The Future is Now

GPS + GLONASS + SBAS = GNSS

Lambert Wanninger

WE ARE ON THE BRINK OF A NEW ERA in satellite positioning and navigation. The excitement that was felt 30 years ago when the first GPS satellite was launched is beginning to be felt again. Back then, instantaneous three-dimensional satellite-based positioning was an entirely new concept. Yes, we did have satellite-based positioning before GPS, but it wasn't instantaneous and it wasn't fully 3D — nor was it very accurate.

Over the past 30 years, thousands of scientists and engineers have developed an amazing range of GPS applications providing positioning accuracies all the way down to the millimeter level. However, some would argue that many of the recent developments, especially in the area of high-accuracy positioning, are just minor enhancements to existing techniques first introduced or foretold years ago. Been there; done that.

INNOVATION INSIGHTS
with Richard Langley

GPS, GLONASS, and SBAS already constitute a system of systems.

But that situation is about to change — and in a big way! New signals and new satellites herald a new era in satellite-based positioning and navigation. Russia's Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) is being revitalized after many years of neglect. With its first launch in 1982, this second global navigation satellite system gave rise to the generic term for all such systems: GNSS. In addition to GLONASS and a modernized GPS featuring new civil and military signals along with new constellations of satellites, we will have Europe's Galileo system (with two GIOVE test satellites already in orbit) and China's Beidou/Compass system (with five satellites already in orbit). Receivers and data-processing techniques will be developed to allow use of all available signals and satellites. The future promises to be just as exciting for GNSS scientists and engineers as the early days of GPS.

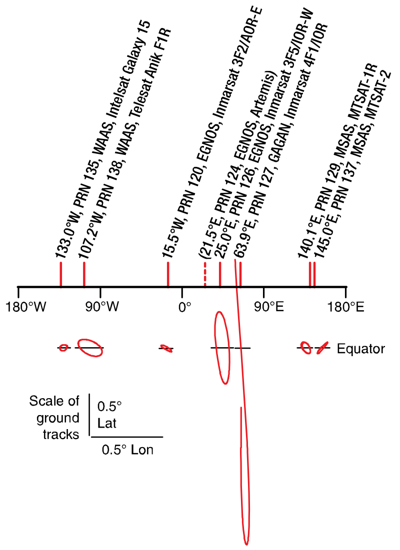
But do we have to wait for these new or enhanced systems to be in place before benefiting from a multi-signal, multi-constellation global navigation satellite system? Definitely not. As this month's column describes, we can sample the future today. The existing GPS satellites, along with the revitalized GLONASS constellation and the satellites of the various geostationary satellite-based augmentation systems, already constitute a system of systems. And receivers currently on the market provide the necessary raw measurement data to yield positioning solutions from this system of systems with potentially more continuity and greater accuracy than those obtained using GPS alone. Listen up: the future is now.

"Innovation" is a regular column that features 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 welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 6.

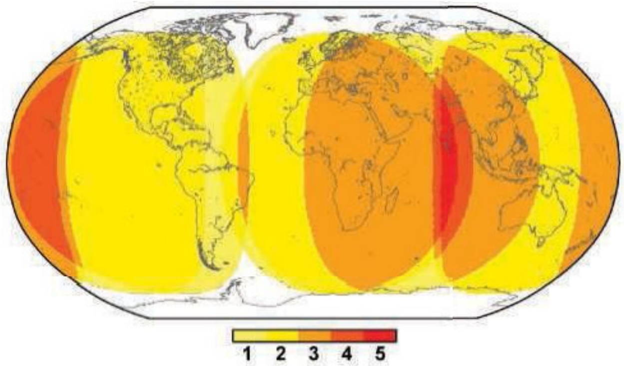
In the future, we will enjoy the benefits of a global navigation satellite system consisting of several independent systems. But do we have to wait for the future? No. The GNSS system of systems is already here. We have the extremely successful American GPS and the partly rebuilt Russian GLONASS, as well as several active geostationary satellite-based augmentation system (SBAS) satellites in orbit. All satellites of these three GNSSs provide us with ranging signals and thus pseudorange (code-phase) and carrier-phase observations usable for positioning and many other applications. This article focuses on the combined use of all readily available GNSS signals for precise positioning applications such as real-time kinematic (RTK) surveying operations, including carrier-phase ambiguity fixing.

