourier Series approximations, the effects of non-zero group delays are clearly illustrated. Figure 2 compares an infinite bandwidth correlation peak to a symmetric, series-approximated peak (for $n_{\max}$=11) having $d\mathrm{T_{Gd}} = 0$ for all $n_{\max}$ terms. Also plotted is a series-approximated peak with $d\mathrm{T_{Gd}} = 200$ ns applied only at $f = f_{3dB}$. This implies that the only term to which a time shift was applied was for $n = n_{\max}$= 11. Observe that while the former peaks are symmetric, the latter is not. There is a slight offset in the true peak location corresponding to about 2.0 meters. This correlation peak asymmetry would lead to small range biases relative to the other peaks.

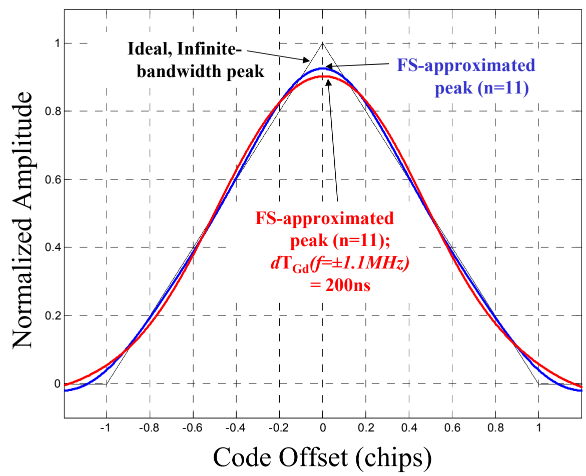

FIGURE 2. A comparison of an ideal, infinite bandwidth correlation peak (black trace) to two Fourier Series-approximated ones ($n_{\max}$=11)—one (blue trace) with a zero, constant group delay response and the other (red trace) with a 200ns differential group delay shift in only the maximum-frequency sinusoids (i.e., at $n = n_{\max}$=11). The non-zero differential group delay shift causes asymmetry in the latter.

Figure 3 shows the same three peaks for for $n_{\max}$=5. Here the effective bandwidth is only approximately 1MHz. This is smaller that is practical for most GPS receivers, however, in this example, the distorting effects of the group delay variations are much more apparent. A 50ns differential group delay—applied for the sine and cosine terms at $n = n_{\max}$=5—offsets the (absolute) peak by approximately 23meters. This correlation peak asymmetry would lead to large range biases relative to the other peaks.

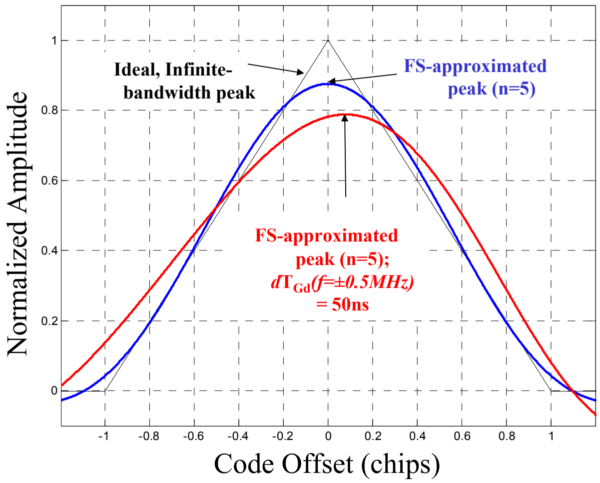

FIGURE 3. A comparison of an ideal, infinite bandwidth correlation peak (black trace) to two Fourier Series-approximated ones (n_{max}=5)—one (blue trace) with a zero, constant group delay response and the other (red trace) with a 50ns differential group delay shift in only the maximum-frequency sinusoids (i.e., at $n = n_{max}$=5). The non-zero differential group delay shift causes asymmetry in the latter.

Filter Types

Typical filters can be generally classified into two types. The first type, infinite-impulse response (IIR), have a group delay response profile that varies as a function of frequency. The second type, popular in digital implementations, have a finite-impulse response (FIR) and have a liner phase response and, hence, have a constant group delay over all frequencies. Accordingly, FIR filters are desirable since they have a differential group delay of zero and thereby preserve the symmetry of correlation peaks. IIR filters will introduce some degree of asymmetry into correlation peaks that will vary according to the magnitude and profile of the differential group delay.

Figure 4 shows the differential group delay profiles of both an IIR (6^{th}-order Butterworth) filter and a 50-tap, FIR (Hamming window) filter. Each filter was designed to have a 2.2MHz bandwidth centered at f_c=0. Note that the 6^{th}-order Butterworth (6oB) has a symmetric, non-zero differential group delay profile; Here, $T_{Gd} \approx 550\,\text{ns}$ (at $f = f_c$) and the maximum dT_{Gd} is nearly 400ns. For the FIR filter, however, $T_{Gd} \approx 244\,\text{ns}$ and $dT_{Gd} = 0$ over all frequencies. (This is true for all linear phase filters.)

