Combined Processing of GPS, GLONASS, and SBAS Code Phase and Carrier Phase Measurements

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BIOGRAPHY

Lambert Wanninger received his Dipl.-Ing. and his Dr.-Ing. in Geodesy from the University of Hannover, Germany. He spent several years at Dresden University of Technology working in the field of GPS. In 2000 he founded Ingenieurbüro Wanninger, which develops software for precise GNSS applications. In 2004 he rejoined Dresden University of Technology as a professor in the Geodetic Institute.

Stephan Wallstab-Freitag received his Dipl.-Ing. in Geodesy from Dresden University of Technology. He spent one year at the Geodetic Institute at Dresden University of Technology working in the field of GNSS. Recently he joined GOM at Braunschweig, Germany, a company which develops optical 3D measurement techniques.

ABSTRACT

Precise (centimetre level) applications require code and carrier phase pseudoranges and differential positioning including carrier phase ambiguity resolution. Objective of this research work is to combine GPS with GLONASS and single-frequency SBAS ranging to gain improved availability, faster ambiguity resolution, and higher accuracy. Although GLONASS and SBAS broadcast orbits and often code observations are of lower accuracy than those of GPS, carrier phase observations are of similar quality. In contrast to GPS, GLONASS requires the estimation of inter-channel biases and SBAS multipath effects of static observations produce biases in the coordinates. Nevertheless, RTK (Real Time Kinematic) and fast static positioning improves considerably if all existing ranging signals are used.

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INTRODUCTION

One of the main limitations of GPS is the small number of satellite signals being available to the user at any one time. In future many more satellites, e.g. of the European Galileo and the Chinese Compass system, will broadcast ranging signals. But even today additional signals are available. Not only that the satellites of the Russian GLONASS provide ranging signals, also the SBAS (i.e. WAAS, EGNOS, MSAS, and GAGAN) satellites enable the users to produce code and carrier phase observations.

In early 2006 several manufacturers of GPS equipment added GLONASS capability to their products. Today many of the dual-frequency receivers on the market are combined GPS/GLONASS receivers. The additional observations are used to gain improved availability and faster ambiguity resolution. The GLONASS-specific difficulty of inter-channel biases (or differential hardware delays) got new importance because now, often mixed baselines are observed. Receiving equipment of the same type may experience similar inter-channel biases so that these biases may almost completely be removed in differential mode (Zinoviev 2005). In mixed baselines, however, the inter-channel biases have to be estimated as additional parameters in the position computation.

Although ranging to the SBAS satellites is one of the main objectives of these augmentation systems (e.g. Ventura-Traveset et al. 2006), this service has seldom been used for precise positioning yet. The presently available single-frequency signals limit the use of SBAS ranging for precise applications to short baselines, where ionospheric effects cancel out by differencing. In future dual-frequency SBAS signals may be available (Soddu et al. 2005) which will make SBAS ranging even more attractive for precise applications.

A coarse estimate of the improvement of positioning performance when adding additional satellite signals can be based on calculated DOP values. Average values for Dresden, Germany reveal that the additional code or carrier phase observations on the signals of the four available geostationary SBAS satellites have a larger positive effect than the 11 GLONASS satellites orbiting in medium heights (Tab. 1). When adding GLONASS and SBAS to the existing GPS constellation twice as many satellite signals are available on average and the DOP values decrease by approximately 25 % as compared to GPS only.

Tab.1: Expected improvement of positioning performance due to an increased number of GNSS satellites, average DOP values calculated for Dresden, Germany, July 2007, 10° elevation mask.

	GPS (30 SV)	GPS+ GLONASS (30+11)	GPS+ SBAS (30+4)	GPS+ GLONASS+ SBAS (30+11+4)
∅ visible SV	8.4	11.7	12.4	15.7
NDOP	0.85	0.72	0.60	0.55
EDOP	0.65	0.60	0.54	0.50
VDOP	1.59	1.36	1.34	1.21
PDOP	1.93	1.66	1.57	1.43

GLONASS ORBITS AND CODE PHASE OBSERVATIONS

There are several differences between GPS and GLONASS which need to be taken into account performing combined processing. Among these are different geodetic reference systems (WGS-84 versus PZ-90 or PZ-90.02 after September 19, 2007) and offsets between system times including leap second differences. These differences are removed by applying appropriate transformation parameters (see e.g. Zinoviev 2005, ICD 2002).

Other differences between GPS and GLONASS have to be dealt with through proper weighting of the observables or by estimating additional parameters. One effect is caused by large differences of orbit accuracies. Presently GLONASS broadcast orbits are worse by a factor of 3 as compared to GPS (Fig. 1). 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 phase-based short baseline RTK hardly any effect can be seen. However, precise differential carrier phase positioning on longer baselines (10 km+) is affected. For all post-processing applications on longer baselines it is recommended to use precise IGS orbits. But even here, accuracy differences exist: precise IGS GLONASS orbits are of lower accuracy (15 cm) than precise IGS GPS final orbits (<5 cm) (IGS 2007). This affects just very long baselines (100+ km).

