# GPS + Modernized GPS + Galileo Signal Timing Biases

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GPS TIMING AND NAVIGATION USER SOLUTIONS ARE BASED ON PSEUDORANGE MEASUREMENTS MADE by correlating user-receiver–generated replica signals with the signals broadcast by the GPS satellites. Any bias resulting from this correlation process within a user receiver tends to be common across all receiver channels when the signal characteristics — code type, modulation type, and bandwidth — are identical. Such common biases will cancel out in the user navigation solution and appear as a fixed bias for timing solutions and some atmospheric signal analyses. New GPS signals and the future Galileo signals are somewhat different than the legacy signals broadcast by GPS satellites today, so new ways of accounting for biases will be needed.

In this month's column, Chris Hegarty, Ed Powers, and Blair Fonville discuss this problem and quantify the timing biases of the different legacy and modernized GPS and Galileo signals broadcast on the L1 frequency and their dependencies on factors such as user-receiver filter bandwidth, filter transfer function, and delay-locked loop correlator spacing. — R.B.L.

Within the next decade, GPS positioning, navigation, and timing (PNT) users can anticipate significant performance improvements as new GPS signals become available and as the European Galileo system is fielded. The new GPS L2 civil (L2C) signal and L1/L2 M-code signals will be broadcast by GPS satellites beginning with the first Block IIR-M satellite, which was launched September 26, 2005. A third civil GPS signal, L5, will be broadcast beginning with the first Block IIF satellite expected in 2007. The Galileo program schedule calls for operations to commence in 2008–2010.

To fully use these emerging capabilities, the PNT community will need a greater understanding of hardware-induced group delays. This article discusses the effects of these biases on the performance of navigation and timing estimates generated from GPS and Galileo pseudorange measurements.

## Causes and Effects

Signal timing biases arise in GPS from many sources. For instance, the current GPS C/A-code and P(Y)-code signals are imperfectly synchronized upon signal transmission, as **Figure 1** illustrates. Timing biases arise from the different analog paths taken by individual GPS signals from their generation through the satellite antenna. The timing bias between the L1 and L2 P(Y)-code signals is inconsequential for most dual-frequency users because the broadcast clock corrections compensate for this bias, under the presumption that a user is combining L1 and L2 pseudorange measurements via the well-known ionosphere-free equation:

$$PR = \frac{PR_{L2P(Y)} - \gamma\, PR_{L1P(Y)}}{1-\gamma}$$

where $PR$ is the ionosphere-free pseudorange, $PR_{L1P(Y)}$ is the L1 P(Y)-code pseudorange, $PR_{L2P(Y)}$ is the L2 P(Y)-code pseudorange, and $\gamma = (f_{L1}/f_{L2})^2 = (1575.42/1227.6)^2$ is the ratio of the L1 to L2 frequency squared. Single-frequency users (L1 or L2) employing the broadcast clock corrections, however, must correct for the L1–L2 timing bias by using the broadcast value of $T_{GD}$ contained in Word 7 of Subframe 1 of the GPS navigation message. The absolute value of the L1–L2 group delay bias is specified to be less than 15 nanoseconds with random variations about the mean less than 3 nanoseconds (two-sigma). Observed values generally are less than 8 nanoseconds in magnitude. Until 1999, broadcast $T_{GD}$ values were derived from factory measurements. Since April 1999, the broadcast values have been provided to the United States Air Force by the Jet Propulsion Laboratory (JPL). At present, the precision of the broadcast $T_{GD}$ values is limited by the nearly 0.5 nanosecond message quantization.