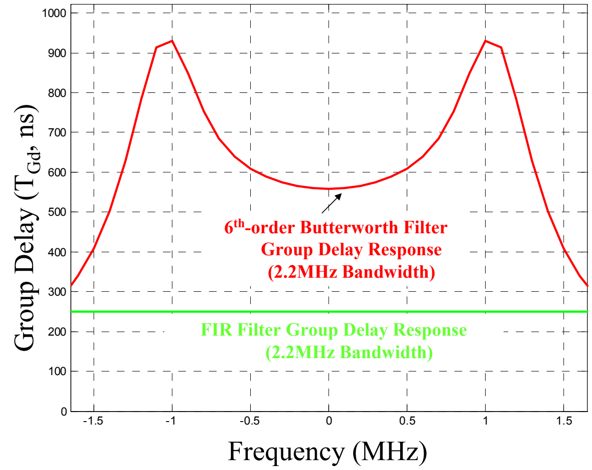

FIGURE 4. Comparison of the group delay responses of an IIR (red) and an FIR filter (green). Both filters have a 3dB bandwidth of 2.2MHz.

Figure 5 compares the correlation peaks filtered by each of these filter implementations to that of an ideal, infinite bandwidth peak. The peak approximation, ${}^{FS}R(\tau)$ (n_{max}=11), is shown once more for reference. The FIR filter, having group differential delay equal to zero, rounds the peak but still preserves peak symmetry. The 6oB filter causes a significant displacement in the location of the peak. Of course, in actual receivers, the measured peak location will vary as a function of receiver pre-correlation bandwidth an correlator spacing. However, it is this kind of asymmetry—introduced in varying degrees by all analog filters—that leads to GEO range biases in actual GPS receivers.

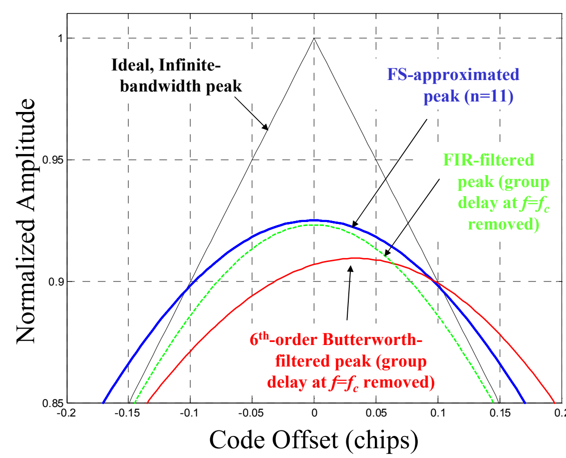

FIGURE 5. Comparison of correlation peaks filtered by an IIR (red) filter and an FIR filter (green). Both filters have a 3dB bandwidth of 2.2MHz. The infinite bandwidth peak (black) and the Fourier Series-approximated peak (in blue, n_{max}=11) with a zero, constant group delay response is also plotted for reference. The 6oB filtered peak is asymmetric and is 9.8m off-center.

VALIDATION

The preceding analysis modeled the ability of differential group delay variations to distort correlation peaks. However, WAAS originally used GEO pseudorange residual comparisons from receiver-to-receiver to measure the effect. This identified the presence of a bias, but did not isolate its cause.

These effects were experimentally demonstrated using actual GPS signal data. Figures 6 and 7 below show the power spectra and resulting correlation peaks for the GPS signal of PRN08. The signals were captured using a high-gain dish antenna. Consequently, there is very little distortion due to multipath and thermal noise. The signal was processed using a software radio GPS receiver to obtain many samples of the correlation peaks.

Each spectrum was filtered via post-processing using an IIR filter prototype having an 18MHz and 3MHz bandwidth, respectively. The 18MHz filter had a maximum dT_{Gd} of 250ns; the 3MHz filter had a maximum dT_{Gd} of 1300ns. Both filters had symmetric, differential group delay profiles. Although the asymmetry in the correlation peak is significantly more apparent for the narrowband (3MHz) filter, it is also present in the 18MHz-filtered peak.

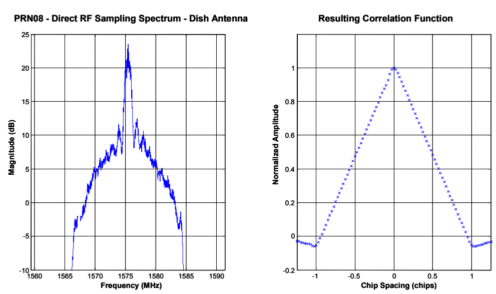

FIGURE 6. Power spectrum and resulting correlation peak of GPS PRN08 after post-processing application of 18MHz filter model. The filter had symmetric group delay profile with a maximum dT_{Gd} of 250ns.

