GNSS Solutions:

GLONASS inter-frequency biases and ambiguity resolution

"GNSS Solutions" is a regular column featuring questions and answers about technical aspects of GNSS. Readers are invited to send their questions to the columnist, **Dr. Mark Petovello**, Department of Geomatics Engineering, University of Calgary, who will find experts to answer them. His e-mail address can be found with his biography at the conclusion of the column.

What are the challenges associated with GLONASS (FDMA) ambiguity resolution and how are they addressed?

While the GNSS industry eagerly awaits the introduction of new global navigation satellite systems such as Galileo and Compass, the Russian Federation has been steadily modernizing its GLONASS system. At the time of writing, 20 GLONASS satellites are in orbit. With launches of six more satellites scheduled this year, a fully operational constellation of 24 satellites could be realized by early 2010.

GLONASS, like GPS, broadcasts carrier phase signals in the L1 and L2 frequency bands. Each GLONASS satellite broadcasts its signals on slightly different frequencies within a given L-band using a technique known as frequency division multiple access (FDMA). Conversely, the GPS signal structure is based on code division multiple access (CDMA) whereby all satellites transmit on the same L1 and L2 carrier frequencies. Each GLONASS satellite can be identified by its signal frequency while individual GPS satellites are distinguished by unique pseudorandom noise (PRN) codes transmitted with the navigation message.

Reliable resolution of the integer ambiguities inherent in the carrier phase measurements is the key to using GPS and GLONASS for high-precision (centimeter level) positioning applications, especially real-time applications. However, the GLONASS ambiguity resolution process is more complicated compared to GPS because of the FDMA signal structure. The remainder of this discussion focuses on the challenges associated with GLONASS ambiguity resolution and how these challenges are addressed.

GPS ambiguities related to *double-difference* carrier phase observations are usually resolved in GPS data processing schemes. The double-difference technique effectively mitigates common errors introduced by the receiver and satellite hardware, including the receiver and satellite clocks, as well as the Earth's atmosphere. Double-difference observations can be formed by subtracting two inter-station single-difference observations.

The inter-station single-difference is derived by subtracting measurements to the same satellite observed simultaneously at two stations. For example, the single-difference and double-difference involving reference station m, rover station k and satellites p and q are pictured in **Figure 1**.

The ambiguity parameters related to GPS (CDMA) L1 or L2 double-difference observations can be written as:

$$\lambda n_{mk}^{pq} = \lambda (n_{mk}^{q} - n_{mk}^{p})\,[metres] \qquad (1)$$

The symbol λ denotes the wavelength of the carrier signal, which is inversely proportional to its frequency. Because all GPS satellites transmit on the same frequencies, all signals in a given L-band will have the same wavelength.

The double-difference integer ambiguity (n_{mk}^{pq}) on the left hand side of (1) is constructed from the inter-station single-difference ambiguities associated with satellites p (n_{mk}^{p}) and q (n_{mk}^{q}), where p is a reference satellite common to all other double-difference observations. The double-difference ambiguities are typically resolved or *fixed* using integer least squares techniques such as LAMBDA.

Double differencing can also be

used when processing GLONASS observations. The receiver and satellite clock errors will also cancel provided the observations are in units of meters. However, the wavelengths of GLONASS signals are not common for all satellites within a given frequency band. Equation (2) can be generalized for FDMA signals by introducing wavelength identifiers for satellites p and q such that:

$$\lambda^q n^{pq}_{mk} + \Delta\lambda^{pq} n^{p}_{mk} = \lambda^q n^q_{mk} - \lambda^p n^p_{mk}\ [metres];\ \Delta\lambda^{pq} = \lambda^q - \lambda^p \quad (2)$$

In addition to the double-difference ambiguity, GLONASS double-difference observations also consist of the single-difference ambiguity related to the reference satellite p scaled by the wavelength difference of the two signals $\Delta\lambda^{pq}$.