C/A-code users have an additional timing bias of the transmitted signals to account for, which is the bias between the L1 C/A-code and P(Y)-code signals. This bias, labeled as $ISC_{L1C/A}$ in Figure 1, is specified to be less than 10 nanoseconds (two-sigma). Typically, observed magnitudes are less than 3 nanoseconds. Although various organizations, including JPL, routinely estimate $ISC_{L1C/A}$, the

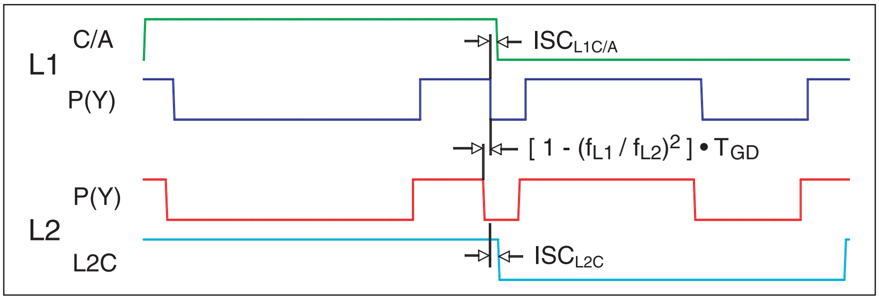
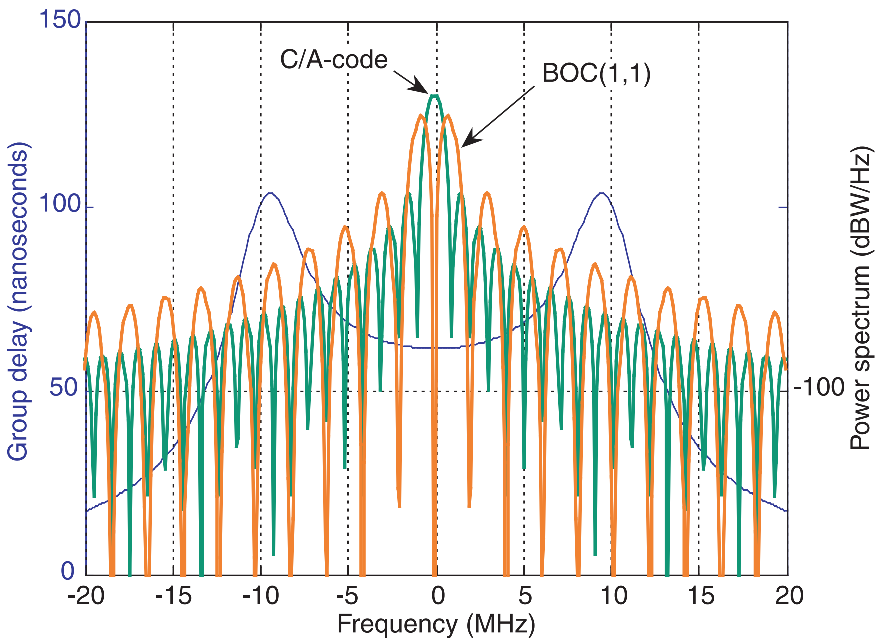



**FIGURE 1** Group delay biases within GPS signals upon transmission

present GPS navigation message unfortunately does not include a field for these data. Future GPS navigation messages, however, will disseminate $ISC_{L1C/A}$ as well as a number of additional group delays (for example, $ISC_{L2C}$ (also illustrated in Figure 1), $ISC_{L5I5}$, and $ISC_{L5Q5}$) that will be introduced on future satellites, which will broadcast the new L2C, M-code, and L5 signals.

When the Galileo system comes online within the next decade, many additional timing biases will be introduced, including a bias between GPS System Time and Galileo System Time. Discussions between the United States and the European Union have resulted in an agreement, inter alia, to disseminate the GPS/Galileo Time Offset (GGTO) via both systems in the future. A preliminary interface specification was developed that also discusses an alternative approach of having GPS–Galileo user equipment directly estimate GGTO using an additional satellite. The expected accuracy of both approaches has been investigated and reported by researchers (**see the "Further Reading" sidebar**). The drawback of the user-equipment-estimation approach may be less severe than has been reported, because an additional measurement is not always required. In challenged environments, such as urban areas, periodic calibration of GGTO may be sufficient because this timing bias is expected to change very slowly.