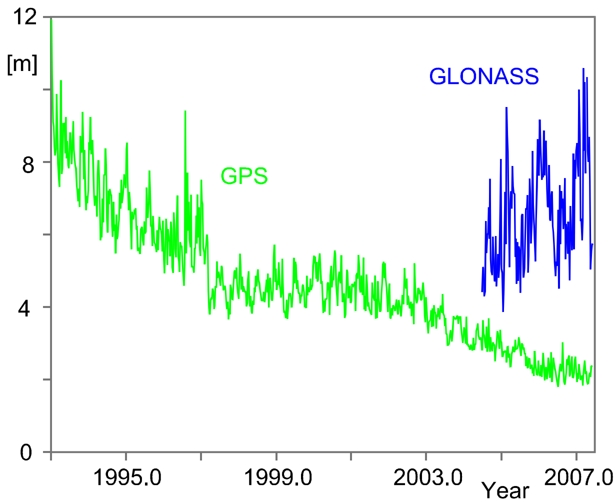

Fig. 1: 3D-accuracy of broadcast ephemeris, based on JPL Analysis Reports (GPS) and IGS IGLOS Orbit Combination Reports (GLONASS).

A further difference lies in the code phase observation quality, which depends on multipath effects and random noise. The GLONASS chip lengths of C/A- and P-codes are twice as large as the chip lengths of the GPS codes (ICD 2002, IS-GPS 2004). Therefore, one would expect a somewhat lower quality of the GLONASS code phase observables as compared to GPS.

Code multipath and noise can be detected and quantified using code and dual-frequency carrier phase observations of a single receiver (Rocken et al. 1995) by

$$MP_1 = C_1 + \frac{f_1^2 + f_2^2}{f_2^2 - f_1^2} \cdot \Phi_1 + \frac{2 f_2^2}{f_1^2 - f_2^2} \cdot \Phi_2 \qquad (1)$$

with
MP_1 – code multipath on C1 plus receiver noise [m]
C_1 – L1 pseudorange: either C/A-Code or P(/Y)-Code [m]
f_1,f_2 – signal frequencies [Hz] of L1 and L2
Φ_1,Φ_2 – carrier phase measurements [m] on L1 and L2

A constant bias due to carrier-phase ambiguities and hardware delays has to be removed. Since the MP_1–observable is very much elevation dependent, we compute RMS values for each elevation bin of size 1 degree and visualize MP_1 as a function of elevation angle. Fig. 2 shows examples of such RMS values for GPS and GLONASS C/A code (C1) and precise code (P1) computed from observations of two receivers from different manufacturers.

To our surprise we found receivers which are able to perform GPS and GLONASS code observations with similar quality (see left panels of Fig. 2). Other receivers, however, produce GLONASS code observations of considerably lower quality as compared to GPS (right panels of Fig. 2). In case of the standard accuracy signal (C/A code) GLONASS observations are here always of lower accuracy (upper right panel). We take this into account by giving the GLONASS code observations a lower weight. The situation is different for the precise code (lower right panel). Here, the two RMS curves intersect because the GLONASS code-correlation channels perform better than the code-free GPS observation technique for signals of low elevated satellites.

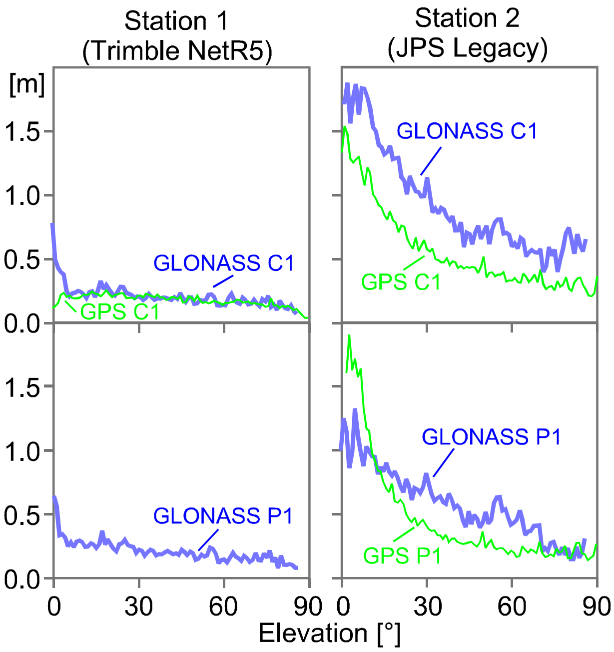

Fig. 2: Comparison of the elevation dependence of MP_1 values for two different receiver types and different code phase observables on L1: C/A-code C1 and precise code P1.