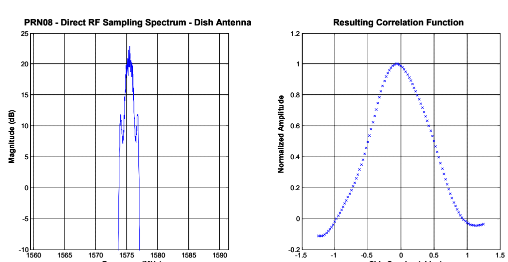

FIGURE 7. Power spectrum and resulting correlation peak of GPS PRN08 after post-processing application of 18MHz filter model. The filter had symmetric group delay profile with a maximum dT_{Gd} of 1300ns.

Figure 8 quantifies the degree of asymmetry induced by the filter group delay effects. It plots the effective pseudorange (PSR), or tracking error, differences as a function of correlator spacings for both the 18MHz and the 3MHz-filtered peaks; also shown is the "non-filtered" result for comparison. In other words, this result forms early-minus-late (E-L) discriminators for all the correlator spacings/samples taken along each respective peak and differences them with the spacing at 0.5 chips. (A dashed vertical line is shown on the figure at this spacing.)

Variation of each line indicates the degree of correlation peak asymmetry. The "non-filtered" case—bandlimited only by the GPS satellite transmit antenna and the high-gain dish antenna—yields the smallest variation. It varies less than one meter over the span of all E-L correlation spacings. (Note that this implies the GPS signal is nearly symmetric upon transmission.) Conversely, the 18MHz-filtered peak shows between two and three meters of (maximum-to-minimum) variation. The 3MHz filter results in the largest (approximately 20 meters, maximum-to-minimum) variations as a function of correlator spacing. Again, these distortions are owed to the various differential group delays of the filters.

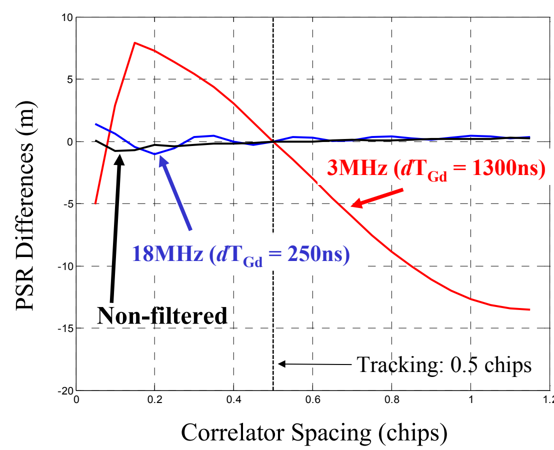

FIGURE 8. Pseudorange differences vs. correlator spacing traces for three received GPS correlation peaks: non-filtered (black), 18MHz-filtered (blue) and 3MHz-filtered (red). The 18MHz and 3MHz filters were implemented in software and had differential group delays of 250ns and 1300ns, respectively.

The next step in the validation effort used physical analog filters with conventional GPS receivers to measure this effect. Figure 9 shows the magnitude and group delay responses of a 2.2MHz filter. (The filter has a differential group delay of approximately 220ns.) Figure 10 depicts the correlator spacings of one (multi-correlator) test receiver used to measure the peak distortion. Those spacings included Prompt, 0.1, 0.2, 0.3, 0.5, 0.7 and 1.0-chip.

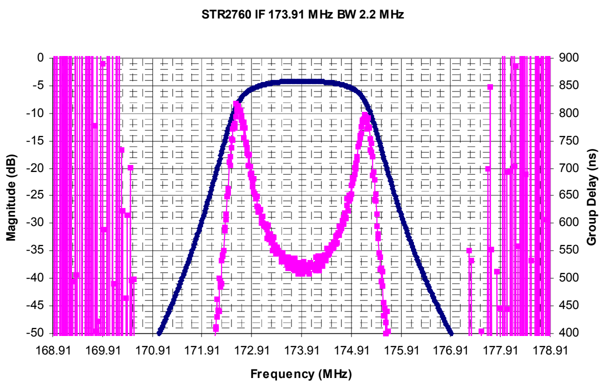

FIGURE 9. Magnitude and group delay response profiles of an actual 2.2MHz analog filter (centered at IF).