User equipment introduces additional timing biases caused by the group delays that are experienced as the received GPS signal travels from the antenna, possibly along a cable run, to the radio- and intermediate-frequency (RF and IF) analog front-end components and then ultimately after digitization to the correlators that are used to estimate signal time-of-arrival. For many navigation users, receiver group delay effects can be ignored because the delay is common to all received signals and thus drops out into the user clock offset without affecting positioning accuracy. User equipment group delays are of much greater importance to timing users, because the clock offset parameter is the estimated quantity of greatest interest. High-precision GPS timing users must calibrate user equipment group delays. Use of dual-frequency GPS signals to study the ionosphere's total electron content also requires consideration of receiver group delay effects.



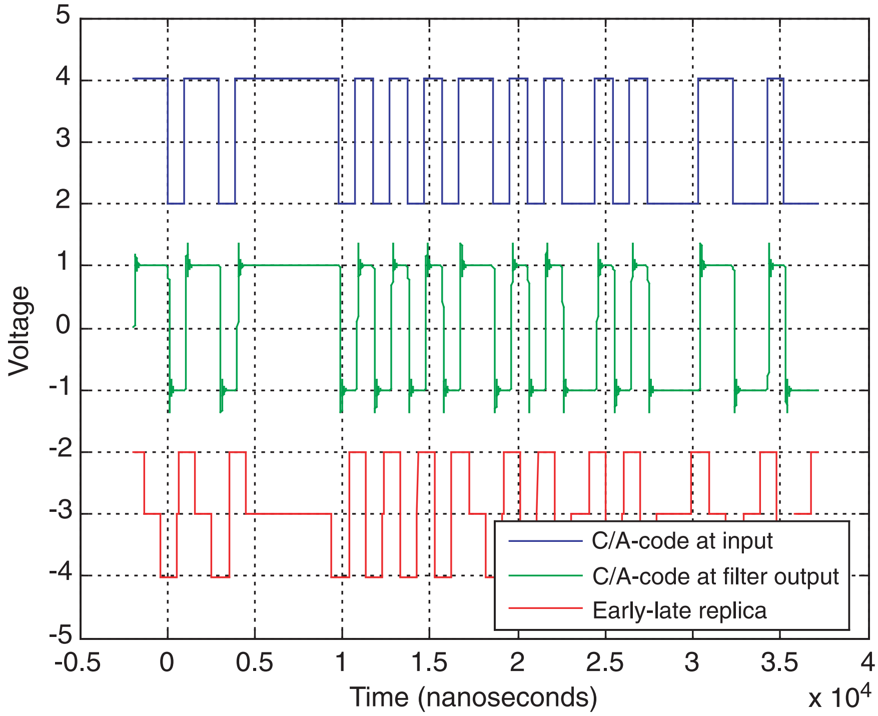

▲ **FIGURE 2** Example group delay response for the RF/IF filtering within a GPS–Galileo receiver and power spectra of the GPS L1 C/A-code signal and BOC(1,1) modulation planned for the Galileo L1 OS signal

User equipment group delays will require more careful treatment for many global navigation satellite system (GNSS) users in the future. For instance, users wishing to combine GPS and Galileo signals will need to account for GGTO. The main purpose of this article is to highlight a receiver group delay problem that arises for dissimilar GNSS signals, even when they are on a common carrier frequency. The problem is illustrated in **Figure 2**, which plots a simulated receiver's RF/IF filtering group delay versus frequency using the left vertical axis. This group delay response corresponds with an ideal (lossless) sixth-order Butterworth filter. Obviously, such a filter is unrealizable. However, a 50nanosecond variation of group delay within a 20-MHz receiver's passband is not atypical. The RF/IF filtering for commercial C/A-code receivers used in aviation exhibit similar group delay characteristics — for example, minimum delay at center frequency and maximum delays near the 3-dB half-power frequencies — with a maximum-allowed group delay differential (that is, group delay at center frequency versus that at 3-dB frequency) of 150–300 nanoseconds, depending on the receiver bandwidth.

Figure 2 also shows (right-hand vertical axis) the power spectra for the GPS L1 C/A-code signal and the binary offset carrier modulation with 1.023-MHz chip rate and 1.023-MHz square wave subcarrier (denoted as BOC[1,1]) planned for the Galileo L1 Open Service (OS) signal. The BOC(1,1) modulation also is planned for use in a future GPS L1 civil signal. Because of these differing power spectra, the group delay experienced by the two signals shown in Figure 2 will not be the same when they pass through the filter. Because most of the power in the C/A-code and OS signals resides within ±2

MHz of L1, one might incorrectly conclude that the group delay difference between the two signals is negligible.