This year, the GPS satellite constellation reached a new height: 31 active satellites in space and thus more GPS ranging signals available than ever before. But, for many applications, this still is not enough. As we all know from our own experiences, signals are often obstructed at many locations. More satellite signals can help increase GNSS availability. And more ranging signals improve positioning accuracy as well. Hence, the use of all available GNSS signals generally improves positioning performance.

Over the past year, the number of active GLONASS satellites increased from about 12 to 16. Most of the GLONASS satellites operating are the so-called M-type, which have a longer expected lifetime of about seven years. Nevertheless, this is still much shorter than the lifetimes of GPS satellites. Another six GLONASS satellites are expected to be launched in 2008. Presently, due to lack of satellites, GLONASS cannot be used reliably as a stand-alone system. However, its signals are very useful in combination with those of GPS. In recent years, the combination of GPS and GLONASS has become widely accepted among high-precision users, although the full potential of combined GPS



▲ **FIGURE 1** SBAS satellites, their orbital positions and ground tracks (March 2008)



▲ **FIGURE 2** Number of SBAS satellites visible (March 2008)

and GLONASS ambiguity resolution has not often been exploited.

The main objective of the SBAS satellites is to broadcast GPS augmentation information. Several independent but compatible systems exist: the American Wide Area Augmentation System (WAAS), the European Geostationary Navigation Overlay Service (EGNOS), the Indian GPS Aided GEO Augmented Navigation System (GAGAN; factoid: "gagan" means "sky" in Hindi), and the Japanese MTSAT Satellite-based Augmentation System (MSAS). Today, seven active SBAS satellites broadcast their signals. One more satellite, the EGNOS Artemis satellite, is set unhealthy since it is being used by industry to perform tests on the system. The SBAS satellites are located in geostationary orbits at a height of about 36,000 kilometers above the Earth's equator. Most SBAS satellites are "stationary" (keeping pace with the Earth's rotation) to within fractions of a degree in latitude and longitude. Others perform deviations from an equatorial position or even follow slightly inclined orbits. **FIGURE 1** gives an impression of the SBAS satellite longitudinal distribution and their orbit variations.

More and more receivers are capable of not only decoding the SBAS messages (to improve standalone code-based positioning accuracy and integrity) but also of making code and carrier-phase measurements on the signals. Whereas the service areas for GPS augmentation are limited to regions within the corresponding ground-station network, SBAS for ranging works wherever the signals can be received. Users of the SBAS ranging signals may consider WAAS, EGNOS, GAGAN, and MSAS as one GNSS, although this GNSS is not a standalone positioning system because of the small number of satellites and their distribution in the sky.

At mid-latitude locations, the geostationary satellite signals are received from fairly low elevation angles — often below 30 degrees — and thus are prone to signal attenuation and blockage by obstructions. On the other hand, if you are able to receive the signal at a particular location, the satellite is not going to disappear but provides you with ranging information 24 hours per day. The satellite geometry is more favorable closer to the Earth's equator, where SBAS satellites are typically observed at much higher elevation angles. **FIGURE 2** shows the present SBAS satellite visibility. Three or more SBAS satellites are visible at low to mid latitudes throughout most of the African, European, and Asian continents.

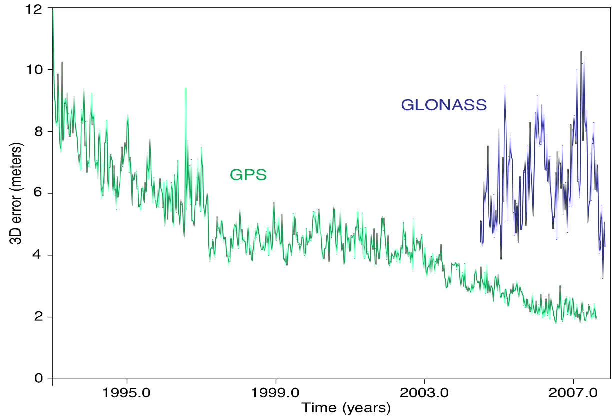
Although ranging to the SBAS satellites is one of the main objectives of these augmentation systems, the services have seldom been used for precise positioning. The presently available GPS-like single-frequency (L1) signals limit the use of SBAS ranging for precise applications to short baselines, where ionospheric effects cancel out by differencing. In the future, dual-frequency SBAS signals may be widely available which will make SBAS ranging even more attractive for precise applications. (WAAS currently transmits an L5 signal along with L1 but it is not intended for end users at this time.)