GLONASS INTER-CHANNEL BIASES

One of the main differences of GLONASS in comparison to GPS is the Frequency Division Multiple Access (FDMA) approach, which results in the use of several adjacent frequencies for the broadcast signals. Furthermore, none of the many GLONASS frequencies is exactly identical with one of the two GPS frequencies. Consequently, different hardware biases exist in GPS and GLONASS receiving channels as well as between GLONASS channels. It is expected that these inter-channel delays may change in time due to, for example, temperature changes (Dodson et al. 1999). Receiving equipment of the same type may experience similar inter-channel biases so that they can almost completely be removed in differential mode (Zinoviev 2005).

Thus, the combined processing of GPS and GLONASS carrier phase observations in differential mode requires the estimation of two independent receiver clock unknowns, one for the GPS signals and one for GLONASS. In addition, the GLONASS inter-channel biases need to be estimated as well. Pratt et al. (1998) suggested that the inter-channel biases are linearly dependent on signal frequency. We have estimated inter-channel biases in several ten baselines of various GPS/GLONASS-receivers and always found a dominant linear dependence.

This experience with GPS and GLONASS (and SBAS) carrier phase observations led to the following observation equations for single-difference observables $\Delta\Phi$ [m]:

$$\Delta\Phi_{a,b}^{GPS/SBAS,i} = \Delta R_{a,b}^{i} + c_0 \cdot \Delta\delta t_{a,b}^{GPS/SBAS} + \lambda \cdot \Delta N_{a,b}^{i} + \varepsilon_{\Delta\Phi} \qquad (2)$$

$$\Delta\Phi_{a,b}^{Glonass,i} = \Delta R_{a,b}^{i} + c_0 \cdot \left(\Delta\delta t_{a,b}^{Glonass} + k^{i} \cdot \Delta\delta h_{a,b}^{Glonass}\right) + \lambda \cdot \Delta N_{a,b}^{i} + \varepsilon_{\Delta\Phi} \qquad (3)$$

Subscripts *a,b* stand for the stations involved, the superscript *GPS,* or *Glonass (*or *SBAS)* indicates the GNSS satellite system, the superscript *i* specifies the individual satellite number. Furthermore,

ΔR -	single difference of ranges satellite – receiver [m], which is a function of the baseline coordinates,
c_0 -	speed of light in vacuum [m/s],
$\Delta\delta t^{System}$ -	Difference of receiver clocks, which are different for GPS and GLONASS due to different hardware delays in the receivers [s],
$\Delta\delta h^{Glonass}$ -	Difference of inter-channel biases of the two receivers for adjacent GLONASS frequencies [s],
k -	GLONASS channel number [-],
λ -	signal wavelength [m],
ΔN -	single difference of carrier phase ambiguity [-],
$\varepsilon_{\Delta\Phi}$ -	sum of all uncorrected systematic and random errors in the single-difference observable [m].

This approach was realized in the baseline software Wa1 including a combined ambiguity fixing for both, GPS and GLONASS 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. All baseline processing results presented in this paper were produced using this software.

Fig.3 visualizes the difficulties caused by GLONASS inter-channel biases. It shows L1 double-difference (DD) residuals of two short baselines, one observed with receivers of the same type, the other observed with receivers from different manufacturers. Ground truth baseline coordinates were obtained from several days of GPS observations. Antenna phase centre corrections were applied. Carrier phase ambiguities were estimated and fixed, i.e. removed. What remains in the DD residuals are the remaining effects of uncorrected systematic and random errors. In 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. In the baseline with two receivers of the same type, these inter-channel biases are so small, that they have hardly any effect on the estimated coordinates (Fig. 3). In the mixed baseline, however, they reach more than 2 cm for adjacent GLONASS frequencies. This means that the maximum effect on double differences reaches more than one L1 wavelength for this receiver combination and a presently maximum channel number difference of $\nabla k_{\max} = 12$.

An important aspect for the handling of these GLONASS inter-channel biases is their stability in time and their dependence on temperature. In order to obtain a better understanding we conducted several experiments. The results of two of these experiments are presented here.

First of all we were interested in the long term stability of these inter-channel biases. This requires long-term observations of two receivers with a small distance between their antennas. We found an appropriate data set from the IGS station Wettzell in Germany. At this site several GPS and GPS/GLONASS receivers are operated simultaneously. The observation data is available from the servers of Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt, Germany. From end of 2002 until early 2004 two GPS/GLONASS receivers from different manufacturers were operated: an Ashtech Z-18 at station WTZZ and a JPS Legacy at station WTZJ. The distance between the two antennas was just 2.5 m.