As the following sections will show, the observed pseudorange error due to the user equipment's group delay response will vary greatly for each signal depending on the tracking technique implemented. Modern high-quality receivers generally exploit the high-frequency content of the C/A-code to reduce multipath errors, and future receivers are expected to do the same for the L1 OS. For timing users who employ network analyzers to measure group delays for certain user-equipment components such as active antennas, the offset between signal zero-crossings before and after specific components are not necessarily the same as the group delay observed using correlation processing.




▲ **FIGURE 3** Simulated C/A-code signals

## Simulation Results

To better illustrate the effects discussed at the end of the previous section, we ran a simple time-domain simulation. We emulated a variety of current and future GNSS signals using a 491.04-MHz sample rate. The signals were passed through a digital sixth-order Butterworth filter with 20-MHz two-sided bandwidth, as defined by the 3-dB attenuation points, which is the same filter whose group delay response was plotted in Figure 2. The output of the filter then was correlated with the difference of early and late replicas of the corresponding signal. Correlation with early–late replicas of the desired signal is part of the delay locked loop (DLL) processing used by most GPS receivers. Those receivers estimate signal time-of-arrival by steering the timing of the replicas so that the average correlation of the received signal with the early–late replica is zero.

As an example, **Figure 3** shows the simulated signals that correspond to the C/A code. The top trace in Figure 3 is a 40-microsecond portion of the C/A-code signal that was input into the filter. The middle trace is the output of the filter (for example, the C/A-code signal bandlimited to 20 MHz), which is noticeably delayed with respect to the input. The bottom trace is the difference between an early and late replica of the C/A-code signal with a 1-chip (~977.5 nanoseconds) spacing between the early and late replicas. The vertical biases between the waveforms shown in Figure 3 are arbitrary — they were added to facilitate simultaneous viewing. In this particular case, the timing bias between the zero crossings of the input and output signal for any particular C/A-code epoch is 66.25 nanoseconds, whereas the timing bias between the zero crossing of the input and the time-of-arrival estimated using a DLL with 1-chip early–late spacing is only 60.32 nanoseconds.

**Figure 4** presents the resultant group delays measured for a variety of GNSS signals and for DLLs implemented with early–late spacing ranging from 10 to 1000 nanoseconds. (Note that we evaluated only the range of early–late spacings that makes sense for each particular signal type.) In general, the group delays were largest for the narrowest early–late spacings that were considered. This result can be explained intuitively as follows: The early–late replica waveform within a coherent DLL consists of windows around each edge of the received signal with the width of each window being equal to the early–late correlator spacing. As the correlator spacing is narrowed, the window width decreases and the high-frequency content of the early–late replica increases. The net result is that the DLL increasingly emphasizes high-frequency components of the received signal, for which the RF/IF filtering imparts greater delays.

It is interesting to note that in the limit as the early–late spacing becomes increasingly small, the group delay that is measured using a DLL corresponds to the group delay measured from the filter output's zero crossings. This result should not be a surprise. Correlating the received signal with early and late replicas and then differencing is equivalent to correlating with one signal produced by differencing the early and late replicas (see bottom waveform in Figure 3). The early-late replica waveform can be viewed as a set of "windows" around the received signal's zero-crossings that get smaller as the early-late spacing is diminished. In other words, in the absence of noise, a DLL with infinitely small early–late correlator spacing, which is the optimal time-of-arrival estimator in white noise, will produce the same time-of-arrival estimate as would be obtained by measuring the timing of the received signal's zero crossings. Of course, measuring time-of-arrival for live GNSS signals is impossible by directly observing the zero-crossings because the received signals are buried beneath the noise. However, zero-crossing measurements often are obtained using network analyzers in some calibration methods.

