

# The Effect of Nominal Signal Deformations on ARAIM Users

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## ABSTRACT

Predictions of the future performance of ARAIM users depend on a thorough understanding of the nominal performance of the satellites from all constellations. This generally requires long-term, careful monitoring and analysis of all the signals of interest in order to determine future real-world performance expectations. To date, relatively little work has gone into analyzing the effects that nominal range biases, such as signal deformations could have on ARAIM performance.

In this paper, nominal signal deformation measurements, analysis techniques, and results previously used for GPS and SBAS (Space-Based Augmentation Systems) are extended to ARAIM. Measured data previously used to characterize the GPS nominal biases on L1 C/A code is used to estimate the effects of potential nominal range biases on several future satellite navigation ranging signals including GPS L5, Galileo E1 and E5a, and GLONASS L1 and L2. The possible user receiver implementations for each respective signal are modeled to find the range of biases for typical users. Stanford University's Matlab Accuracy and Availability Simulation Tool (MAAST) is then used to predict ARAIM user vertical protection levels (VPLs) given these biases. It is found that traditional approach for applying the worst-case pseudorange bias to all signals may be inadequate to assure integrity. The biases may vary significantly depend on the codes and frequencies considered, and they are constellation-specific. Ultimately, acceptable ARAIM performance may rely on practical user receiver design constraints and more sophisticated integrity analyses to minimize the effects of pseudorange biases on the VPL.

## ADVANCED RECEIVER INTEGRITY MONITORING (ARAIM) AND RANGE BIASES

Advanced Receiver Autonomous Integrity Monitoring (ARAIM) potentially provides high-integrity navigation worldwide with minimal ground monitoring. In other words, ARAIM offers the same or better performance as

regional ground-based or space-based augmentation systems (i.e., GBAS and SBAS, respectively) at greatly reduced costs. However, ARAIM has a much higher reliance on past experience of satellites and error models of their signals and failure modes than traditional augmentation systems. This poses a particular challenge since ARAIM will rely on satellites constellations that are significantly less mature and understood than GPS. For this reason, experience with GPS must be leveraged to the extent possible to analyze the potential performance of ARAIM users.

ARAIM analyses make assumptions about a number of parameters to assess future user performance. Among the most significant are the following:

- number of satellite constellations
- types of constellation or constellation service provider
- the number of satellites per constellation
- the probability of a satellite fault
- the probability of a constellation-wide fault
- the broadcast URA of the satellites
- the maximum range bias magnitude

Each of these assumptions affects the results predicted by ARAIM analyses. However, while much attention has been given to modeling and validating the effects random errors (i.e., errors that directly enter into the URA validation) have on ARAIM performance, relatively little attention has been given to modeling, understanding, and validating the model and effects of unmodeled range biases.

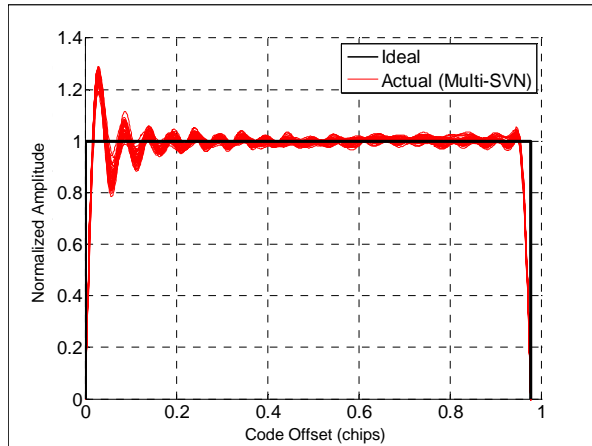
For the purposes of this paper, biases will refer specifically to tracking error biases. These are biases that come from minor distortions of the correlation peaks within the user receivers. Because these distortions vary from signal-to-signal, they cause pseudorange errors which can lead to erroneous position errors, even in the absence of other error sources. Such biases may include (but are not necessarily limited to) low-frequency multipath, antenna group delay variations, and nominal

satellite signal deformations. This paper focuses only on the effects of nominal signal deformation biases.

## ARAIM AND NOMINAL SIGNAL DEFORMATIONS

Biases caused by signal deformations are often particularly challenging to observe and to analyze. Nominal signal deformations are subtle distortions of the transmitted signals caused by differences in the signal generating hardware onboard the satellites. These variations in the transmitted signal create ranging errors that depend on receiver implementation.

Nominal signal deformations on the GPS C/A code (L1) and the new civil code (L5) and have been measured previously by others and are discussed in detail in [1] and [2] and [3]. (Refer to Figure 1.) The range biases caused by them have also been discussed in the past [4]. Much of the previous work, however, has analyzed these biases in relation to SBAS. These analyses have several assumptions, however, that may not hold true for ARAIM.

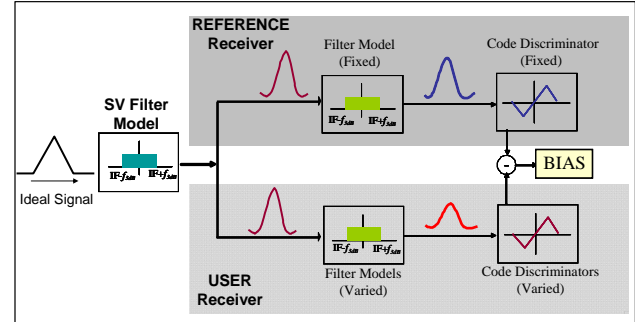


**Figure 1.** Measured GPS C/A code chips for 32 GPS SVs.

For example, SBAS and GBAS user receivers utilize a ground monitoring network that provides real-time differential corrections. Those differential corrections originate from a specific ground reference receiver implementation. As a result, any analysis of signal deformation biases requires knowledge of the design configuration of the reference receiver and constraints on the potential designs of the user receivers.

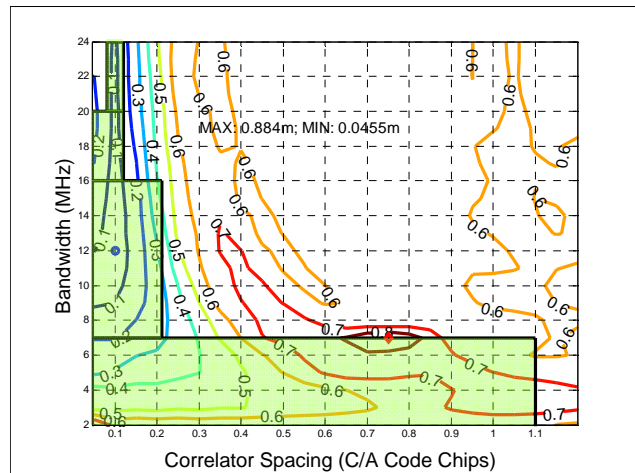
Figure 2 shows a block diagram of the tracking error bias analysis process. The signal model filters the ideal signal first. Then models for the reference receiver and the various user receivers—i.e., various pre-correlation filter

bandwidths, filter group delays, and discriminator correlator spacings—are applied. Next, on each signal, discriminators of particular correlator spacings are implemented. The bias errors from nominal signal formations are simply the differences between the computed user receiver and reference receiver tracking solutions for each distorted signal.