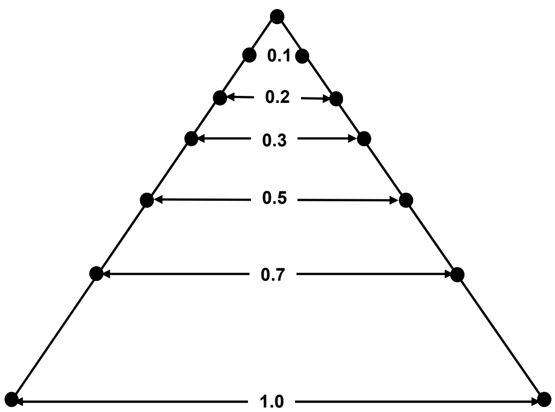

FIGURE 10. Correlator spacing configuration of test receiver.

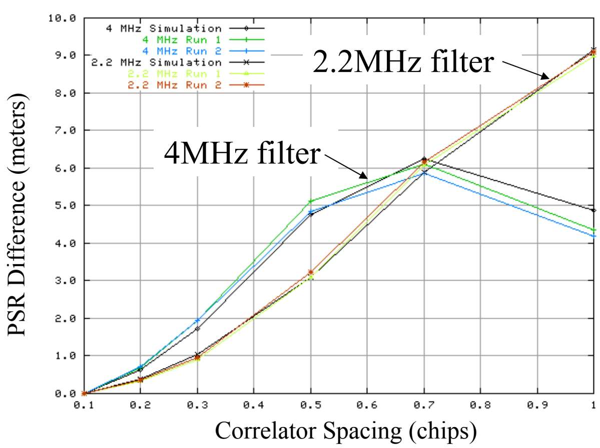

FIGURE 11. Pseudorange differences vs. Correlator Spacing traces for two actual filters: 2.2MHz and 4MHz. Each had differential group delays of approximately 220ns and 150ns, respectively. (Their group delay profiles were symmetric.)

The results of this test are plotted in Figure 11. In addition to the 2.2MHz filter case, a 4MHz filter was also examined for comparison. For both filters tested, there are three traces. Two correspond to actual test trials; a third plots the errors predicted by a simulation based on knowledge of the receiver front-end filter group delay responses in addition to those of the narrowband filters under scrutiny. (The exact group delay profile of the test receiver is manufacturer-proprietary and is not included in this paper.) For both test filters, the correspondence between the simulation and the data is within 1 meter. The maximum asymmetry, measured relative to 0.1-chip spacing, was as large as 9 meters for the 2.2MHz filter and 6 meters for the 4MHz filter.

This plot confirms three important things. First, it verifies that range biases (due to correlation peak distortion) may be introduced by real filters and experienced by actual receivers. Second, it shows that the range biases will vary as a function of receiver correlator configuration. Third, it proves that precise knowledge of the group delay profiles of the filters of concern can yield reasonable predictions of correlation peak distortion and, hence, the resulting range bias effects.

Figure 12 plots similar correlation peak asymmetry results from measurements taken on an actual GEO signal obtained using a 3-foot dish antenna. The same test receiver (Test Receiver 1) is plotted in addition to a second, similarly-configured receiver (Test Receiver 2). Test Receiver 1 shows a maximum distortion of only 30cm. Test Receiver 2 experiences a distortion of about 70cm.

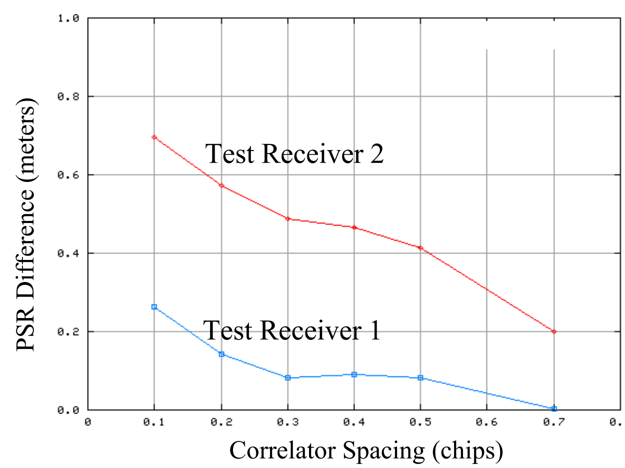

FIGURE 12. Pseudorange differences vs. Correlator Spacing traces for two test receivers measured on a live GEO signal (using a 3-foot dish antenna).

Two important facts are apparent from this plot. First, the effect of the group delay profile of the actual GEO signal filters is not as significant as that of the 2.2MHz analog filters examined previously. (Refer to Figure 9.) Also, there is significant variation between receivers of the same type or part number simply due to manufacturing tolerances and subsequent component-to-component variability. In addition, note that group delay responses of *these* two test receivers do not cause significant correlation peak distortion. This is likely also due to a less distorting (i.e., less symmetric) differential group delay response of the receiver precorrelation filters.