The relative delay between signals is of greater importance than the absolute user equipment group delays. For instance, future receivers designed to combine C/A code- and L1 OS signals must know GGTO precisely to provide accurate position and time estimates. The results in Figure 4 indicate that the bias between C/A-code and Galileo OS BOC(1,1) signal measurements will be a function of the DLL implementation. The change in the bias with DLL implementation could be as large as 1 nanosecond for the group delay response shown in Figure 2 and as large as several nanoseconds for a typical commercial receiver with 150 nanoseconds group delay differential across the passband. Thus, a broadcast GGTO value must be combined with a known receiver-induced bias — for example, by having the equipment manufacturer or user calibrate the bias — or alternatively, the user equipment must estimate the combination of the GGTO and receiver-induced biases. Problems with the former technique may arise because of variations of the user equipment group delay response due to production tolerances and changes in the ambient temperature.

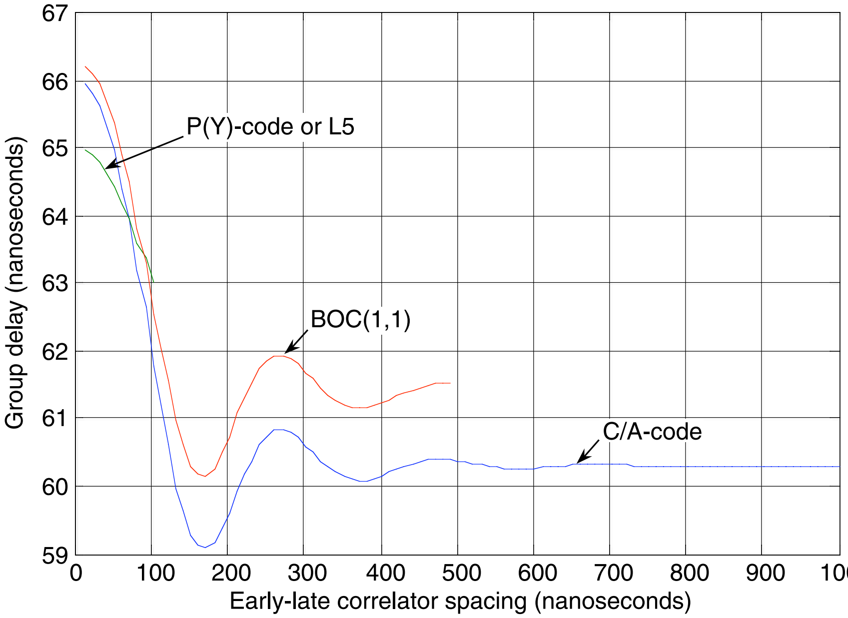



**FIGURE 4** Example group delay response for the RF/IF filtering within a GPS–Galileo receiver and power spectra of the GPS L1 C/A-code signal and BOC(1,1) modulation planned for the Galileo L1 OS signal

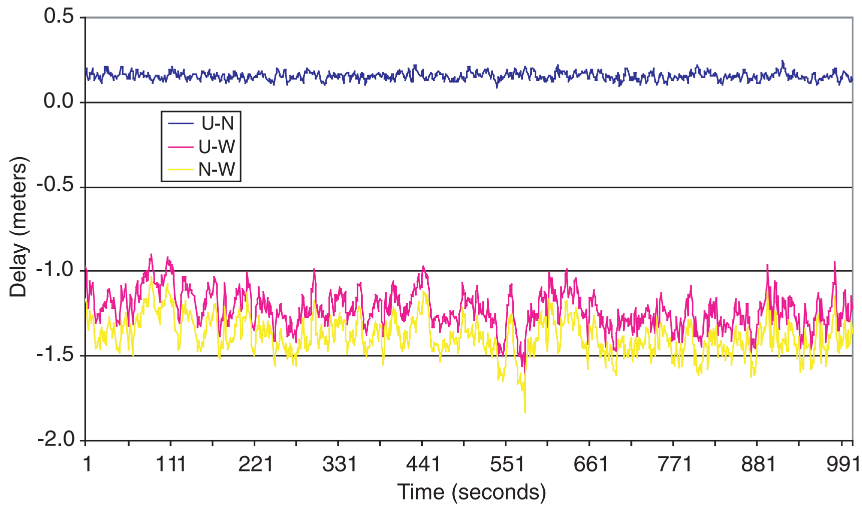



**FIGURE 5** Differential group delays measured between channels of a commercial GPS C/A-code receiver using three early–late correlator spacings