We cannot simply estimate the single-difference reference ambiguity along with the double-difference ambiguity using only carrier phase measurements. This approach would lead to a singular solution with more unknowns than observations. Instead, these two ambiguities could be lumped together in a modified ambiguity term. However, the modified ambiguity would no longer be an integer and, hence, could not be fixed.

In practice, the single-difference reference ambiguity is often estimated with the aid of pseudorange observations.

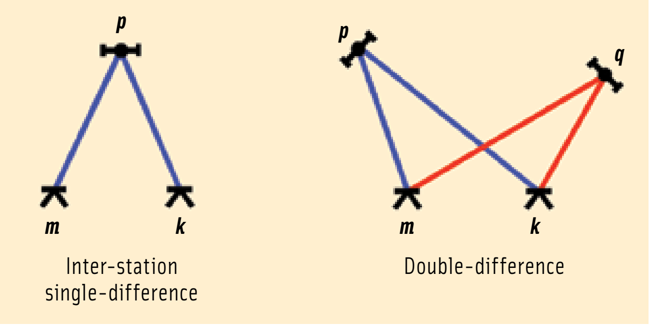
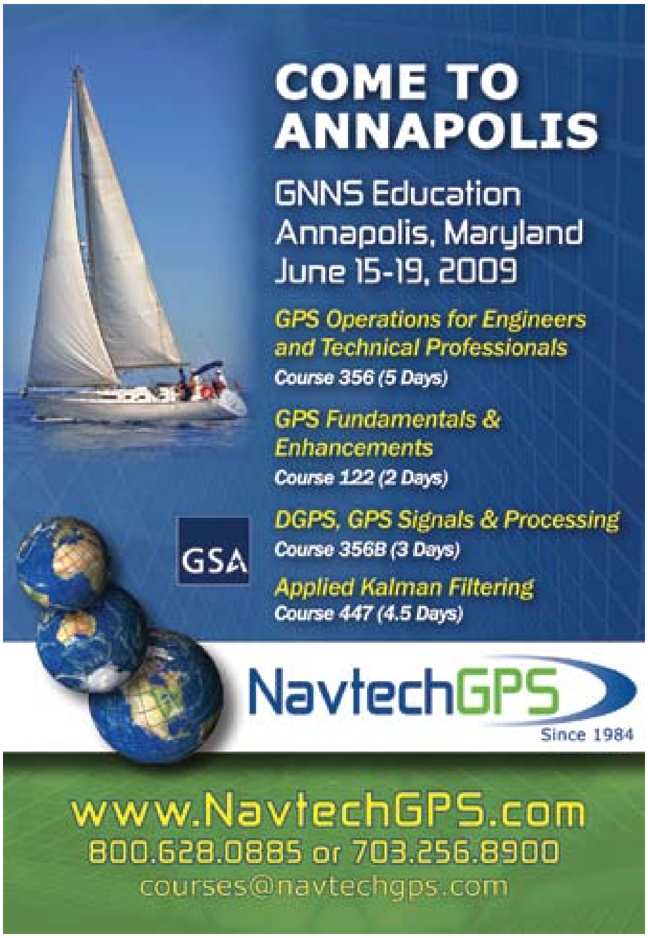