**Figure 2.** Block diagram of the signal deformation bias analysis process

Figure 3 shows a contour plot for the maximum (magnitudes of) nominal deformations applicable to current and future SBAS receivers tracking GPS L1 C/A code with early-minus-late (EML) discriminators. The areas shaded in green highlight the user receiver configurations that are allowed for aviation users by the Minimum Operational Performance Standard (MOPS) [5]. For this result, the reference receiver had a filter bandwidth of 24MHz and 0.1-chip EML discriminator spacing. Note that the errors are less than 20 cm in the regions nearest the reference configuration but are as large as 90 cm for configurations that differ substantially from it.

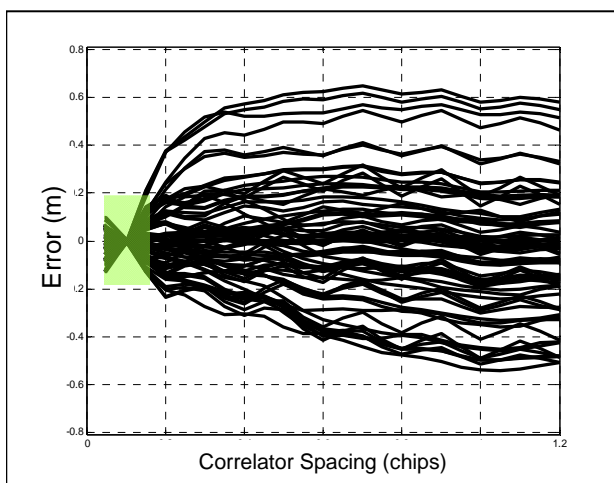


**Figure 3.** Contour plot of the maximum signal deformation bias errors for early-minus late (EML) receivers tracking GPS L1 C/A. Allowed SBAS receiver configurations are in green highlighted areas. (Reference receiver is 24MHz, 0.1-chip spacing.)

Note that as SBAS is modernized to incorporate the L5 signal, the receiver designs with nominal signal deformations errors greater than approximately 15-20 cm will likely be excluded. This is in anticipation of dual-frequency ranging, which amplifies these biases.

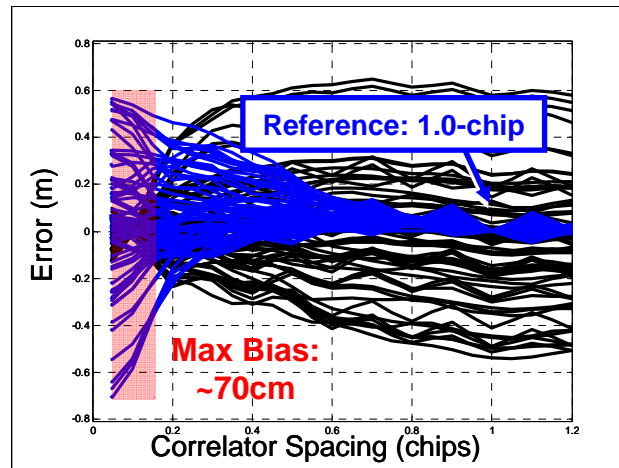
The dual-frequency receivers being contemplated for SBAS and ARAIM will likely have the same design configurations. However, the effective reference receiver for ARAIM will not be selected with aviation integrity in mind. Instead, the ground reference will be the receivers chosen by the constellation service providers (CSP)—U.S.A. (GPS), European Union (Galileo), Russia (GLONASS), or China (Beidu). And each CSP will optimize its services for all potential navigation purposes, not just aviation. The ground segment for GPS, for instance, provides corrections for the C/A code using L1-P(Y) code receivers. These may or may not be corrections that approximate the SBAS reference receiver (24MHz, 0.1-chip). They could easily provide corrections more akin to a 1.0-chip chip receiver. This means ARAIM may need to cope with signal deformation errors that are significantly larger than those of SBAS.

Figure 4 shows the case for user receiver designs (for GPS L1 C/A code) with a bandwidth of 20MHz and EML discriminator correlator spacings ranging from 0.05 C/A chips. The green shaded area indicates the area allowed for SBAS receivers. The blue traces in Figure 5 illustrate how the same bias errors would change assuming a reference receiver of 1.0-chip spacing. In other words, in the case of SBAS, the errors would remain below 20 cm, but if the reference spacing was significantly different, those same user receivers could experience nearly 70 cm of error.



**Figure 4.** Early-minus-late signal deformation tracking error biases for 20 MHz user receivers and reference receiver with 24 MHz, 0.1-chip correlator spacing.

Allowed SBAS user receiver correlator spacings are in green highlighted area.



**Figure 5.** Early-minus-late signal deformation tracking error biases for 20 MHz user receivers. BLACK: Reference receiver has 24 MHz, 0.1-chip correlator spacing; BLUE: Reference receiver has 20 MHz, 1.0-chip correlator spacing; Allowed SBAS/ARAIM user receiver correlator spacings are in red highlighted area.

For the current constellation of GPS satellites and users, ARAIM integrity analyses would need to presume the larger errors are present. These are the worst-case user bias errors when the reference and user receivers are mismatched (when the receiver bandwidths are both 20MHz wide). GPS-III, the next generation of GPS satellites, however, will likely provide corrections for the C/A code that are applicable to the 0.1-chip spacing. In that case the smaller, SBAS-like (~20 cm) signal deformation error assumptions would apply. Of course, this would only help those user receivers capable of using those newer signals and their correction messages. Users equipped with legacy receivers would not benefit from this improvement.

## NOMINAL SIGNAL DEFORMATIONS ON ALTERNATE SIGNALS

While the nominal signal deformation characteristics for GPS C/A code have been measured, there is no comparable set of code measurements on the L5 code. Many L5-capable satellites have yet to be launched. (The first such satellite (SV, however, was measured and the results compared favorably to those on the C/A code [6].)

Even less has been done to characterize the signal deformations on GLONASS and Galileo signals. At the time of writing of this paper, the Galileo constellation has only four SVs on-orbit. The GLONASS constellation is full, but its satellites broadcast on L1 and L2 only. While

this makes it a good candidate for prototyping ARAIM algorithms, if the signal at L2 cannot be used for aviation. All these constellation uncertainties make estimating the signal deformation characteristics of these additional signals problematic. Still, it is possible leverage our experience with the GPS codes to gain insight into how signal deformation biases on all these additional signals could ultimately affect ARAIM performance.