## Hardware Measurements

We also conducted hardware experiments to determine the level of group delay variation with DLL configuration for a typical commercial GPS unit. For the experiments, we used a GPS C/A-code signal simulator to emulate one GPS C/A-code signal. The simulator was connected directly to a commercial GPS receiver using a cable. The GPS C/A-code receiver was configured so that three channels would track the same C/A-code signal, but each would use a different early–late correlator spacing. The three spacings that were employed were:

- Ultranarrow (U) — 1⁄20 C/A-code chip (~50 nanoseconds)
- Narrow (N) — 1⁄10 C/A-code chip (~100 nanoseconds)
- Wide (W) — 1 C/A-code chip (~1 microsecond)

The exact RF/IF filter characteristics of the receiver were unknown, but the manufacturer indicated that the overall RF/IF response and group delay was dominated by an 18-MHz (two-sided) surface acoustic wave (SAW) IF filter. We recorded the pseudorange measurements from the three channels and determined their differences.

**Figure 5** and **Table 1** (page 54) show the results. Note that each differential pseudorange involving the wide DLL is biased by more than 1 meter (3.3 nanoseconds). As predicted, a substantial variation of observed pseudorange error with DLL correlator spacing appears to be caused by the receiver's group delay response. An unexpected result, however, was that the wide DLL pseudorange measurements were larger than the ultranarrow and narrow measurements. This result is contrary to the simulated results presented earlier in this article. We speculate that the IF SAW filter in the test receiver has a group delay response that is significantly different from the model used in the previous section; that is, that the group delay response is greater at band center than near the 3-dB frequencies. It is common for IF SAW filters to exhibit an erratic group delay response across their passbands.

## Summary and Conclusions

In this article, we discussed group delays among current and future GNSS signals and in particular group delays that arise as a result of filtering within a GNSS receiver. Simulation and hardware results indicate that group delay differences on the order of several nanoseconds can arise between signals of different modulation types on the same carrier frequency or for signals of the same type that are processed using different DLL implementations. These effects must be well understood and compensated for by GNSS receiver manufacturers, service providers, and systems engineers, or they could consume unacceptably large portions of the error budgets for a number of high-precision GNSS timing, navigation, and scientific applications.

## Disclaimer

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## Acknowledgments

The authors would like to thank Pat Fenton of NovAtel for helpful discussions regarding the hardware measurements. This article is based on the paper "Accounting for Timing Biases Between GPS, Modernized GPS, and Galileo Signals," which was presented at the 36th Annual Precise Time and Time Interval Meeting in Washington, D.C., on December 7–9, 2004, and an updated version of the paper with the same title presented at ION GNSS 2005, the 18th Technical Meeting of the Satellite Division of The Institute of Navigation in Long Beach, California, on September 13–16, 2005.

## Manufacturers

The hardware measurements reported in this article were performed using an OEM3 receiver with special firmware from **NovAtel Inc.** (*www.novatel.ca*)

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**BLAIR FONVILLE** received his M.S. degree in electrical engineering from the University of Alabama at the close of 2003 and immediately began work for the USNO. His primary focus at the observatory is the characterization of noise processes and precision measurement of phase delays through communication systems equipment such as for the Two-Way Satellite Time and Frequency Transfer System and GPS.

**TABLE 1** Statistics of Differential Group Delays

| Measurements | Mean (meter) | Standard Deviation (meter) |
|---|---|---|
| Ultranarrow minus narrow | +0.16 | 0.02 |
| Ultranarrow minus wide | –1.22 | 0.11 |
| Wide minus narrow | –1.38 | 0.11 |

"Innovation" is a regular column featuring discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by **RICHARD LANGLEY** of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who appreciates receiving your comments and topic suggestions. To contact him, see the "Columnists" section on page 6 of this issue.