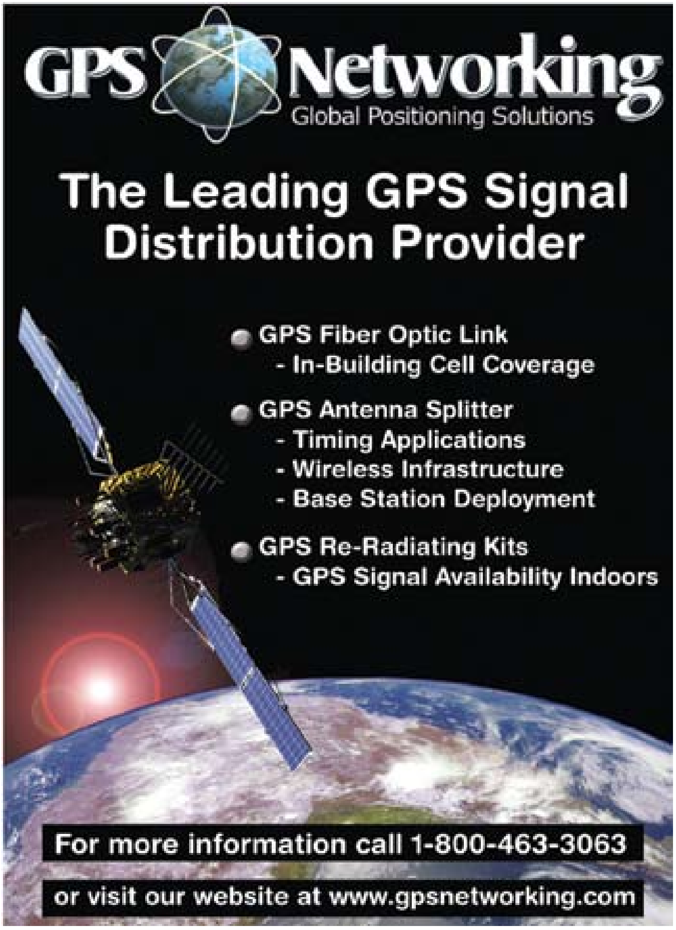
FIGURE 1 The double-difference is the difference between two single-difference observations. Double-differencing is used extensively in data processing to effectively mitigate many of the common errors affecting GNSS observations.

For example, the reference ambiguity can be estimated using Equation (3):

$$n^p_{mk} = round\left[\frac{P^p_{mk} - \phi^p_{mk}}{l^p}\right][cycles] \quad (3)$$

The symbols P and ϕ represent the single-difference pseudorange and phase observations, respectively. Once the single-difference reference ambiguity has been determined,





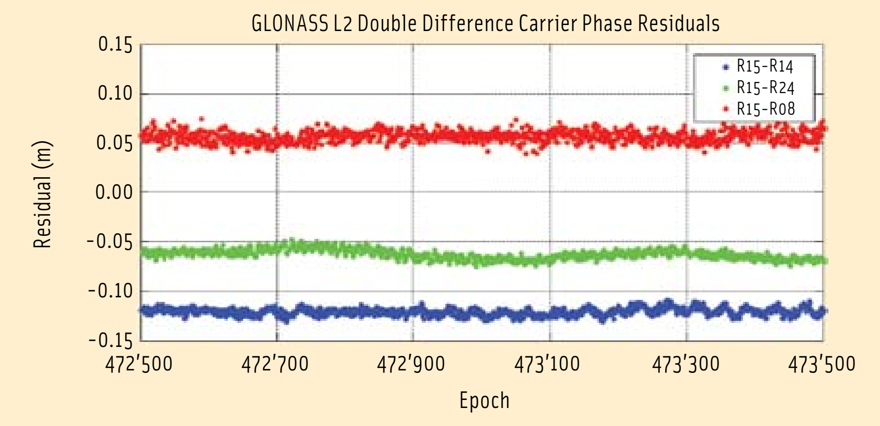


FIGURE 2 **The GLONASS double-difference carrier phase observations associated with this pair of mixed receiver types are affected by significant inter-frequency biases that may lead to unreliable ambiguity resolution if not handled appropriately.**

we can resolve the double-difference ambiguities using integer least squares in much the same way as for GPS.

However, other factors must be taken into consideration. Equation (3) is influenced by pseudorange random measurement error, multipath, ionospheric errors and receiver dependent biases. These residual errors make it difficult to resolve the reference ambiguity to its correct integer value.

Equation (2) clearly indicates that any error in the reference ambiguity will be absorbed by the double-difference ambiguity as a function of the delta wavelength term. For example, approximately 4.6 millimeters of error will be introduced for every meter of error in the reference ambiguity if the maximum difference between GLONASS wavelengths is involved.