To model the effects of signal deformation biases on users the following procedure was used:

- 1) Obtain models of the nominal signal deformations on the L1 signals from each GPS satellite.
- 2) Apply the models to the various codes corresponding to the constellations of interest, namely GPS, Galileo, and GLONASS.
- 3) Determine the ranges of signal deformation bias errors for all potential ARAIM user receiver configurations.
- 4) Simulate the affect these biases have on ARAIM user VPLs.

*1. Obtain models of the nominal signal deformations on the L1 signals from each GPS satellitel.*

In the absence of measurements for all the PRN codes on the various signals, a model for nominal signal deformations was derived from high-resolution measurements of the transmitted GPS C/A codes. The ideal PRN codes,  $C_{ideal,j}$  were removed from each measurement  $C_{meas,j}(t)$  to form  $J$  filter transfer functions as shown in Equation 1. (The total number of nominal deformation transfer functions,  $J$ , equaled the number of GPS PRN code measurements.)

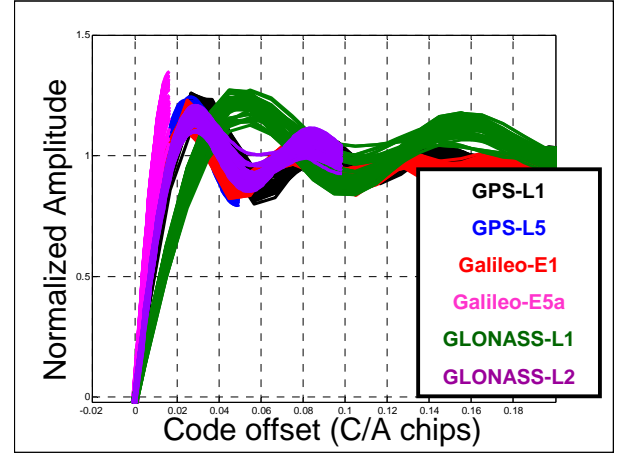
$$H_{nom,j}(f) = \frac{\int_{-\infty}^{\infty} C_{meas,j}(t) e^{-j2\pi ft} dt}{\int_{-\infty}^{\infty} C_{ideal,j}(t) e^{-j2\pi ft} dt} \quad j = 1 \text{ to } J \quad \text{Eq. 1}$$

*2. Apply the models to the various signals corresponding to the constellations of interest, namely GPS, Galileo, and GLONASS.*

Once the transfer functions were obtained, they were applied to the signals of interest according to Equation 2. Figure 6 plots the chip transitions (up to one-half the chip width) for each the six signals, relative to the L1 C/A code chip. This includes the two civil signals for GPS (L1 and L5), two for Galileo (E1 and E5a), and two for GLONASS (L1 and L2). Figure 7 plots the

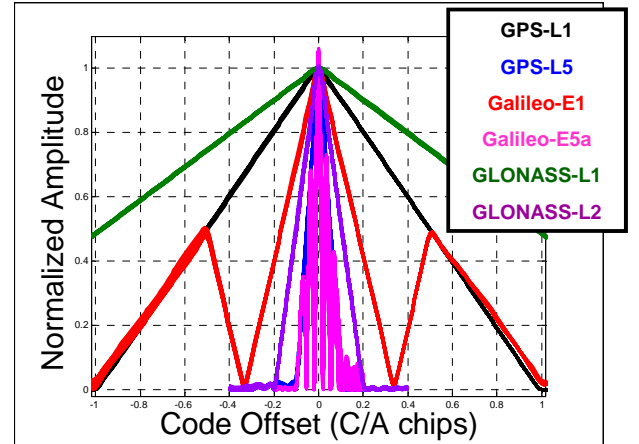
corresponding nominally-distorted correlation peaks for these signals. (Equation 3 provides the general equations for the correlation functions.)

$$C_{nom,j}(\tau) = \int_{-\infty}^{\infty} H_{nom,j}(f) C_{ideal,j}(f) e^{j2\pi f\tau} df \quad (\text{Eq. 2})$$



**Figure 6.** Modeled nominal signal deformations on all six codes. (Chip transitions shown only.)

$$R_{nom,j}(\tau) = \int_{-\infty}^{\infty} C_{nom,j}(f) C_{ideal,j}^*(f) e^{j2\pi f\tau} df \quad (\text{Eq. 3})$$

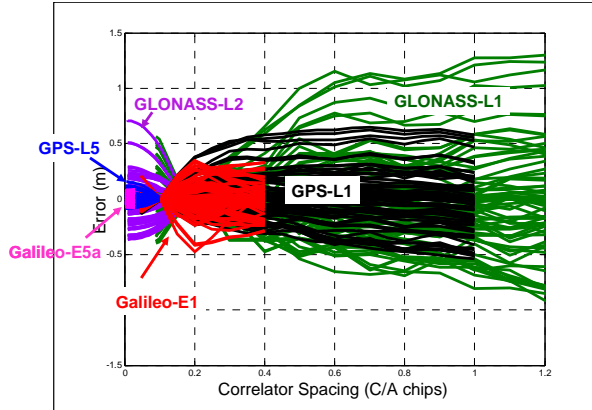


**Figure 7.** Modeled nominal signal deformations on the correlation peaks for all six codes.

*3. Determine the ranges of signal deformation bias errors for all potential ARAIM user receiver configurations*

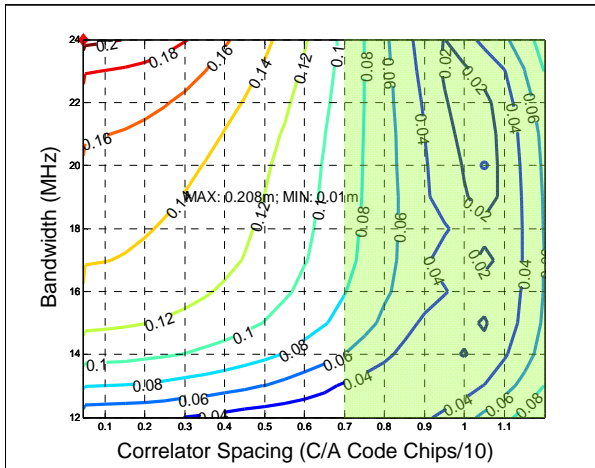
For a 20 MHz user receiver, the tracking errors at all EML correlator spacings for each respective signal are shown in Figure 8. The span of errors is highly dependent on the signal to which the distortion model is applied. As would be expected with multipath mitigation properties, the wide-bandwidth, higher-modulation signals (i.e., L5,

E5a) tend to have smaller ranges of signal deformation bias errors.