We processed all daily observation files with Wa1 software, fixed the carrier-phase ambiguities and estimated the inter-channel bias differences $\Delta\delta h^{Glonass}$, one value per day (Fig. 4). The peak to peak variations of the estimated values are about 1 mm and thus very small. No seasonal (temperature) effects and no aging effects are observed. A jump, however, occurred when the antenna was exchanged from TRM29659.00 NONE to JPSREGANT_SD_E NONE at station WTZJ on April 4, 2002.

Furthermore, we tried to determine the temperature dependence of the inter-channel biases. We conducted experiments similar to those of Dodson et al. 1999. We recorded observations of 2 GPS/GLONASS receivers of a short baseline or zero baseline. One of the receivers, a Leica GRX 1200 GG PRO, was chilled for several hours. The temperature difference at the outside of the receiver reached more than 20 degrees Celsius. Unfortunately, we were not able to determine the inside temperature of the equipment. The other receiver, a JPS Legacy, remained unchanged.

The inter-channel bias differences of a 9 day long experiment are shown in Fig. 5. No effect of the temperature change can be observed. But the change of antenna and antenna cables for one of the receivers in order 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 mm (Fig. 5).

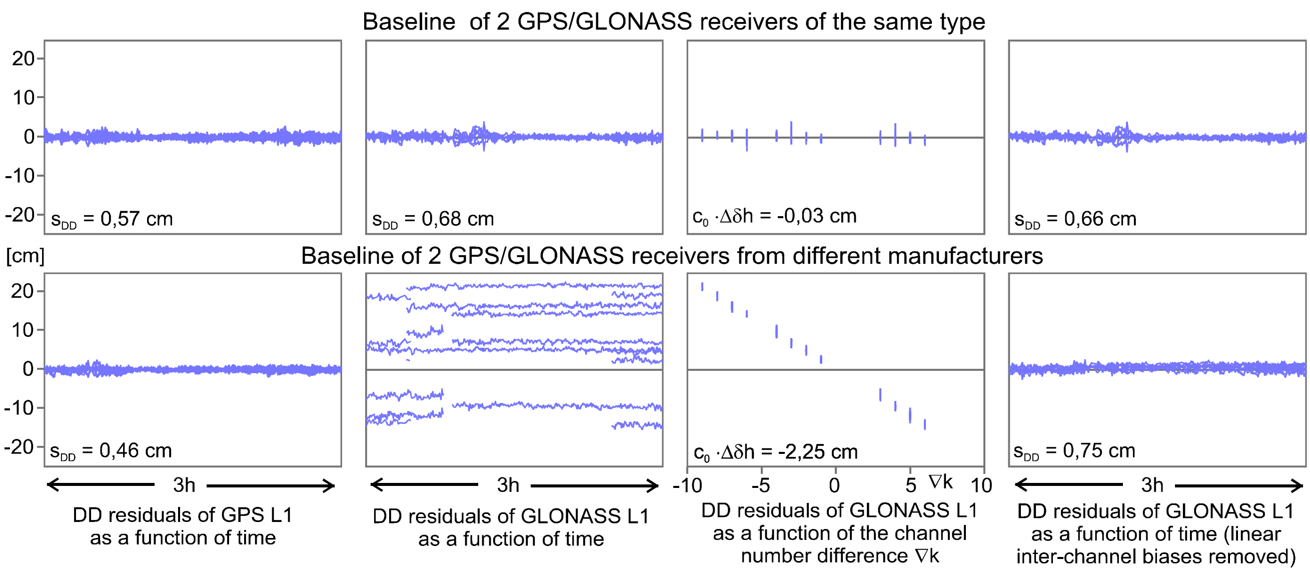

Fig: 3: Double difference (DD) residuals of two short GPS/GLONASS baselines.

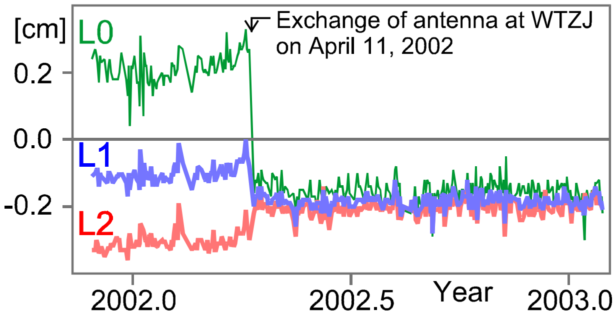

Fig. 4: Daily estimates of the inter-channel bias differences $c_0 \cdot \Delta\delta h^{Glonass}$ in the short baseline WTZZ (Ashtech Z-18) and WTZJ (JPS Legacy) at Wettzell, Germany during a period of more than one year. Shown are results for L1, L2, and the ionosphere-free linear combination L0.