SPECIFICATIONS

Since the correlation peak distortion caused by differential group delay variations is a real effect and it can be modeled, it is possible to predict the net range biases for some users of the GEO signal. To do this the following three filter models (i.e., group delay responses) and configurations are of most importance: the user receiver, the ground/reference receiver, and the GEO signal filter. (Note that although the GPS correlation peak itself has a small amount of asymmetry (Refer to Figure 8.) due to transmission filtering, for conservatism, the GPS signal is modeled as having infinite bandwidth.)

User Receiver Configuration

The MOPS specifies a constraint on both the magnitude response for user receiver filters and their differential group delays. Filter magnitude response does not directly cause the range biases of concern here. However, for completeness, Figure 13 shows the magnitude responses of several 10MHz (single-sided) filter prototypes. Note that although the 6th-order Butterworth has the widest transition bandwidth, its post-correlation response still meets the MOPS filter attenuation specification.

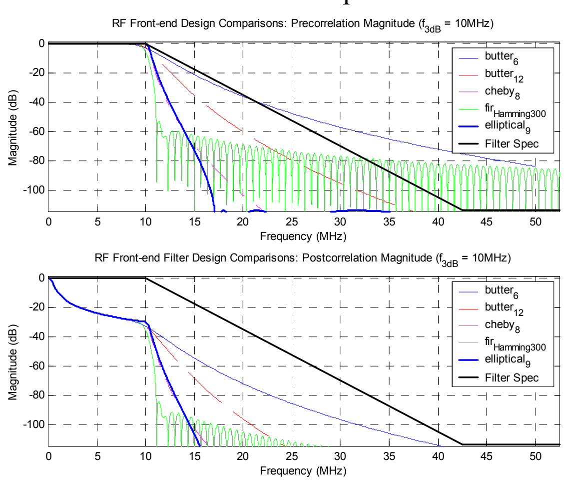

FIGURE 13. Various filter design implementations compared to the MOPS intereference mitigation requirement. (TOP: Pre-correlation; BOTTOM: Post-correlation.)

The constraint on user filter group delay is shown in Figure 14. For receiver bandwidths less than 7MHz, the MOPS permits this number to be as large as 600ns. For all other bandwidths, the maximum specification is 150ns. Also plotted is the maximum differential group delay of the 6oB filter designed at each of these bandwidths. Note that it is not as conservative as it can be. Recall (from Figure 4) that its perfectly symmetric, non-zero group delay profile is the most conservative one; however the MOPS—and many actual component specification sheets—have no requirement on the symmetry of the passband group delay profile.

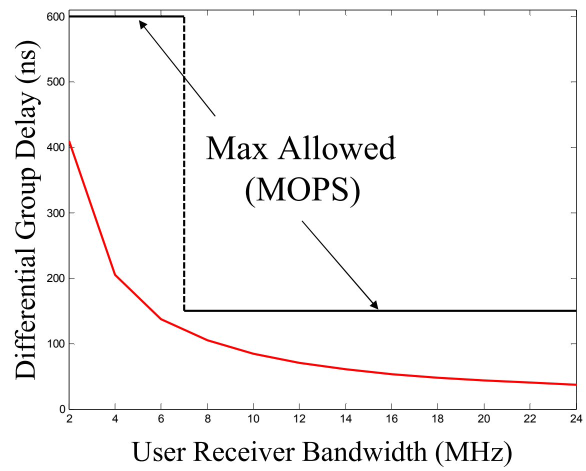

FIGURE 14. Maximum passband differential group delay specification for WAAS and LAAS compared to that of a 6th-order Butterworth filter.

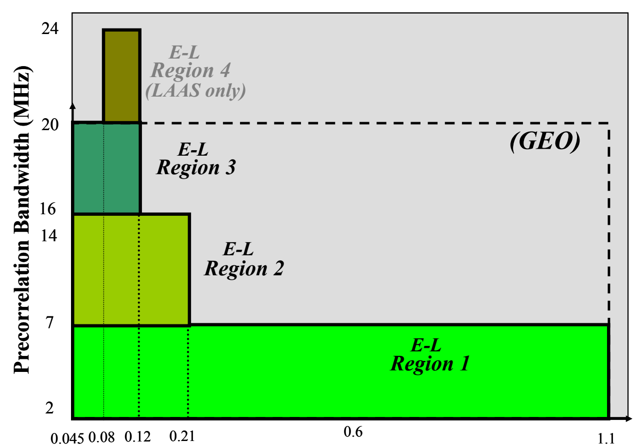

FIGURE 16. MOPS-allowed early-Minus-Late user receiver configurations.

User receivers have additional constraints on their configurations. The discriminator type must be either early-minus-late (E-L) or double-delta (ΔΔ). Figure 15 shows only the valid E-L receiver configurations. Note that for GPS tracking, user receivers are confined to three (WAAS) or four (LAAS) regions in this design space specified by front end bandwidth and correlator spacing. Conversely, the correlator spacing for the GEO signal is defined over the entire rectangular region between 0.045 to 1.1 chips and between 2 to 20MHz. This means the GEO spacing may differ from GPS tracking even in the same receiver. As suggested in the previous section, this discrepancy may contribute to even larger GEO range biases.