Orbit Accuracy

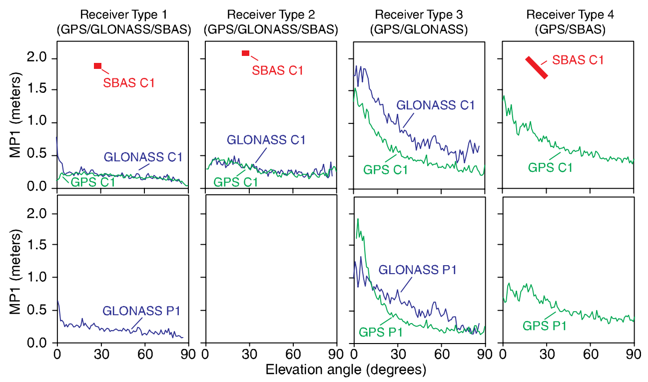
Large differences among the three GNSSs exist with respect to the quality of their broadcast orbits and satellite clock corrections. Whereas for most relative positioning applications, satellite clocks and thus errors in the satellite clock corrections have hardly any effect on the positioning accuracy, broadcast orbit errors can significantly influence performance.

As it stands now, the accuracy of GLONASS broadcast orbits is worse by a factor of three compared to GPS (see **FIGURE 3**). The effect of this accuracy difference on differential GNSS depends on the baseline length and the positioning mode selected. For code-based single-frequency GNSS or carrier-phase-based short baseline RTK, hardly any effect of this reduced accuracy can be seen. However, precise differential carrier-phase positioning on longer baselines (longer than about 10 kilometers) *is* affected. For all post-processing applications on longer baselines, the most accurate solution is achieved using the precise orbits produced by the International GNSS Service (IGS) or other organizations. But even here, accuracy differences exist: precise IGS GLONASS orbits are of lower accuracy (15 centimeters) than IGS precise GPS final orbits (less than 5 centimeters). This difference, however, affects only very long baselines (longer than about 100 kilometers).

No precise orbit information is available for SBAS satellites. And thus no statistics exist on their broadcast orbit accuracy. But practical experience shows that the orbit accuracy of WAAS, GAGAN, and MSAS is high enough for single-receiver absolute code-based positioning and for short-range RTK applications. Unfortunately, the situation with EGNOS is different. EGNOS satellites broadcast orbit and clock information of very low quality, too low for almost all positioning applications. There is just one



▲ **FIGURE 3** 3D-accuracy of broadcast ephemeris, based on Jet Propulsion Laboratory analysis reports (GPS) and IGS orbit combination reports (GLONASS)



▲ **FIGURE 4** Elevation-angle-dependence of multipath and noise effects on code-phase observables for four receivers of different type

positioning mode where EGNOS satellite signals may be used right now: very short baselines. For RTK-like positioning, they should not exceed several decameters. Here, even large broadcast orbit errors have only a small effect on the differenced observables. The large clock and orbit errors of the EGNOS satellites prevent use of their signals for practical applications. Still, EGNOS observations from very short baselines demonstrate the potential of adding SBAS signals to a GNSS constellation.

Code Ranging

A further difference between different GNSSs lies in their code-phase observation quality, which depends primarily on multipath effects and random noise. The GLONASS chip lengths of the C/A- and P-codes are twice as long as the chip lengths of the corresponding GPS codes. Therefore, one would expect a somewhat lower quality of the GLONASS code-phase observables compared to those of GPS. Furthermore, the GPS-like signals of the SBAS satellites do not have exactly the same characteristics as GPS signals. The bandwidth of the L1 signals transmitted by Inmarsat-3 satellites used by EGNOS, for example, is just 2.2 MHz and thus the use of wider correlators, which produce noisier measurements, is required.