Reliable ambiguity resolution could be compromised if this induced bias becomes significant. However, we can usually estimate the single-difference reference ambiguity with sufficient accuracy for reliable ambiguity resolution — if the same brand of receiver is used in the double-difference. However, residual receiver-dependent biases may cause a significant bias in the single-difference reference ambiguity estimate when different receiver types are involved.

In general, the hardware and signal processing architecture of a receiver will introduce frequency-dependent biases in the pseudorange and carrier phase measurements. These variations in the measurements, which may be different for code and phase, are commonly known as *inter-frequency* biases.

The pseudorange and carrier phase receiver biases for all GPS signals will be the same for a given L-band since all satellites transmit on the same L1 and L2 frequencies. These biases effectively cancel in double-difference observations, even if different types of reference and rover receivers are used. Conversely, all GLONASS satellites transmit on different frequencies; so, these biases may even be different for signals in the same L-band.

The tracking channels in state-of-the-art GLONASS receivers may be calibrated to minimize the magnitude of these inter-frequency biases in the L1 and L2 observations. Furthermore, receiver-dependent biases are generally consistent for instruments developed by the same manufacturer. As a result, receiver biases are effectively minimized in single and double-difference observations and will not affect ambiguity resolution if the same brand reference and rover receivers are involved.

However, GLONASS double-difference phase observations for heterogeneous receiver pairs can be influenced by significant inter-frequency biases. **Figure 2** shows the GLONASS L2 double-difference carrier phase residuals for a mixed pair of state-of-the-art geodetic-quality receivers separated by approximately two meters. Estimates of the receiver-satellite geometry as well as the single and double-difference ambiguity terms were removed from the raw double-difference observations to form the residuals.

The expected value of the double-difference residuals for such a short baseline is approximately zero. However, the residuals in Figure 2 are affected by significant inter-frequency biases approaching 0.5 cycles (~12 cm).

These biases may be attributed to *real* variations in GLONASS phase measurements introduced by the FDMA receiver architecture and *apparent* inter-frequency biases induced by an incorrect estimate of the single-difference reference ambiguity. Remember that any error in the reference ambiguity will be common to all double-differences; however, the error will manifest as inter-frequency biases because of the frequency-dependent delta wavelength term in Equation (2).

The data presented in Figure 2 represents a typical example of the inter-frequency biases observed when the double-difference baseline consists of different receiver types. These biases need to be estimated and removed from the observations in order to resolve the double-difference GLONASS ambiguities reliably.

However, the task of estimating inter-frequency biases for mixed receiver types is not a trivial task, particularly in real-time. In practice, separating inter-frequency biases from other error sources and the ambiguity terms is difficult. For this reason, many software solutions do not attempt to fix GLONASS ambiguities if different receiver brands are involved. Instead, the inter-frequency biases are absorbed by the real-valued or *float* estimates of the GLONASS ambiguities.

This approach generally improves the GPS solution, especially ambiguity resolution performance. However, the full potential of GLONASS will only be realized if the GLONASS ambiguities are fixed to integers.