## Further Reading

**For a description of the legacy and L2C GPS signals and navigation messages, see**

*Navstar GPS Space Segment/Navigation User Interfaces, Interface Specification, IS-GPS-200 Revision D*, prepared by ARINC Engineering Services LLC, El Segundo, California, December 2004.

**For a description of the L5 GPS signal and navigation messages, see**

*Navstar GPS Space Segment/Navigation User Interfaces, Interface Specification, IS-GPS-705*, prepared by ARINC Engineering Services LLC, El Segundo, California, April 2005.

**For further details about GPS satellite interfrequency biases, see**

"GPS Satellite Interfrequency Biases" by C. Yinger, W. Feess, R. Di Esposti, A. Chasko, B. Cosentino, D. Syse, B. Wilson, and B. Wheaton in *Proceedings of the 55th Annual Meeting of The Institute of Navigation*, Cambridge, Massachusetts, June 28–30, 1999, pp. 347–354.

"New and Improved: The Broadcast Interfrequency Biases" by B.D. Wilson, C.H. Yinger, W.A. Fees, and C. Shank in *GPS World*, Vol. 10, No. 9, September 1999, pp. 56–66.

"The 2 SOPS User Range Accuracy (URA) Improvement and Broadcast Inter-Frequency Bias ($T_{GD}$) Updates" by M. Rivers, in *Proceedings of ION GPS-2000*, the 13th Technical Meeting of the Satellite Division of The Institute of Navigation, Salt Lake City, Utah, September 19–22, 2000, pp. 2,551–2,555.

**For additional discussions about the GPS–Galileo relative timing biases, see**

"GPS/GALILEO Time Offset: Preliminary Interface Definition" by J. Hahn and E. Powers, attachment to the *Agreement on the Promotion, Provision and Use of Galileo and GPS Satellite-based Navigation Systems and Related Applications*, which was signed by representatives of the United States and the member states of the European Union in Dublin, Ireland, on June 26, 2004.

"Time Dissemination and Synchronization for Galileo Users" by A. Moudrak, J. Furthner, A. Konovaltsev, H. Denks, and J. Hammesfahr in *Proceedings of The Institute of Navigation National Technical Meeting*, San Diego, California, January 26–28, 2004, pp. 323–332.

"GPS Galileo Time Offset: How It Affects Positioning Accuracy and How to Cope with It" by A. Moudrak, A. Konovaltsev, J. Furthner, A. Hornbostel, and J. Hammesfahr in *Proceedings of ION GNSS 2004*, the 17th Technical Meeting of the Satellite Division of The Institute of Navigation, Long Beach, California, September 21–24, 2004, pp. 660–669.

"Interoperability on Time: GPS-Galileo Offset Will Bias Position" by A. Moudrak, A. Konovaltsev, J. Furthner, J. Hammesfahr, A. Bauch, P. Defraigne, S. Bedrich, and A. Schroth in *GPS World,* Vol. 16, No. 3, March 2005, pp. 24–32.

**For assessments of the effects of multipath on GNSS signals, see**

"Multipath Mitigation: How Good Can It Get with New Signals?" by L.R. Weill in *GPS World*, Vol. 14, No. 6, June 2003, pp. 106–113.

"Multipath Performance of the New GNSS Signals" by C. Hegarty, M. Tran, and J.W. Betz in *Proceedings of The Institute of Navigation National Technical Meeting*, San Diego, California, January 26–28, 2004, pp. 333–342.

**For the seminal paper on delay lock loops, see**

"The Delay Lock Loop Discriminator — an Optimum Tracking Device" by J.J. Spilker Jr. and D. T. Magill in *Proceedings of the Institute of Radio Engineers*, Vol. 49, No. 9, 1961, pp. 1,403–1,416.

**For a discussion of the effect of surface acoustic wave filters on GPS receiver preamplifier performance, see**

"Performance Degradation in GPS-Receivers Caused by Group Delay Variations of SAW-Filters" by T. Muller in *Microwave Symposium Digest*, Proceedings of the 1998 IEEE MTT-S International Microwave Symposium, Baltimore, Maryland, June 7–12, 1998, pp. 495–498.