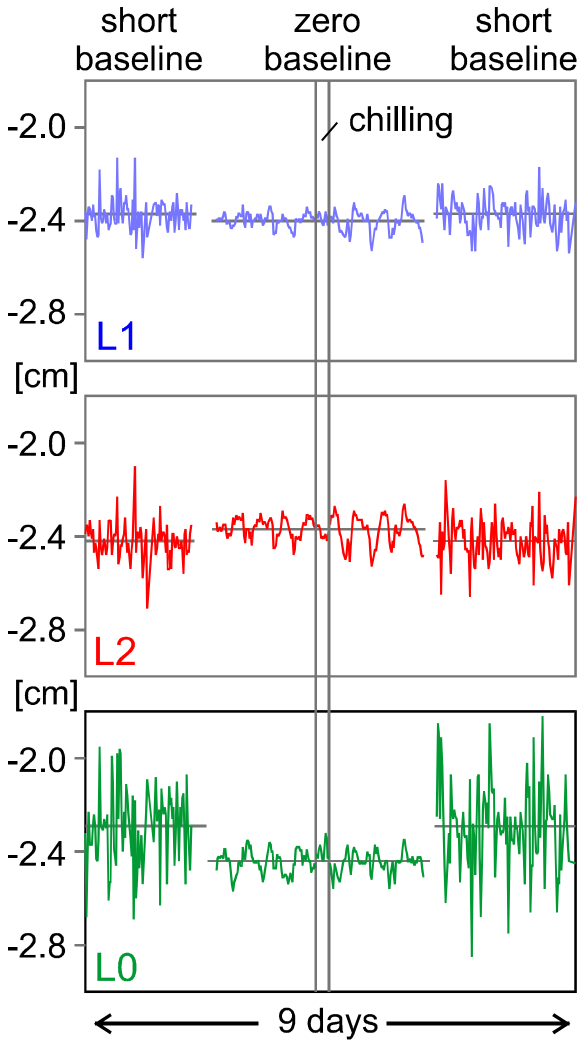

Fig. 5: Inter-channel bias differences $c_0 \cdot \Delta\delta h^{Glonass}$ of two receivers from different manufacturers before, during, and after a chilling experiment.

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 2.5 cm. They are estimated from the baseline observations after fixing of the ambiguities. If these bias differences exceed a few millimetres, reliable ambiguity fixing gets much more difficult or can not be performed at all for positioning techniques like RTK (Real Time Kinematic). We therefore recommend introducing a priori values of the biases into the data processing to support ambiguity resolution.

We estimated approximate values $c_0 \cdot \Delta\delta h^{Glonass}$ from the observations gathered in short mixed baselines. The correction values presented in Tab. 2 are only valid for firmware versions of receivers of early 2007. Large changes of these values may occur if a manufacturer modifies pre-correction values applied by the receiver firmware. The accuracies of the values in Tab. 2 are on the level of a few millimetres. Higher accuracies can not be obtained due to effects which do not depend on the receiver itself but on the antenna and antenna cable. We also found that a distinction of L1 and L2 corrections is not necessary on this level of accuracy. Hence, Tab. 2 contains a single value for each receiver pair.

Tab. 2: Estimates of GLONASS inter-channel bias differences $c_0 \cdot \Delta\delta h^{Glonass}$ in centimetres for several receiver pairs.

	Ashtech Z-18	JPS Legacy, TPS E_GGD, TPS Net-G3	Leica GRX 1200 GG PRO	Trimble NetR5
Ashtech Z-18	0.0	0.0	2.4	-0.7
JPS Legacy, TPS E_GGD, TPS Net-G3	0.0	0.0	2.4	-0.7
Leica GRX 1200 GG PRO	-2.4	-2.4	0.0	-3.1
Trimble NetR5	0.7	0.7	3.1	0.0

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 could, 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 presently experience with RTK ambiguity resolution in mixed GLONASS baselines. A priori values as presented in Tab. 2 can only be a provisional solution.

COMBINED GPS/GLONASS PROCESSING RESULTS

Following the maxim "the more satellites the better" we expect faster and more reliable ambiguity resolution and more precise positioning results by adding GLONASS satellites to our data processing. On the other hand broadcast orbit accuracy of GLONASS is considerably lower than that of GPS. And the GLONASS code observations of some receivers are of lower quality (see above). No real accuracy difference is expected for the phase observations except that an additional parameter for the inter-channel biases must be estimated. In conclusion we would expect a better positioning performance adding GLONASS satellite to GPS. In the present situation, however, with just a few available GLONASS satellites at any one time (about 4 on average as compared to 8 to 12 for GPS) any positive effects can only be very limited.