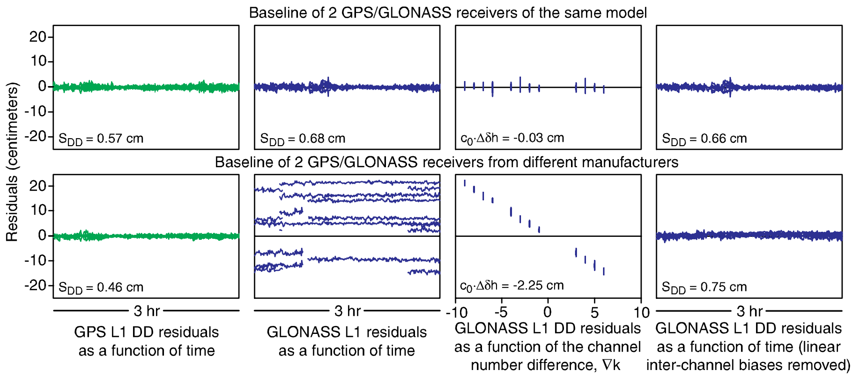
FIGURE 4 shows the elevation-angle-dependent code-ranging quality of four dual-frequency receivers, of different type, based on 24-hour data sets collected at TU Dresden. The signal quality was estimated using the so-called MP1 observable, a certain linear combination of code and dual-frequency carrier-phase observations. Forming this linear combination gives us a virtually geometry- and atmosphere-free observable in which the remaining "signal" is primarily code multipath and code noise. SBAS code observations cannot be handled in the same way since dual-frequency carrier-phase observations do not exist or are not readily available. Quality estimates for SBAS were gained from short baseline data of pairs of different types of identical receivers. Receiver Type 1 is able to track all three kinds of GNSS signals. Receiver Type 2 is a dual-frequency GPS/GLONASS/SBAS receiver that does not provide a P(Y)-code observable on the L1 frequency. Type 2 receivers only provide a C/A-code observable on L1. Receiver Type 3 has no SBAS capability, whereas the forth receiver type is not able to track GLONASS signals but offers four SBAS channels.

Some receivers are able to make GPS and GLONASS code observations with similar quality (receiver Types 1 and 2 as shown in Figure 4). Other receivers, however, produce GLONASS code observations of considerably lower quality compared to GPS (some receiver Type 3s): in the case of the standard accuracy signal (C/A-code), GLONASS observations are of lower accuracy for the complete range of elevation angles (see the upper panel for receiver Type 3 in Figure 4). The situation is different for the precise code (lower panel for receiver Type 3). Here, the two root-mean-square (RMS) error curves intersect because the GLONASS code-correlation channels perform better than the code-free GPS observation technique for signals of low-elevation-angle satellites.

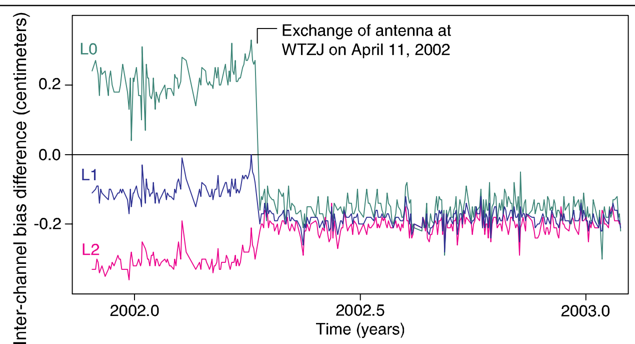
All except one of the four receivers were able to perform SBAS code and carrier-phase measurements. Receiver Types 1 and 2 tracked just two SBAS satellites, both at almost the same elevation angle. Receiver Type 4 made use of all its SBAS channels and tracked four SBAS signals incident from elevation angles between 15 and 30 degrees. SBAS code quality is always considerably lower compared to GPS/GLONASS. In a combined GNSS data processing scheme, these quality differences must be taken into account. SBAS code observations have to be given a lower weight compared to GPS/GLONASS code observations. It must be lower by a factor of two to six depending on the receiver type.