Reference Receiver Configuration

In general, reference receiver configurations may be described as a subset of the user receivers. In fact, for WAAS, only one correlator spacing and bandwidth is required to describe them. Also, it is possible for their maximum differential group delays to be better known and characterized that those specified for users in the MOPS.

Actual WAAS (and LAAS) reference stations, however, use multiple receivers. As shown previously, different receivers may have significantly different passband group delay responses. This may be modeled as a net "effective" group delay response of a single receiver having a specific correlator spacing and bandwidth. For this analysis, the (conservative) symmetric group delay profile was assumed, and the maximum effective differential group delay assumed was 100ns. This is a typical (i.e., non-conservative) assumption

GEO Signal Filter

The GEO signal itself is perhaps most difficult to characterize. It is shaped by a combination of filters including the signal generator IF filter, a post upconverter filter, and a narrowband filter on the satellite (as part of the communications payload). A thorough characterization of these filters and their composite differential group delay effects is still pending. However, for modeling purposes, a nominal maximum differential group delay of 100ns was selected. (Again, a symmetric group delay profile was assumed.)

RESULTS

Figures 17-21 use all the aforementioned specifications to model the GEO bias—relative to GPS—and plot the expected errors (in meters). The figures are 2-D contour plots of the errors plotted as a function of user receiver pre-correlation bandwidth and GPS (E-L) correlator spacing. Note that, in general, ΔΔ receiver GEO bias errors follow similar trends, however, for simplicity that analysis is not included here.

Figure 17 plots the maximum expected GEO range bias that would result from ideal receivers tracking a non-ideal, narrowband (2.2MHz) GEO filter group delay response. In other words, it utilizes constant group delay, FIR filters for both the user and reference receiver filters. The correlator spacing in the reference receiver for both GPS and GEO signals was 0.1-chip (at a 16MHz bandwidth). Assuming a perfect, infinite bandwidth GPS peak, the filtered GPS correlation peaks in these receivers remain symmetric and introduce no additional biases. In addition, Figure 17 assumes the user implements the same discriminator configuration (i.e., E-L correlator spacing) to track both the GPS and GEO signals. In this way the differences between the signals is minimized.

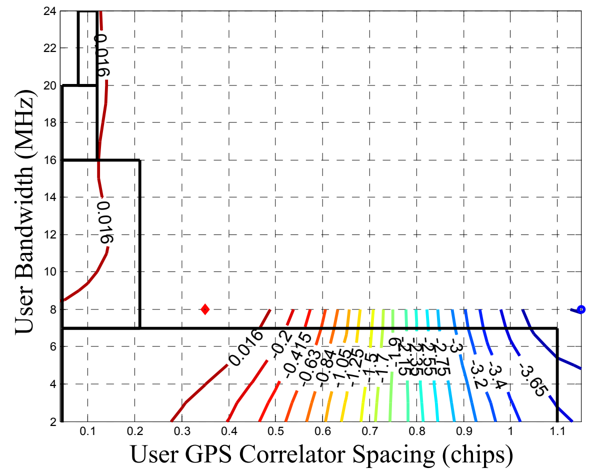

FIGURE 17. User maximum GEO range bias contours (in meters) for an ideal, non-distorting (FIR) reference and user receiver filter and a user receiver that has the same discriminator configuration for both GPS and GEO signals. The reference receiver has a 16MHz bandwidth and 0.1-chip spacing for both GPS and GEO signals. Only the GEO signal is filtered with a non-zero (symmetric) differential group delay filter ($dT_{Gd,max}$=100ns).

This figure reveals that despite relatively optimistic assumptions for reference and user receiver configurations, several E-L user receiver configurations may experience an unacceptably large bias due solely to the GEO filter group delay characteristics. The largest errors exceed 3.5 meters for narrowband, wide correlator receivers.

Figure 18 models nearly the same conditions as does Figure 17, however it introduces the additional complexity of a non-ideal user receiver filter. Here, a 6th-order Butterworth model is used; it has a maximum dT_{Gd} that varies with bandwidth as described previously in Figure 14. (The reference receiver filter is still modeled as having constant group delay.) Additionally, all the user receivers modeled here track the GEO with a correlator spacing of 0.5 chips; their GPS correlator spacings still vary according to the horizontal axis of the plot.