We compared GPS to GPS+GLONASS on several baselines. Tab. 3 summarizes the results for a 10 km mixed baseline observed with a Leica GRX 1200 GG PRO and a JPS Legacy. The 12 hours of observations were split into 360 sessions of 2 minutes each to simulate RTK-like ambiguity resolution. Other processing parameters:

- dual-frequency observations,
- elevation mask 10°,
- hardly any signal obstructions,
- low multipath,
- broadcast orbits,
- antenna phase center corrections applied,
- elevation dependent weighting of the observations,
- GLONASS code observations down-weighted by a factor of 2 as compared to GPS,
- same weights for GLONASS and GPS phase observations.

Tab. 3: Baseline processing results for a 10 km baseline: coordinate accuracy before and after ambiguity fixing for 360 samples of 2 min each.

	GPS	GPS + GLONASS
average # of SV	8.0	11.6
Combined Float/DGNSS Std. Dev. N/E/Up [cm]	18 / 20 / 25	15 / 19 / 20
Fixed solution # valid solutions (of 360) Std. Dev. N/E/Up [cm]	 358 0.54 / 0.49 / 1.00	 359 0.53 / 0.48 / 0.93

Both presented solution types, firstly the combined float-phase / DGNSS-code solution before ambiguity resolution and secondly the fixed solution, show a slightly higher performance when using GPS + GLONASS. The average number of satellites increased by 45%. Positioning accuracies improved for both solution types and in all coordinate components for at least a few percent on average. This proofs that GLONASS carrier phase measurements are of similar quality as the GPS carrier phases. The more satellites the better results can be achieved.

We were also interested in the positioning performance in long static baselines with observation sessions of 24 h. Here, we processed combined GPS/GLONASS observations data of some European IGS stations. All these stations are equipped with JPS Legacy receivers. Baselines range from about 250 km to almost 1400 km. No ambiguity resolution was performed for baselines longer 1000 km. We processed the complete data set of 2006 and the first three months of 2007, i.e. in maximum 455 sessions depending on the availability of observations files. Other processing parameters:

- dual-frequency observations,
- elevation mask 5°,
- hardly any signal obstructions,
- mostly low multipath,
- precise IGS orbits with accuracies: GPS < 5cm and GLONASS 15 cm (IGS 2007),
- antenna phase center corrections applied,
- elevation dependent weighting of the observations,
- same weights for GLONASS and GPS phase observations,
- estimation of tropospheric zenith delays.

Tab. 4: Baseline processing results for long baselines based on 455 sessions of 24 h hours each.

LEIJ – WETJ (248km)	GPS	GPS + GLONASS
average # of SV	12.1	16.3
percentage of obs. with ambiguities fixed	98.8	98.0
Fixed solution Std. Dev. N/E/Up [cm]	0.26/0.22/0.70	0.25/0.22/0.70

LEIJ – ZIMJ (613 km)	GPS	GPS + GLONASS
average # of SV	10.9	14.9
percentage of obs. with ambiguities fixed	95.8	94.2
Fixed solution Std. Dev. N/E/Up [cm]	0.44/0.44/1.14	0.42/0.42/1.19

LEIJ – CAGZ (1381 km)	GPS	GPS + GLONASS
average # of SV	10.5	14.3
Float solution Std. Dev. N/E/Up [cm]	3.5/1.5/4.2	3.5/1.5/4.4

For some baselines, we removed a seasonal trend in the coordinate time series before calculating standard deviations. The results (Tab. 4) show that, although the average number of satellite signals increased by more than 35 %, no overall improvement in coordinate accuracy could be achieved. One reason may be found in the lower accuracy of precise IGS GLONASS orbits (15 cm) as compared to IGS GPS final orbits (<5 cm) which results in lower weights for GLONASS observations as compared to GPS observations.

SBAS SATELLITES AND OBSERVATION EQUATION

Presently 10 SBAS satellites are available for ranging applications (Fig. 6). In Europe we are able to receive the signals of the three EGNOS satellites and the recently launched first GAGAN satellite. The EGNOS Artemis satellite (PRN 124) is currently set unhealthy because it is used by industry to perform various tests on the system (ESA 2007). Nevertheless, all ranging measurements using the Artemis satellite were of high quality so that we were able to include them in our data processing.