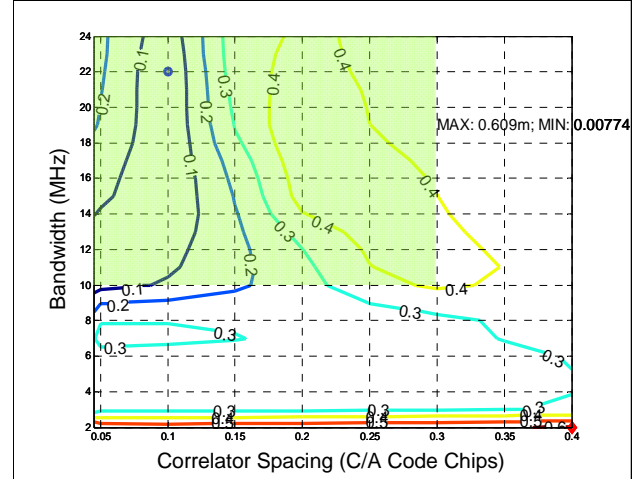


**Figure 8.** Early-minus-late signal deformation tracking error biases for 20 MHz user receivers. Reference receiver has 20 MHz; reference correlator spacings for each signal are as specified in Table 1.

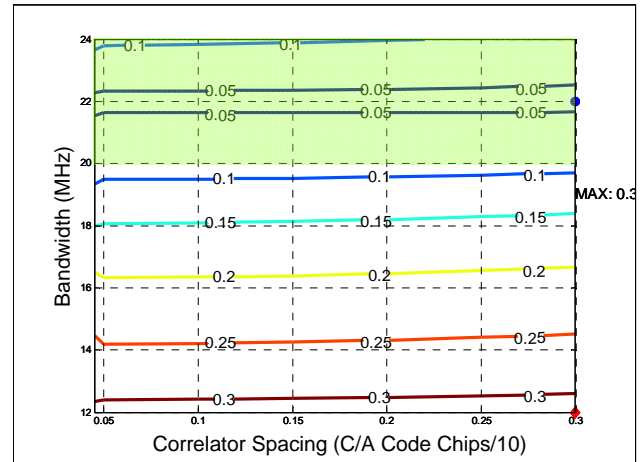
Figures 9 through 13 plot all the assumed user errors for the full span of expected receiver filter bandwidths and correlator spacings, relative to their respective code chipping rates. (For each signal, a practical reference receiver configuration was assumed; this configuration is identified in each figure caption.) The green highlighted areas highlight the typical (i.e., expected) user receiver configurations. Table 1 summarizes the maximum expected biases for each satellite constellation and signal discussed in this paper and plotted in Figures 9 through 13.



**Figure 9.** Contour plot of the projected GPS L5 signal deformation bias errors for early-minus late (EML) receivers. “Typical” receiver configurations are in green highlighted areas. (Reference receiver is 24 MHz, 1.0-chip spacing.)

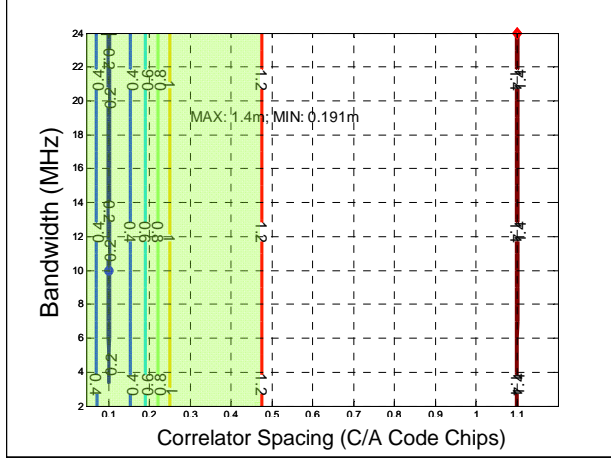


**Figure 10.** Contour plot of the projected Galileo E1 signal deformation bias errors for early-minus late (EML) receivers. “Typical” receiver configurations are in green highlighted areas. (Reference receiver is 24 MHz, 0.1-chip spacing.)

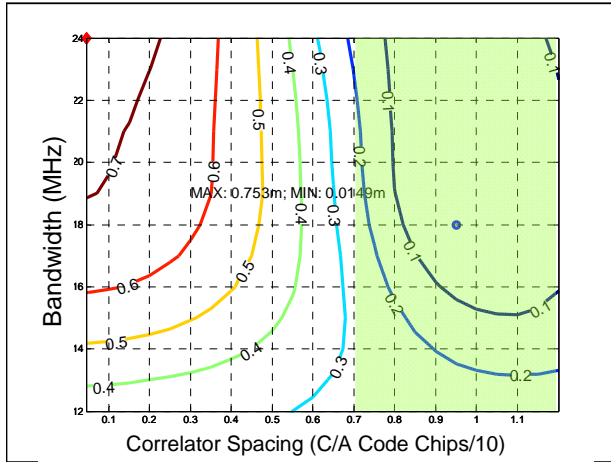


**Figure 11.** Contour plot of the projected Galileo E5a signal deformation bias errors for early-minus late (EML) receivers. “Typical” receiver configurations are in green highlighted areas. (Reference receiver is 24 MHz, 0.3-chip spacing.)





**Figure 12.** Contour plot of the projected GLONASS L1 signal deformation bias errors for early-minus late (EML) receivers. “Typical” receiver configurations are in green highlighted areas. (Reference receiver is 24MHz, 0.1-chip spacing.)



**Figure 13.** Contour plot of the projected GLONASS L2 signal deformation bias errors for early-minus late (EML) receivers. “Typical” receiver configurations are in green highlighted areas. (Reference receiver is 24MHz, 1.0-chip spacing.)

Note that the results of Table 1 apply to single-frequency users. However, ARAIM relies on two signal frequencies to remove the ionospheric delay errors. This means any single-frequency biases must be multiplied by the scaling factors used in forming the dual-frequency pseudorange. Simplified expressions for the dual-frequency pseudorange equations ( $\rho_{DF}$ ) are given in Equations 4 and 5 for the L1/L5 (for GPS and Galileo satellites) and L1/L2 combinations (for GLONASS satellites), respectively.

$$\rho_{DF} = 2.26\rho_{L1/E1} - 1.26\rho_{L5/E5a} \quad (\text{Eq. 4})$$

$$\rho_{DF} = 2.546\rho_{L1} - 1.546\rho_{L2} \quad (\text{Eq. 5})$$

**Table 1.** Estimated Maximum Signal Deformation Bias Errors for Early-Minus-Late (EML) User Receivers

| Signal         | Reference Correlator Spacing (chips) | Max User Signal Deformation Bias Errors (m) |           |
|----------------|--------------------------------------|---|-----------|
|                |                                      | Typical User                                | All Users |
| GPS – L1 (C/A) | 0.1                                  | 0.6   | 0.9       |
| GPS – L5       | 1.0                                  | 0.1   | 0.2       |
| Galileo – E1   | 0.1                                  | 0.4   | 0.6       |
| Galileo – E5a  | 0.3                                  | 0.1   | 0.3       |
| GLONASS – L1   | 0.1                                  | 1.2   | 1.4       |
| GLONASS – L2   | 1.0                                  | 0.2   | 0.75      |

Recall from Figure 8 that signal deformations biases can be positive as well as negative. This implies that the worst-case dual-frequency errors occur when the signs of the biases between signals add constructively with each other (i.e., positive on L1 but negative on L5 or L2). Since it is impossible to know when this situation arises and for which users it is true, current ARAIM integrity analyses compute position solutions for a worst-case user—one for which the biases on each signal sum to their largest magnitudes on each dual-frequency pseudorange. Table 2 summarizes the maximum (i.e., worst-case) signal deformation bias errors ARAIM assumes for each constellation under this condition.