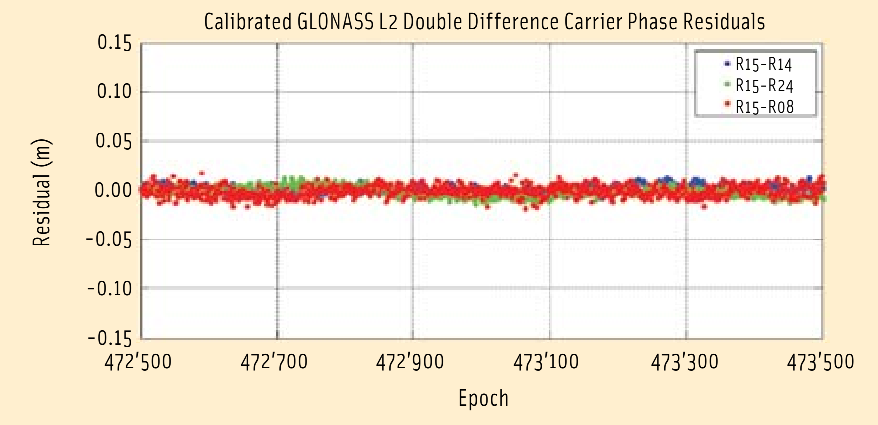


FIGURE 3 **The inter-frequency biases affecting the GLONASS double-difference phase observations in Figure 2 have been effectively mitigated. Consequently, the double-difference ambiguities can then be fixed reliably using integer least squares techniques.**

Rather than estimating inter-frequency biases together with other unknowns such as ambiguities, the inter-frequency biases for various receiver combinations can be pre-calibrated on a so-called *zero baseline* or very short baseline in order to control various error sources including atmospheric errors and multipath. This approach to estimate inter-frequency biases is possible because the receiver biases are generally stable over time.

Unlike antenna phase center variation (PCV) calibrations, no accepted *standard* calibration tables for receiver dependent biases currently exist in the public domain. Therefore, manufacturers normally calibrate different receiver brands against their own reference using proprietary techniques. **Figure 3** shows the results of a proprietary solution implemented in real-time software developed by Leica Geosystems to mitigate the inter-frequency biases evident in Figure 2.

Mark Petovello is an Assistant Professor in the Department of Geomatics Engineering at the University of Calgary. He has been actively involved in many aspects of positioning and navigation since 1997 including GNSS algorithm development, inertial navigation, sensor integration, and software development.

Email: mark.petovello@ucalgary.ca

The inter-frequency biases visible in Figure 2 that might prevent ambiguity resolution are no longer present in the data. This result represents a significant step towards interoperability among different brands of receivers.

However, the calibration approach does have some limitations. First, the processing software needs to know which types of receivers are involved in order to apply the appropriate calibration values. This is not an issue if open data exchange formats such as RTCM SC-104 v3 (real-time format) and RINEX v2 and v3 (post-processing format) are used, because they contain the relevant receiver type information.

Secondly, manufacturers need to ensure that the unit-to-unit receiver biases for a given type of instrument are consistent. This issue is currently being addressed within the RTCM SC-104 committee, which draws representatives from government, academia, and industry, including most receiver manufacturers.

Finally, the calibrated double-difference observations may still be affected by residual inter-frequency biases caused by unit-to-unit receiver variations, temperature differences, and aging hardware components. However, the magnitudes of these residual biases are typically only a small fraction of the signal wavelength. Therefore, they do not present a significant issue for ambiguity resolution.

In summary, GLONASS (FDMA) double-difference carrier phase observations consist of a single-difference reference ambiguity term in addition to the usual double-difference ambiguity. Furthermore, GLONASS observations may be affected by inter-frequency biases. These two issues are not normally associated with GPS (CDMA) observations and will hinder or even prevent reliable ambiguity resolution if not handled correctly.

The Russian Federation plans to add CDMA signals to the GLONASS signal structure as part of its modernization program, beginning with the L3 frequency. However, Russian Space Agency officials have indicated that FDMA signals will be retained for the foreseeable future in order to ensure backward compatibility with FDMA-only receivers.

Therefore, the issues that affect GLONASS ambiguity resolution today will also be relevant in the future. Resolving the issues in practice is challenging, especially in real-time and when different receiver brands are involved.

Nevertheless, these issues are manageable and once they have been addressed, the addition of GLONASS observations in a high-precision GNSS solution can certainly improve positioning performance compared to GPS alone.

FRANK TAKAC

Frank Takac received a bachelor and master of applied science from RMIT University in Melbourne, Australia. He joined Leica Geosystems in 2002 and has been involved in the development of Leica's high-precision GNSS product range. Frank currently leads the GNSS positioning algorithms group responsible for real-time and infrastructure software. IG