Carrier-Phase Equations

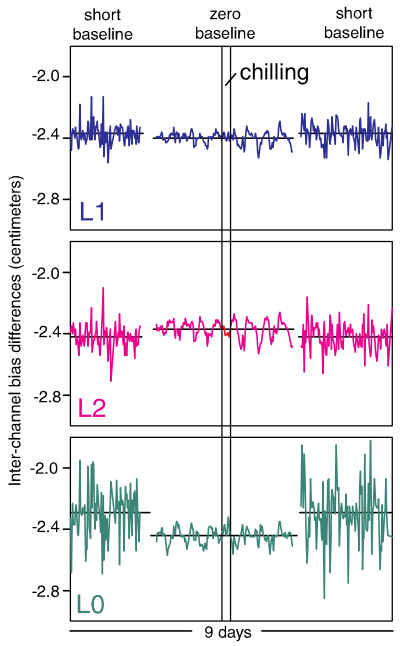
One of the main differences between GLONASS and GPS/SBAS is its frequency division multiple access (FDMA) approach, which requires the use of several adjacent frequencies for the broadcast signals. Furthermore, none of the many GLONASS frequencies is identical to one of the two GPS frequencies. Consequently, different hardware biases exist for GPS/SBAS and GLONASS receiving channels as well as between GLONASS channels. Thus, the combined processing of GPS/SBAS and GLONASS carrier-phase observations in differential mode requires the estimation of two independent receiver clock unknowns, one for the GPS/SBAS signals and one for GLONASS. In addition, the GLONASS inter-channel biases



▲ **FIGURE 5** Double-difference (DD) residuals on two short GPS/GLONASS baselines



▲ **FIGURE 6** More than a year of daily estimates of the inter-channel bias difference $c_0 \cdot \delta h^{GLONASS}$ on the short baseline WTZZ-WTZJ (at Wettzell, Germany)



▲ **FIGURE 7** Inter-channel bias differences $c_0 \cdot \delta h^{GLONASS}$ of two receivers from different manufacturers before, during, and after a chilling experiment

need to be estimated as well. GLONASS inter-channel bias differences were determined in tens of baselines of various GPS/GLONASS receiver pairs, and it was found that a dominant linear dependence on signal frequency always exists.

FIGURE 5 visualizes the difficulties caused by GLONASS inter-channel biases. It shows L1 double-difference (DD) residuals on two short baselines: one observed with receivers of the same model, the other observed with receivers from different manufacturers. Ground-truth baseline coordinates were obtained from several days of GPS observations. Antenna phase-center corrections were applied. Carrier-phase ambiguities were estimated and fixed (that is, removed from the data). What remains in the DD residuals are the effects of uncorrected systematic and random errors. On this short baseline, they are mainly caused by multipath. In the case of GLONASS observations, inter-channel biases may have a large effect as well. On the baseline with two receivers of the same model, the inter-channel bias differences are so small that they have hardly any effect on the estimated baseline coordinates. This finding has been confirmed for many receiver types: receiving equipment of the same type exhibits similar inter-channel biases so that their effect disappears in differential mode.

In the mixed baseline scenario shown in the lower panels of Figure 5, however, the effect of different inter-channel biases reaches more than 2 centimeters for adjacent GLONASS frequencies. This means that the maximum effect on double differences exceeds one L1 wavelength for this specific receiver combination and taking into account that the maximum GLONASS channel number difference is 13 (corresponding to a frequency difference of 7.3 MHz). Modeling these inter-channel bias differences as a linear function of signal frequency removes their effect completely. The remaining GLONASS residuals are almost as small as those of GPS.

This experience with GPS/SBAS and GLONASS carrier-phase observations led to the following observation equations for the between-receiver single-difference observables, ΔΦ(in meters):

$$\Delta\Phi_{a,b}^{GPS/SBAS,i} = \Delta R_{a,b}^{i} + c_0 \cdot \Delta\delta t_{a,b}^{GPS/SBAS} + \lambda \cdot \Delta N_{a,b}^{i} + \varepsilon_{\Delta\Phi}$$

$$\Delta\Phi_{a,b}^{GLONASS,i} = \Delta R_{a,b}^{i} + c_0 \cdot \left(\Delta\delta t_{a,b}^{GLONASS} + k^{i} \cdot \Delta\delta h_{a,b}^{GLONASS}\right) + \lambda \cdot \Delta N_{a,b}^{i} + \varepsilon_{\Delta\Phi}$$

where subscripts *a,b* stand for the stations involved, the superscript GPS/SBAS and GLONASS indicate the GNSS satellite system, and the superscript *i* specifies the individual satellite. Furthermore, ΔR is the single difference of the satellite-receiver ranges (in meters); c_0 is the vacuum speed of light (in meters per second); $\Delta\delta t^{system}$ is the difference of the receiver clocks (in seconds), which depends on the satellite systems due to different receiver hardware delays; $\Delta\delta h^{GLONASS}$ is the difference of inter-channel biases of two receivers for adjacent GLONASS frequencies; k is the GLONASS channel number (unitless); λ is the signal wavelength (in meters); ΔN is the single difference of carrier-phase ambiguity (unitless); and $\varepsilon_{\Delta\Phi}$ is the sum of all uncorrected systematic and random errors in the single-difference observable (in meters).