**Table 2.** Maximum Signal Deformation Biases on Each Pseudorange

| Constellation | Max Dual-Frequency User Signal Deformation Bias Errors (m) |           |
|---------------|--|-----------|
|               | Typical User   | All Users |
| GPS           | 1.48   | 2.29      |
| Galileo       | 1.03   | 1.73      |
| GLONASS       | 3.36   | 4.72      |

## EFFECT OF NOMINAL SIGNAL DEFORMATION BIASES ON ARAIM USER PERFORMANCE

Several metrics are generally used to evaluate ARAIM user performance. Among others, these include accuracy ( $\sigma_{acc}$ ), availability, and the horizontal and vertical protection levels (HPL and VPL, respectively). In this paper, the VPL was used to evaluate the effects of

nominal signal deformation biases on ARAIM user performance because it provides perhaps the best insight into how these pseudorange biases can lead to user position errors. A threshold of 35 meters was selected as a very simple metric for distinguishing acceptable user VPLs from unacceptably large ones.

**Table 3.** Summary of Signal Deformation Bias Cases for MAAST Runs to Evaluate ARAIM VPL Performance

| Signal Deformation (SD) Bias Case No.           | Constellations   |   |
|---|--|---|
|   | GPS (24) + Galileo (30)  | GPS (24) + GLONASS (23)   |
| <b>1.</b><br>No SD bias                         | GPS: 0 m<br>GAL: 0 m<br><br>(Figure 14)  | GPS: 0 m<br>GLO: 0 m<br><br>(Figure 20)   |
| <b>2.</b><br>Constant 75 cm Biases              | GPS: 0.75 m<br>GAL: 0.75 m<br><br>(Figure 15)  | GPS: 0.75 m<br>GLO: 0.75 m<br><br>(Figure 21)   |
| <b>3.</b><br>Known Biases, Typical Receivers    | GPS L1: U[-0.6 0.6]<br>GPS L5: U[-0.1 0.1]<br><br>GAL E1: U[-0.4 0.4]<br>GAL E5a: U[-0.1 0.1]<br>(single-frequency errors (m), uniformly distributed)<br><br>(Figure 16) | GPS L1: U[-0.6 0.6]<br>GPS L5: U[-0.1 0.1]<br><br>GLO L1: U[-1.2 1.2]<br>GLO L2: U[-0.2 0.2]<br>(single-frequency errors (m), uniformly distributed)<br><br>(Figure 22) |
| <b>4.</b><br>Known Biases, All Receivers        | GPS L1: U[-0.9 0.9]<br>GPS L5: U[-0.2 0.2]<br><br>GAL E1: U[-0.6 0.6]<br>GAL E5a: U[-0.3 0.3]<br><br>(Figure 17)   | GPS L1: U[-0.9 0.9]<br>GPS L5: U[-0.2 0.2]<br><br>GLO L1: U[-1.4 1.4]<br>GLO L2: U[-0.75 0.75]<br><br>(Figure 23)   |
| <b>5.</b><br>Unknown Biases, Typical Receivers  | GPS: 1.48 m<br>GAL: 1.03 m<br><br>(Figure 18)  | GPS: 1.48 m<br>GLO: 3.36 m<br><br>(Figure 24)   |
| <b>6.</b><br>Unknown Biases, All User Receivers | GPS: 2.29 m<br>GAL: 1.73 m<br><br>(Figure 19)  | GPS: 2.29 m<br>GLO: 4.72 m<br><br>(Figure 25)   |

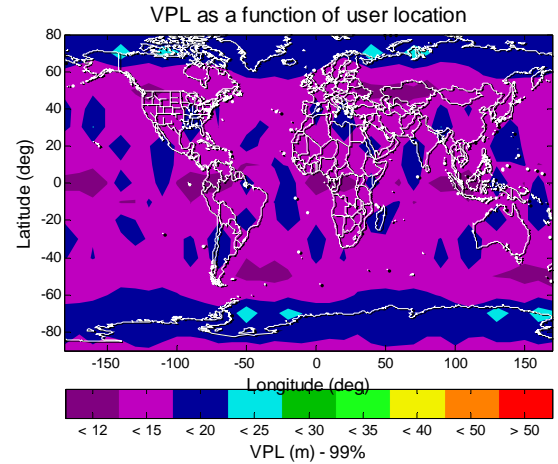
Stanford's Matlab Algorithm Availability Simulation Tool (MAAST) was used to generate VPL contours for a total of 12 nominal bias scenarios. (MAAST is available online and implements the ARAIM algorithms as described in [7].) All of these scenarios are summarized in Table 3. Six cases apply to simulated GPS + Galileo constellations, and the other six apply for simulated GPS + GLONASS constellations; both used a simulated time step of 300 seconds. All other ARAIM parameters were held constant for all cases. The values for the key parameters are as follows:

- Number of satellite constellations: 2

- Constellations used
  - GPS + Galileo
  - GPS + GLONASS
- Number of satellites per constellation
  - GPS: 24 SVs
  - Galileo: 30 SVs
  - GLONASS: 23 SVs
- Probability of a satellite fault:  $P_{\text{sat}} = 10^{-5}$
- Probability of a constellation-wide fault:  $P_{\text{const}} = 10^{-5}$
- Broadcast URA of the satellites: 0.75m
- VPL Performance Evaluation Metric:
  - all VPLs <35m
- Maximum range bias magnitude: (See Table 3.)

#### GPS + Galileo

Figures 14 through 19 show color map VPL results for ARAIM users using only the GPS (24) and Galileo (30) constellations. In the case where there are no biases on any signals, as shown in Figure 14, the VPL threshold is easily met. In fact, no VPLs exceed 25 meters in this case. The 35-meter limit becomes significantly more difficult to meet when biases are nonzero, however.