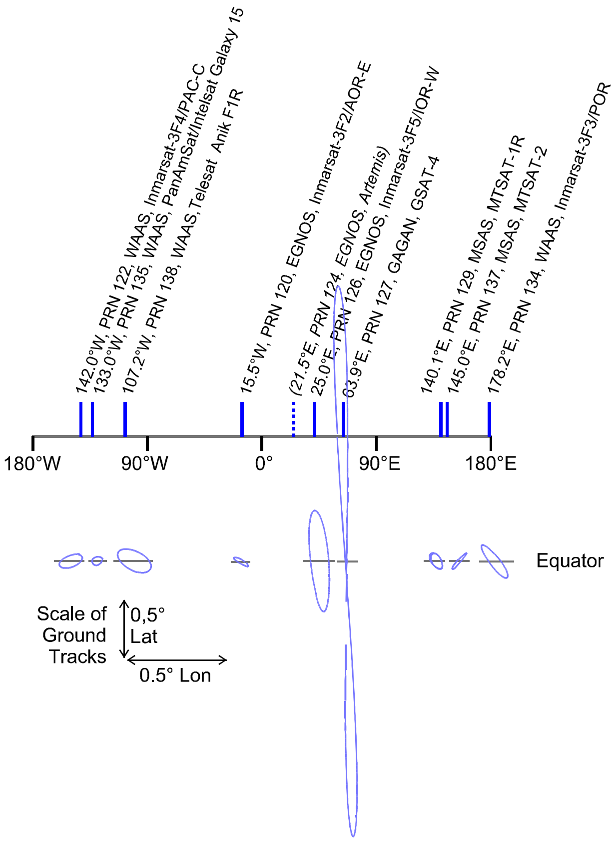

Fig. 6: Presently available SBAS satellites for single-frequency ranging, their orbital positions and ground tracks.

The observation equation for the combined processing of GPS/SBAS differential positioning has already been presented in the GLONASS part of this paper, see equation (2). Offsets between GPS and SBAS system time cancel out by differencing. No differences in the receiver hardware delays of GPS and SBAS signals were found. SBAS range biases as suggested by Phelts et al. 2004 could not be identified. They may have canceled out by differential positioning using receivers of the same type.

QUALITY OF SBAS CODE OBSERVATIONS

The GPS-like signals of SBAS satellites do not have exactly the same characteristics as GPS signals. The bandwidth of the L1-signals transmitted by Inmarsat-3 satellites is just 2.2 MHz (Kinal and Razumovsky 2006) and the use of wider correlators produces noisier measurements.

In order to quantify code noise and multipath from single frequency observations we modified the algorithm to obtain the MP_1 observable:

$$MP_1' = C_1 - \Phi_1 \qquad (4)$$

with
$MP_1{}'$ – code multipath on C1 plus receiver noise [m] from single frequency observations,
C_1 – L1 pseudorange [m],
Φ_1 – carrier phase measurements [m] on L1.

With single-frequency data we have to account for code-carrier ionospheric divergence. Therefore, we do not just estimate a single bias but bias plus trend to remove ambiguity, differential hardware, and ionospheric effects. Furthermore, we reestimate bias and trend once per hour. Afterwards RMS values for each elevation bin are calculated. Elevation dependent RMS values of dual-frequency GPS MP1 and single-frequency GPS MP1´ are shown in Fig. 7. They agree so well, that we can use this modified algorithm for estimating the quality of SBAS code measurements.

We can conclude from Fig. 7 that SBAS code observation quality is lower than that of GPS observations. We therefore reduced the weight of SBAS code observations by a factor of 2 as compared to GPS.

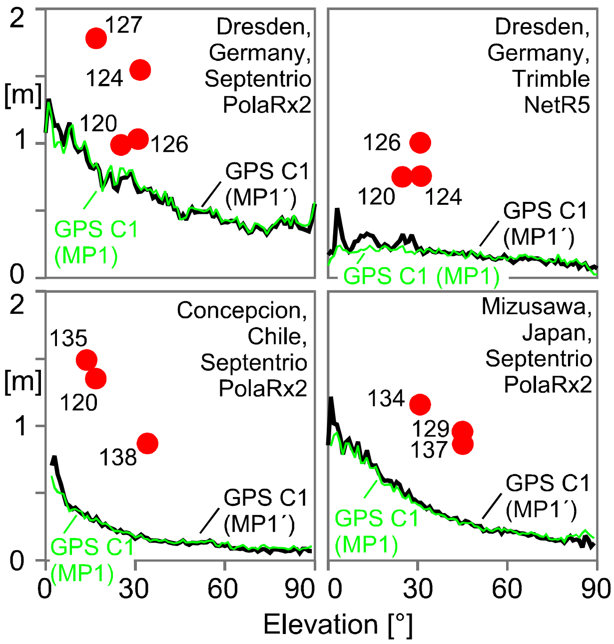

Fig.7: Comparison of the elevation dependence of $MP_1´$ values for GPS and SBAS C1 signals.

COMBINED GPS/SBAS PROCESSING RESULTS

We tested the combined GPS/SBAS processing in several baselines observed in Germany. The observing stations were free of any obstructions and hence we could gather code and carrier phase observations of 4 SBAS satellites, three of EGNOS and the one GAGAN. In baselines of more than a few hundred metres in length, we experienced difficulties due to the very low accuracy of the EGNOS orbits. Therefore, only results of short (few m) baselines are presented here. They show the potential of a combined GPS/SBAS processing. We had only a single GPS/GLONASS/SBAS receiver available, but several Septentrio PolaRx2 GPS/SBAS receivers. Hence, the analysis is limited to a comparison of GPS with GPS/SBAS.