This approach to processing GNSS data was realized in the baseline software *Wa1* including a combined ambiguity fixing for GPS, GLONASS, and SBAS observations. Wa1 processing is based on single-difference observations. It thus avoids all the difficulties of GLONASS ambiguity resolution which occur if double-difference observables are used.

Stability of GLONASS Inter-channel Biases

An important consideration in the handling of these GLONASS carrier-phase inter-channel biases is their stability in time and their dependence on temperature. To obtain a better under-

	Group A	Group B	Group C	Group D
Group A	0.0	2.4	-0.7	4.0
Group B	-2.4	0.0	-3.1	1.6
Group C	0.7	3.1	0.0	4.7
Group D	-4.0	-1.6	-4.7	0.0

▲ **TABLE 1** Estimates of GLONASS inter-channel bias differences $c_0 \cdot \delta h^{GLONASS}$ in centimeters for various receiver pairs. For receiver group members, see the Manufacturers section.

standing of the effects, several experiments were conducted at Geodätisches Institut, TU Dresden. The results of two of these experiments are presented here.

First of all, the long-term stability of the inter-channel bias differences was investigated. This required long-term observations from two receivers with a small distance between their antennas. An appropriate data set is available from the IGS site *Wettzell* in Germany. At this site, several GPS and GPS/GLONASS receivers are operated simultaneously. The observation data is obtainable from the servers of Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt. From the end of 2002 until early 2004, two Type 3 GPS/GLONASS receivers from different manufacturers were operated at Wettzell: one at station WTZZ and one at station WTZJ. The distance between the two antennas was just 2.5 meters.

All daily observation files were processed with the Wa1 software, including carrier-phase ambiguity fixing and estimation of inter-channel bias differences $\Delta\delta h^{GLONASS}$, one value per day (see **FIGURE 6**). The peak-to-peak variations of the estimated values are very small — about 1 millimeter. No seasonal (temperature) effects and no aging effects are observed. A jump, however, occurred when the antenna was changed from one kind of choke-ring antenna (IGS code: TRM29659.00 NONE) to another (IGS code JPSREGANT_SD_E NONE) at station WTZJ on April 4, 2002.

Furthermore, an attempt was made to find the temperature dependence of the inter-channel biases. For this purpose, two GPS/GLONASS receivers of different types collected observations on a short baseline and also on a zero baseline (sharing the same antenna). The Type 2 receiver was chilled for several hours. The temperature difference outside the receiver reached more than 20 degrees Celsius. Unfortunately, the inside temperature of the equipment remained unknown. The Type 3 receiver operated under constant environmental conditions.

The inter-channel bias differences of a 9-day-long experiment are shown in **FIGURE 7**. No effect of the temperature change can be observed. But the change of antenna and antenna cables for one of the receivers, needed to observe a zero baseline, produced a jump in the $c_0 \cdot \Delta\delta h^{GLONASS}$ time series. This jump is most striking in the ionosphere-free linear combination where it amounts to 1.4 millimeters.

The analysis of the GLONASS observation data in mixed baselines showed that the inter-channel bias differences, $c_0 \cdot \Delta\delta h^{GLONASS}$, can be as large as 5 centimeters. They are estimated from the baseline observations after ambiguity fixing. If these bias differences exceed a few millimeters, reliable ambiguity fixing gets much more difficult or cannot be performed at all for positioning techniques such as RTK. *A priori* values of the inter-channel bias differences are necessary to support ambiguity resolution.

Estimates of the GLONASS inter-channel bias differences were determined based on short baseline observations. The correction values presented in **TABLE 1** are only valid for receiver firmware versions of 2007–2008. Large changes of these values may occur if a manufacturer modifies pre-correction values applied by the firmware. The accuracy of the values shown in Table 1 is on the level of 1 millimeter. Higher accuracy cannot be obtained due to effects that do not depend on the receivers but rather on the antennas and antenna cables. No distinction between L1 and L2 corrections seems to be necessary at this level of accuracy. Hence, Table 1 contains a single value for each receiver pair valid for both frequencies.