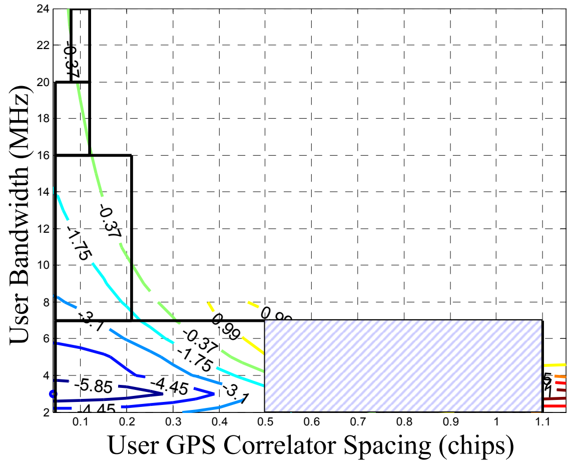

FIGURE 18. User maximum GEO range bias contours (in meters) for an ideal, non-distorting (FIR) reference filter and a 6th-order Butterworth user receiver filter. All user receivers have a GEO correlator spacing fixedat 0.5 chips. (User configurations with wider GPS spacings are grayed out.) The reference receiver has a 16MHz bandwidth and 0.1-chip spacing for both GPS and GEO signals. The GEO signal is filtered with a non-zero (symmetric) differential group delay filter (dT$_{Gd,max}$=100ns).

As a result of these additional, less optimistic assumptions, the biases increase and vary more significantly across all allowed configurations. Even the bias errors for the wideband (e.g,, >7MHz) receivers become more significant here. The largest biases occur for narrowband, narrow correlator (e.g., <0.3 chip spacing) receivers. It should be noted that these are allowed configurations but are generally not likely to be implemented. Even less realistic configurations are those receivers which would propose to track narrowband GEO signals at spacings *wider* than they do GPS signals. These types of receivers would result in perhaps the largest biases for this case; however they have been discounted in this analysis.

Figure 19 plots exactly the same receiver filter conditions as does Figure 18, however it changes the (fixed) user receiver GEO correlator spacing to 1.0-cip spacing instead of 0.5 chips. Here, the GEO-GPS differences are increased even further, and this manifests itself as an overall increase in the expected GEO range bias.

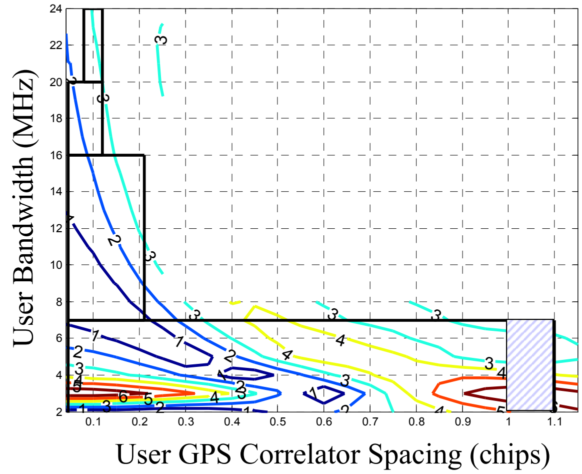

FIGURE 19. User maximum GEO range bias contours (in meters) for an ideal, non-distorting (FIR) reference filter and a 6th-order Butterworth user receiver filter. All user receivers have a GEO correlator spacing fixed at 1.0 chip. (User configurations with wider GPS spacings are grayed out.) The reference receiver has a 16MHz bandwidth and 0.1-chip spacing for both GPS and GEO signals. The GEO signal is filtered with a non-zero (symmetric) differential group delay filter (dT$_{Gd,max}$=100ns).

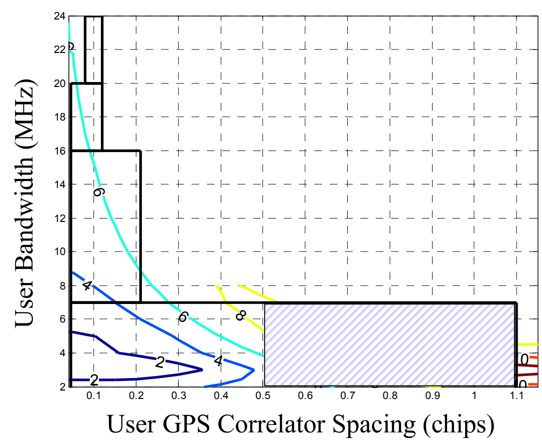

FIGURE 20. User maximum GEO range bias contours (in meters) for an IIR reference filter (symmetric group delay response, dT$_{Gd,max}$=100ns) and a 6th-order Butterworth user receiver filter. All user receivers have a GEO correlator spacing fixed at 0.5 chips. (User configurations with wider GPS spacings are grayed out.) The reference receiver has an 8MHz bandwidth and 0.1-chip spacing for GPS and 1.0-chip spacing for the GEO signal. The GEO signal is filtered with a non-zero (symmetric) differential group delay filter (dT$_{Gd,max}$=100ns).