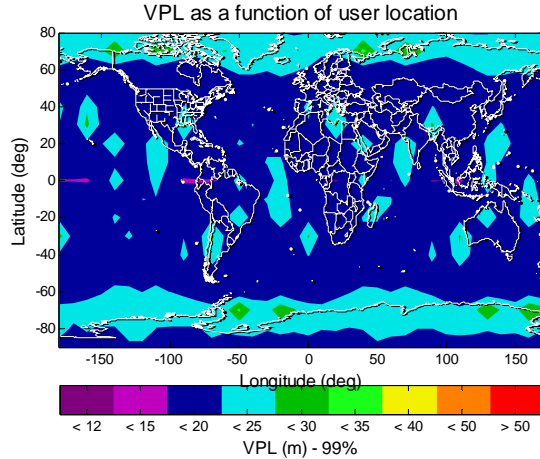


**Figure 14.** Case 1. ARAIM VPLs worldwide for GPS (24 SVs) + Galileo (30 SVs) and no pseudorange biases.

When a small, constant bias of 75 cm is assumed, the maximum VPLs increase significantly. Figure 15 shows the case where this magnitude of bias is placed on the dual-frequency pseudoranges for both GPS and Galileo SVs. The figure reveals that while the VPLs do become relatively large in some places, they still remain below 35 meters.

Note that for dual-frequency SBAS users (i.e., the user receivers and ground receivers are nearly matched), an assumption of 75 cm would be somewhat conservative. In fact, a 75 cm dual-frequency bias roughly equates to a

nominal deformation bias of about 25 cm on L1 and 15 cm on L5, for GPS and Galileo signals. This is larger than the expected biases typical dual-frequency users (i.e., high-bandwidth, narrow correlator) of SBAS should expect since the ground reference receiver has a similar configuration.

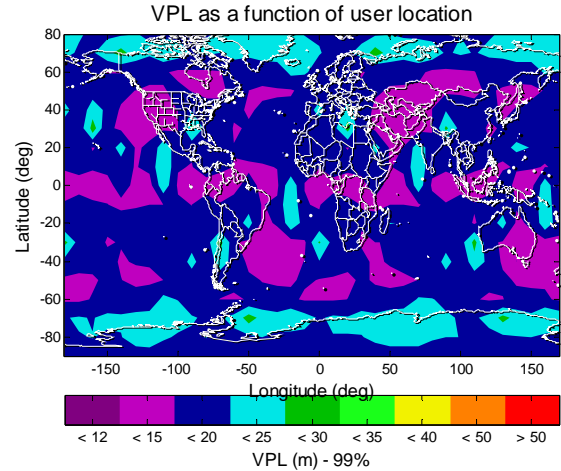


**Figure 15.** Case 2. ARAIM VPLs worldwide for GPS (24 SVs) + Galileo (30 SVs); constant 75 cm pseudorange bias.

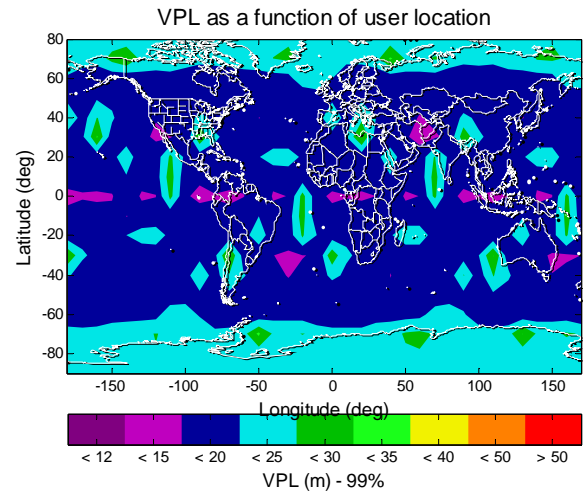
Case 3 introduces the signal-dependent nominal biases computed previously. If the biases on each signal and SV were known, that information could be used to reduce the conservatism in the integrity analysis. Frequently, the signs of the biases and those of dual-frequency range equation (Eq. 4) combine favorably, provide some cancellation, and thereby allow for some error reduction. Figure 16 illustrates this case.

With a uniform distribution of biases on each signal for typical ARAIM receiver designs (as specified previously in table 2), the maximum VPLs are, in fact, slightly smaller (<30 m instead of <35 m) than those that result from the previous, more conventional bias assumption of 0.75 cm on each signal. This holds despite the fact that the typical ARAIM user receiver designs considered herein are less restrictive than those of traditional SBAS receiver designs, which the previous case presumed.

When the allowed user receiver designs are broadened further, the errors do increase. However, as shown in Figure 17, they still remain less than 35 meters. Unfortunately, knowledge of the bias on each satellite signal is something we seldom have. As a result, worst case (i.e., maximum bias error) assumptions are generally used to ensure the errors are well-bounded and users are protected.



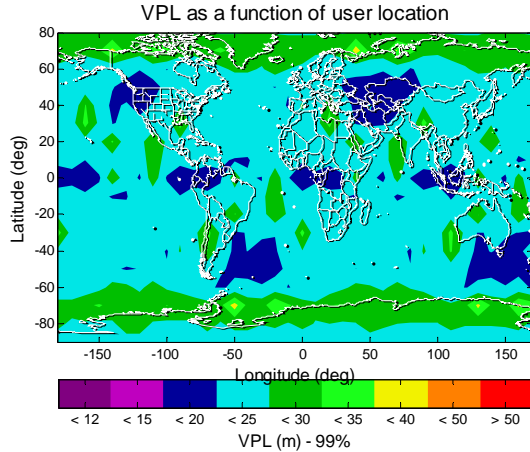
**Figure 16.** Case 3. ARAIM VPLs worldwide for GPS (24 SVs) + Galileo (30 SVs); typical user receiver designs; known, uniformly-distributed signal deformation biases.



**Figure 17.** Case 4. ARAIM VPLs worldwide for GPS (24 SVs) + Galileo (30 SVs); all user receiver designs; known, uniformly-distributed signal deformation biases.

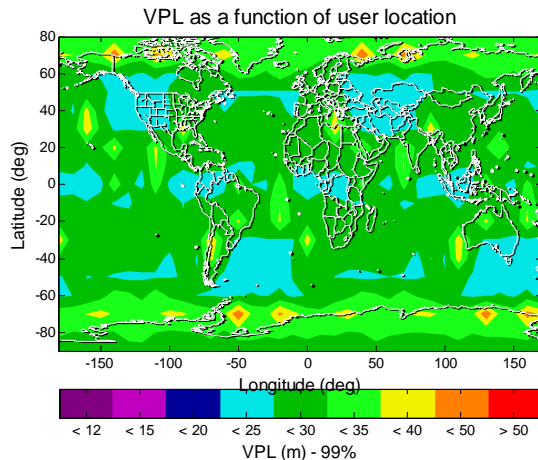
Figure 18 shows the case for typical ARAIM receiver designs assuming the worst-case biases are present on each dual frequency range. This is a similar analysis to that computed for Figure 15; however, in this case, the biases are specific to each constellation. In addition, these biases are come from more appropriate estimates of the nominal signal deformation characteristics of the signals. And, as is clear from Table 2, the new bias estimates are significantly larger than 75 cm. As a result, the VPLs do exceed 35 meters in some locations.