It would be advantageous for all GNSS users if the manufacturers of GPS/GLONASS receivers could agree on a common level of these inter-channel biases and if they could apply appropriate corrections to the GLONASS observations in their receiver firmware. This would, of course, not completely remove the difficulty of inter-channel biases in mixed baselines, because part of the problem is caused by the antennas and antenna cables. But it could remove most of the difficulties we now experience with RTK ambiguity resolution in mixed GLONASS baselines. A *priori* values as presented in Table 1 can only be a provisional solution.

Combined Results

Following the maxim "the more satellites the better," adding GLONASS and SBAS satellites to GPS data processing should result in better positioning performance: higher availability, faster and more reliable ambiguity resolution, and more precise positioning results. On the other hand, SBAS code observations are of much lower quality compared to those of GPS/GLONASS observations. No real accuracy difference is expected for the phase observations except that an additional parameter for the GLONASS inter-channel biases must be estimated.

TABLE 2 summarizes the results of an experiment performed on a very short baseline (a few meters) observed with two identical Type 2 receivers. This receiver model is able to observe the signals of all-in-view GPS/GLONASS satellites and up to two SBAS satellites. The baseline had to be this short to be able to include SBAS observations from EGNOS satellites with its poor broadcast orbit quality. The almost 30 hours of static observations were split into sessions of 2 minutes each to simulate RTK-like ambiguity resolution. Other processing parameters included:

- dual-frequency observations, except for SBAS
- elevation mask angle 10 degrees
- few signal obstructions
- low multipath
- broadcast orbits
- antenna phase-center corrections applied
- elevation-angle-dependent weighting of the observations
- SBAS code observations down-weighted by a factor of five compared to GPS/GLONASS
- same weights for GPS, GLONASS, and SBAS carrier-phase observations.

	GPS	GPS+GLONASS	GPS+SBAS	GPS+GLONASS+SBAS
average # of SV	8.4	12.5	10.4	14.5
Combined Float/DGNSS				
RMS N/E/Up (cm)	13 / 21 / 17	11 / 15 / 14	13 / 19 / 17	11 / 14 / 14
Fixed solution				
# valid solutions (of 886)	881	885	881	885
RMS N/E/Up (cm)	0.27 / 0.21 / 0.46	0.22 / 0.18 / 0.40	0.20 / 0.18 / 0.39	0.18 / 0.16 / 0.35

▲ **TABLE 2** Baseline processing results for a short baseline: Coordinate accuracy before and after ambiguity fixing for 886 samples consisting of 2 minutes of 1-Hz sampled observations each

Several solutions were computed: GPS only, GPS plus GLONASS, GPS plus SBAS, all three GNSS together (see Table 2). The combined solution of carrier-phase float plus DGNSS-code represents the positioning accuracy before ambiguity resolution. A high positioning accuracy at this step of the processing supports successful and reliable ambiguity resolution. Fixed solutions could not be obtained for all of the 886 samples. In very few cases, the algorithm refused ambiguity fixing. The valid solutions were compared to the well-known baseline coordinates and RMS values were computed for all three coordinate components.

During the experiment, the average number of GPS satellites tracked was 8.4. GLONASS added 4.1 satellites on average and SBAS another 2 continuously tracked signals. On average, 14.5 satellite signals were available, tracking all GNSS signals, with a minimum of 10 and a maximum of 19.

As shown in Table 2, the accuracy of the combined float/DGNSS-solution and thus the ability to successfully fix the carrier-phase ambiguities considerably improved by including GLONASS signals. The 3D position error was reduced by 22 percent compared to solutions based on GPS only. The positive effect of the two additional SBAS signals, however, amounts to just six percent, and thus it is almost negligible. The SBAS carrier-phase observations are not able to contribute any geometrical information to a float solution because the satellites are "fixed" in the sky. Furthermore, the SBAS code observations are of much lower quality compared to those of GPS/GLONASS, and thus they are not able to noticeably improve the positioning performance.