Figure 20 introduces additional complexity by modeling the reference receiver filter as an 8MHz IIR filter with a symmetric group delay response ($dT_{Gd,max}$=100ns). In addition, the reference receiver implements a GEO correlator spacing (1.0 chip) that is not matched to its GPS spacing (0.1 chip). All other filters and configurations are as they were for Figure 18. (The user GEO correlator spacing was again fixed at 0.5-chips.) In this scenario, the errors become even larger for the wideband user receiver configurations than for the narrowband ones.

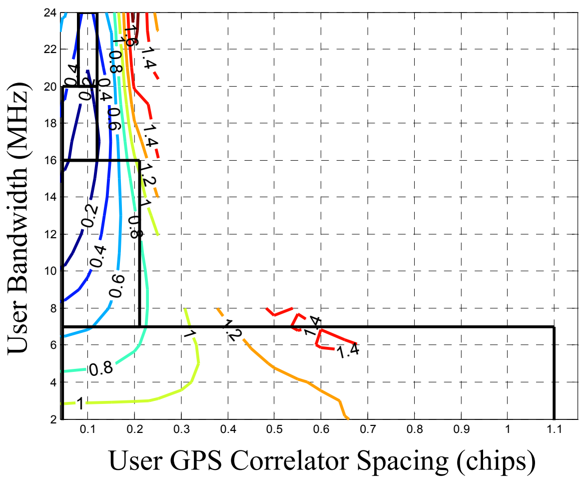

FIGURE 21. User maximum GEO range bias contours (in meters) for an IIR reference filter (symmetric group delay response, $dT_{Gd,max}$=100ns) and a 6th-order Butterworth user receiver filter. All user receivers have the same correlator spacing for both GPS and GEO signals. The reference receiver has an 18MHz bandwidth and 0.1-chip spacing for both GPS and GEO signals. The GEO signal is filtered with a non-zero (symmetric) differential group delay filter ($dT_{Gd,max}$=100ns).

In the event that a wideband GEO may be assumed, this analysis predicts that things may improve significantly for all receivers of interest. Still, the bias may not become negligibly small for all users. Figure 21 plots the case for a 20MHz GEO filtered with a symmetric differential group delay response and $dT_{Gd,max}$=100ns. The reference receiver filter was similarly modeled with an 18MHz bandwidth. The user receiver filters were again modeled with the 6oB filter. Both reference and user receiver discriminators tracked GPS and GEO signals with identical correlator spacings. The reference receiver GPS/GEO correlator spacing was 0.1 chips; the user receiver GPS/GEO correlator spacing was varied according to the horizontal axis. Under these conditions, the figure reveals that over a meter may remain for narrowband user in this case.

CONCLUSIONS

Due to filtering effects and differential group delay differences between GEO and GPS signals, ranging biases on the narrowband WAAS GEOs are present. And, if left unaccounted for, they may be significant for some users. Wideband (e.g., 20MHz bandwidth) GEOs should significantly reduce these biases overall, but in some instances they still may remain unacceptably large. Calibration of these errors, as an option for mitigating this threat, is unfortunately complicated by the following factors:

- Variable user receiver configurations *including net filter passband group delay responses*. (Note that such group delay profiles are not always included in hardware component specification sheets.)
- Component-to-component variability
- Modeling/simulation fidelity
- Temporal variations

Many receiver configuration options for simultaneous GPS-GEO tracking exist. However, to meet the MOPS (Section 2.1.4.1.3) 1-meter RMS specification on GEO ranging there are actually fewer practical strategies [1]. For one, whenever possible, GPS and GEO discriminator configurations should be identical inside a given receiver. In addition, the group delay ripple specification in component selection should be minimized. This may be effectively realized through either ensuring antisymmetric passband group delay responses or through implementing some form of group delay equalization. Without taking such pre-emptive design measures, it may be impossible to conform to the MOPs requirement.

The challenge of integrity analyses will be to take credit for less conservative receiver filter behaviors for which there are (currently) no MOPS specifications. A refined GEO filter model—one that takes advantage of a less conservative group delay response—may serve to reduce the predicted bias errors. (Work in developing such a model is currently underway.) In addition, refined reference receiver filter and general configuration assumptions may further reduce any overly-conservative error predictions presented here.

ACKNOWLEDGMENTS

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REFERENCES

[1] Minimum Operational Performance Standards (MOPS) for WAAS, DO229C.

[2] Phelts, R. E., Akos, D. M., Enge, P. K., "Robust Signal Quality Monitoring and Detection of Evil Waveforms," *Proceedings of the 13th International Technical Meeting of the Satellite Division of the Institute of Navigation*, ION-GPS-2000, pp. 1180-1190.

[3] Porat, Boaz, *A Course in Digital Signal Processing*, John Wiley and Sons, Inc., 1997, pp. 11-20.