**Figure 18.** Case 5. ARAIM VPLs worldwide for GPS (24 SVs) + Galileo (30 SVs); typical user receiver designs; worst-case signal deformation biases.

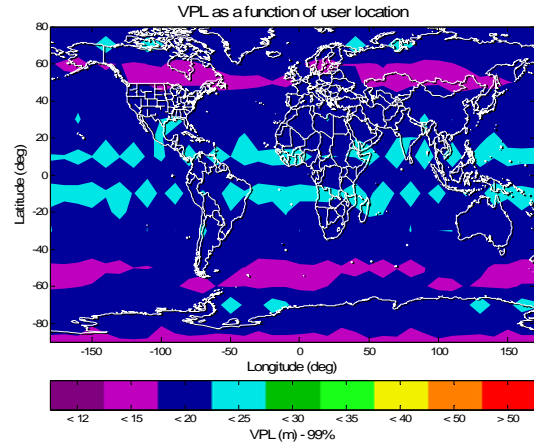
The impact of these more-plausible bias assumptions, in combination with this conservative analysis approach, is made even clearer in Figure 19. When more receiver designs are permitted, the VPLs approach 50 meters in some locations. Even the minimum VPL becomes as large as 20 meters.



**Figure 19.** Case 6. ARAIM VPLs worldwide for GPS (24 SVs) + Galileo (30 SVs); all user receiver designs; worst-case signal deformation biases.

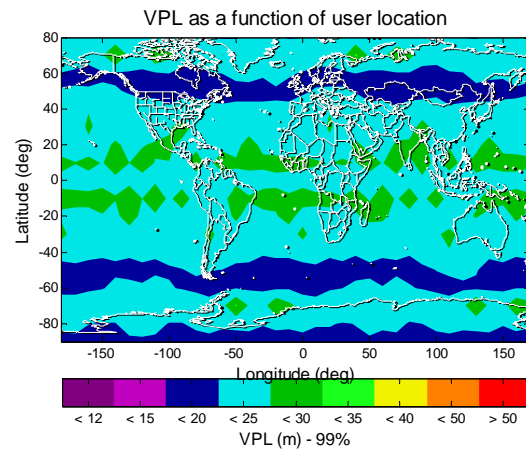
Figures 20 through 25 show the VPL results for ARAIM users of the GPS and GLONASS constellations. In general, the VPLs for these cases follow the same patterns as they did for the GPS+Galileo scenarios. The GLONASS constellation, however, was simulated with only 23 SVs; this allowed for generally weaker geometries. In addition, due to differences in code structures and the signal frequencies, the magnitudes of the biases were larger on GLONASS pseudoranges. (Refer to Figure 8.) Both of these conditions caused the ARAIM VPLs to be significantly higher with GLONASS

than they were when the Galileo constellation was simulated. (This is particularly true for the minimums.)

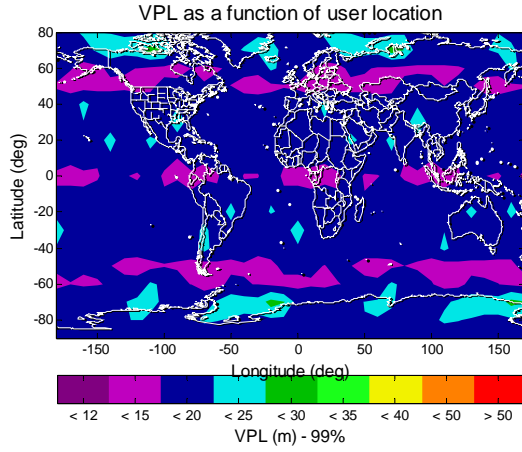


**Figure 20.** Case 1. ARAIM VPLs worldwide for GPS (24 SVs) + GLONASS (23 SVs) and no pseudorange biases.

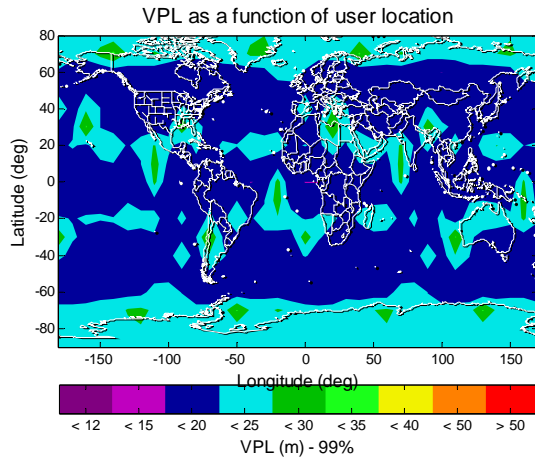
For Case 2 (shown in Figure 21), note that the effective single-frequency bias equivalence for all satellites is a bit more difficult to estimate than it was for the GPS and Galileo constellations in Figure 15. This is because the dual-frequency scaling factors are different for L1 and L2 than they are for L1 and L5. Still, a GLONASS-only constellation would require a 23 cm bias on L1 and 10 cm bias on L2 to result in a dual-frequency pseudorange bias of 74 cm. It follows that the assumption of a 75 cm bias on all pseudoranges would likely not be a sufficiently conservative assumption for ARAIM users of GLONASS L1/L2.



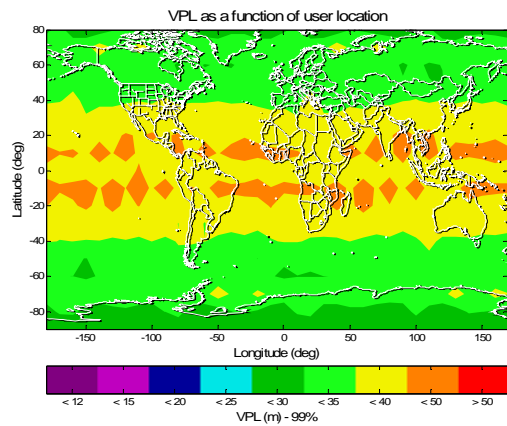
**Figure 21.** Case 2. ARAIM VPLs worldwide for GPS (24 SVs) + GLONASS (23 SVs); constant 75 cm pseudorange bias.



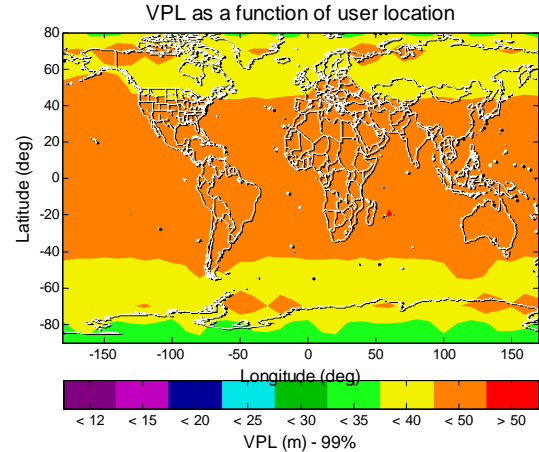
**Figure 22.** Case 3. ARAIM VPLs worldwide for GPS (24 SVs) + GLONASS (23 SVs); typical user receiver designs; known, uniformly-distributed signal deformation biases.