After ambiguity fixing, adding GLONASS or SBAS to a GPS constellation improved the positioning accuracy by 26 percent. This shows that GLONASS and SBAS carrier-phase measurements are of similar quality as those obtained from GPS signals. Here, the two SBAS carrier-phase observations contributed a bit more to a combined GNSS solution than all GLONASS signals.

The expected result could be achieved: the more satellites available, the better is the performance of ambiguity fixing and the higher is the positioning accuracy.

Conclusions and Outlook

The experiences with combined processing of GPS/GLONASS and GPS/SBAS including carrier-phase ambiguity fixing proved that the additional ranging signals improve not only availability but also achievable accuracy in many precise applications. The difficulties caused by the GLONASS carrier-phase inter-channel biases could be solved through estimation of these biases in the data processing. Nevertheless, *a priori* corrections of these biases are required for RTK positioning in mixed baselines. Such *a priori* values have been estimated for several pairs of receiver types.

At this time, the EGNOS satellite orbit and clock parameters are of such poor quality that precise differential positioning is limited to very short baselines. It could, however, be shown that EGNOS and all the other SBASs can contribute to precise carrier-phase positioning although they currently provide just single-frequency user ranging signals.

The outlook of precise GNSS positioning is bright, because a larger number of GLONASS and SBAS satellites are expected in the near future. Hence, there is no need to wait for Galileo or Compass to relish the advantages of using more than one of the global navigation satellite systems. ⊕

Acknowledgments

Observation data from various sources was used in this study. Many data sets were made available by Institut für Planetare Geodäsie of TU Dresden; Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt; State Survey Departments of Saxony and Saxony-Anhalt; and several other institutions often through their contributions to IGS and the European Reference Frame (EUREF) permanent network. Many more data sets were observed by staff and students of Geodätisches Institut, TU Dresden, often produced with completely different applications in mind. The author would like to thank all those who (sometimes unknowingly) contributed to this research work.

Manufacturers

Eleven different receiver models were used in the studies: **Ashtech** Z-18 (Type 3, Group A, *pro.magellangps.com*), **JPS** Legacy (Type 3, Group A, *www.topcon.com*), **Leica** GRX 1200 GG PRO (Type 2, Group B, *www.leica-geosystems.com*), **NovAtel** OEMV-3 (Type 2, Group B, *www.novatel.ca*), **Septentrio** AsteRx2 (Type 1, Group 4, *www.septentrio.com*), Septentrio PolaRx2 (Type 4, no GLONASS capability, *www.septentrio.com*), **TPS** E_GGD (Type 3, Group A, *www.topcon.com*), TPS Legacy (Type 3, Group A, *www.topcon.com*), TPS NET-G3 (Type 1, Group A, *www.topcon.com*), **Trimble** NetR5 (Type 2, Group C, *www.trimble.com*), and Trimble R7 GNSS (Type 2, Group C, *www.trimble.com*).

LAMBERT WANNINGER is a professor of geodesy at Technische Universität Dresden (TU Dresden), Germany. He has been involved in research on precise GNSS positioning since 1990. He holds a Dr.-Ing. degree in geodesy from the University of Hannover, Germany, and a habilitation degree in geodesy from TU Dresden.

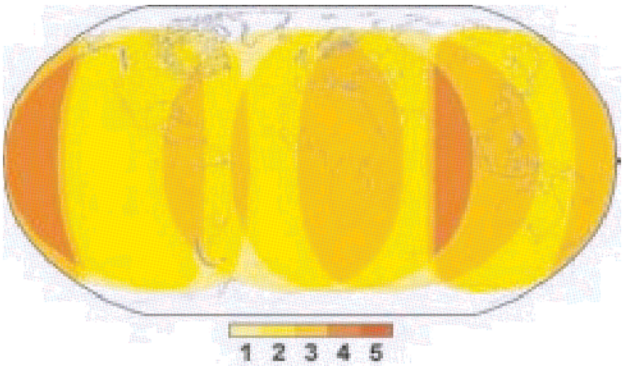
MORE ONLINE

Further Reading

View *gpsworld.com* and click on **Innovation** under **Resources** in the left-hand navigation bar for references related to this articles.

Correction

Figure 2 of "The Future is Now: GPS + GLONASS + SBAS + GNSS" in the July issue of *GPS World* contained an error. The corrected figure is shown here.



▲ **FIGURE 2** Number of SBAS satellites visible (March 2008)