**Figure 23.** Case 4. ARAIM VPLs worldwide for GPS (24 SVs) + GLONASS (23 SVs); all user receiver designs; known, uniformly-distributed signal deformation biases.



**Figure 24.** Case 5. ARAIM VPLs worldwide for GPS (24 SVs) + GLONASS (23 SVs); typical user receiver designs; worst-case signal deformation biases.



**Figure 25.** Case 6. ARAIM VPLs world wide for GPS (24 SVs) + GLONASS (23 SVs); all user receiver designs; worst-case signal deformation biases.

**Table 3.** Summary of Signal Deformation Bias Results for MAAST Runs to Evaluate ARAIM VPL Performance

| Signal Deformation (SD) Bias Case No.         | Constellations                |                               |
|---|-------------------------------|-------------------------------|
|   | GPS (24) + Galileo (30)       | GPS (24) + GLONASS (23)       |
| 1.<br>No SD bias                              | 12 < VPLs < 25<br>(Figure 14) | 15 < VPLs < 25<br>(Figure 20) |
| 2.<br>Constant SD Biases, SBAS-like Receivers | 15 < VPLs < 35<br>(Figure 15) | 20 < VPLs < 35<br>(Figure 21) |
| 3.<br>Known SD Biases, Typical Receivers      | 15 < VPLs < 30<br>(Figure 16) | 15 < VPLs < 30<br>(Figure 22) |
| 4.<br>Known SD Biases, All Receivers          | 15 < VPLs < 35<br>(Figure 17) | 20 < VPLs < 35<br>(Figure 23) |
| 5.<br>Unknown SD Biases, Typical Receivers    | 20 < VPLs < 40<br>(Figure 18) | 35 < VPLs < 50<br>(Figure 24) |
| 6.<br>Unknown SD Biases, All User Receivers   | 25 < VPL < 50<br>(Figure 19)  | 35 < VPLs < 50<br>(Figure 25) |

Table 3 summarizes the results for all the bias and constellation scenarios. Although the VPLs for ARAIM users when the GPS+GLONASS constellations are employed are noticeable larger than the GPS+Galileo

cases, they still remain below 35 m whenever the biases relatively small. The VPLs are also acceptable whenever the biases can be assumed known and provide some degree of cancellation. Using the most conservative analysis approach, however, may present some problems for the future. When the more-plausible, constellation-specific, maximum (i.e., worst case) biases are assumed, the VPLs can quickly become unacceptably large. Unfortunately this is currently the most accepted analysis approach for assuring the integrity of ARAIM users.

## CONCLUSIONS

Previously-measured nominal signal deformations on GPS L1 (C/A code) were used to generate a models that could be applied to the modernized signals on Galileo and GLONASS signals. While these models may eventually prove to be optimistic for the newer constellations and signals, in the absence of measurements for them, this approach provides the capability of estimating the signal deformation biases on receivers that uses their signals.

Typical user receivers were modeled to determine the expected biases on each of the signals of all three constellations. The range of biases errors on the GPS were moderate, and, as expected, the biases on the more-modernized Galileo L1 and L5 codes were relatively small. Because the GLONASS codes (L1 and L2) codes have relatively large chip widths, the range of potential user signal deformation biases relatively large.

Traditional ARAIM pseudorange bias assumptions—e.g., a constant pseudorange bias of 75 cm—may be inadequate. It is a conservative estimate for a typical (dual-frequency) SBAS user receiver, but it presumes the user receivers and ground reference receivers have a similar design configuration. ARAIM solutions, however, rely on a ground reference receiver design that may differ more substantially from the user receiver. Hence, more conservative biases should be assumed.

As expected, the ARAIM VPL performance estimates predicted using the 75 cm bias on all signals easily kept all VPLs below 35 meters. This was true whether Galileo or GLONASS was used in combination with GPS. Due to the smaller constellation size and the larger biases, however, all the cases computed using GLONASS were notably worse than those computed using Galileo. If the biases on each signal could be known, there would be some error reduction, and the VPL criteria could also be met more easily. Since they cannot be known, the constellation-dependent, worst-case bias is usually assumed for integrity. In that case, the VPLs may begin to exceed 35 m for typical ARAIM receiver designs. This

situation worsens as more receiver implementations are relaxed, of course.

The primary approach to help reduce the impact of signal deformation biases is always to consider the user receiver design. Where possible, attempts should be made to minimize the differences in discriminator type, correlator spacing, and pre-correlation bandwidth between the user and ground reference receivers. This may, of course be challenging since SBAS and ARAIM receivers are likely the same. The designs that are being optimized to minimize signal deformations for SBAS, may in fact, worsen them for ARAIM.

Another, perhaps more-practical, way to reduce these effects is to refine the integrity analysis methods for biases. Assuming the worst-case bias occurs at all times and adds coherently on all signals, is currently the only accepted method for treating these kinds of biases. These results illustrate how difficult it could become to meet ARAIM performance goals as the estimates of pseudorange biases become increasingly large.

## REFERENCES

- [1] Wong, G., Phelts, R.E., Walter, T., Enge, P., “Characterization of Signal Deformations for GPS and WAAS Satellites”, Proceedings of the 23rd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2010), Portland, September 2010
- [2] Wong, G., Phelts, R.E., Walter, T., Enge, P., “Alternative Characterization of Analog Signal Deformation for GNSS-GPS Satellites”, Proceedings of the 2011 International Technical Meeting of The Institute of Navigation, San Diego, January 2011
- [3] Phelts, R. E., Walter, T., Enge, P., “Characterizing Nominal Analog Signal Deformations on GNSS Signals”, Proceedings of the 22nd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2009), Savannah, GA, September 2009
- [4] Wong, G., Chen, Y-H., Phelts, R.E., Walter, T., Enge, P., “Measuring Code-Phase Differences due to Inter-Satellite Hardware Differences”, Proceedings of the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2012), Nashville, September 2012
- [5] Minimum Operational Performance Standards (MOPS) for WAAS, DO-229D. RTCA.
- [6] Wong, G., (2014) *Impact of Nominal Signal Deformations on Satellite Systems*, Ph.D. Thesis, Stanford University, Stanford, CA. (Soon to be published.)

- [7] Blanch, Juan, Walter, Todd, Enge, Per, Lee, Young, Pervan, Boris, Rippl, Markus, Spletter, Alex, "Advanced RAIM user Algorithm Description: Integrity Support Message Processing, Fault Detection, Exclusion, and Protection Level Calculation," *Proceedings of the 25th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2012)*, Nashville, TN, September 2012, pp. 2828-2849. (MAAST: <http://waas.stanford.edu/staff/maast/maast.html> )