Two types of solutions were produced from dual-frequency GPS and single-frequency SBAS observations. We used all available observations for the first solution (Tab.5). The combined float/DGNSS solution is based on the L1 phase and code observations of both GNSS systems. Furthermore, we performed ambiguity fixing in a two step procedure, first with dual-frequency GPS observations only and afterwards for all remaining L1 ambiguities including the SBAS phase observations. The second solution (Tab. 6) is a pure single-frequency solution, i.e. the GPS L2 observations were ignored.

In both examples (Tab. 5, 6), the 4 SBAS satellites improved ambiguity resolution and accuracy of the estimated coordinates. Although the SBAS code observations are noisier as those of GPS, the carrier phase measurements, which are the primary observables for both kinds of solutions, seem to be of similar quality.

Tab. 5: Comparison of short baseline (few m) GPS with GPS/SBAS RTK-like positioning: dual-frequency GPS and single-frequency SBAS observations, 2 min of observations, coordinate accuracy before and after ambiguity fixing.

	GPS	GPS + SBAS
ave. # of SV	8.7	12.7
Combined Float/DGNSS Std. Dev. N/E/Up [cm]	16/18/22	15/17/21
Fixed # valid solutions (of 720) Std. Dev. N/E/Up [cm]	713 0.44 / 0.35 / 0.89	712 0.27 / 0.26 / 0.74

Tab. 6: Comparison of short baseline (few m) GPS with GPS/SBAS RTK-like positioning: single-frequency GPS+SBAS observations, 10 min of observations, coordinate accuracy before and after ambiguity fixing

	GPS	GPS + SBAS
ave. # of SV	8.7	12.7
Combined Float/DGNSS Std. Dev. N/E/Up [cm]	3.4 / 6.5 / 4.8	3.3 / 5.1 / 4.8
Fixed # valid solutions (of 144) Std. Dev. N/E/Up [cm]	141 0.37 / 0.25 / 0.82	142 0.25 / 0.21 / 0.69

As stated before, these results are only valid for very short baselines, because the present satellite broadcast orbit and clock information is very poor in case of EGNOS. Much higher quality broadcast orbit and clock information is provided by the other systems (WAAS, MSAS, and GAGAN).

SBAS CARRIER PHASE MULTIPATH

An interesting aspect of SBAS carrier phase processing lies in the time dependence of multipath of a static receiver. In case of GPS multipath effects caused by distant reflectors (1 metre to several metres distance to antenna) produce fluctuations in the carrier phase with periods of a few to several minutes due to the changing position of the satellites. With SBAS, however, the apparent satellite motion is very small and thus multipath effects do not fluctuate but cause a bias.

In order to gain more experiences with this kind of multipath effects we observed a short (few m) baseline with two Septentrio PolaRx2 receivers for several days. The double difference residuals of the satellite signals of PRN 120 and PRN 126 are shown in Fig.8. In short baseline double difference residuals are dominated by multipath effects. The residuals show a 24 h pattern because of the small but still existing satellite motion which repeats about every 24 h, cf. Fig.6. This pattern changes during the test period of 8 days. The broadcast orbit data revealed that orbit maneuvers took place for both satellites. The largest changes in orbit happened to PRN 120 on days 149 and 150. They are the main cause for the change in multipath pattern.

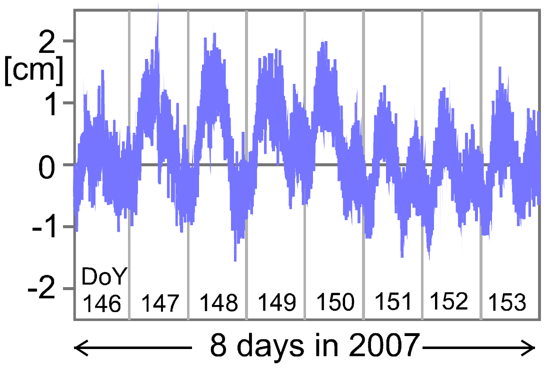

Fig. 8: Double difference carrier phase L1 residuals of PRN 120 and PRN 126 in a short static baseline.

As expected we observed SBAS carrier phase multipath effects unlike from those of GPS because of the completely different satellite orbits. SBAS multipath can be stable for several hours and thus it causes a bias. It can not be mitigated by time stacking even over time periods of several hours. But since the geostationary satellites slightly move in elevation and azimuth over time periods of 24 h some mitigation takes place. Nevertheless, for observation time spans of more than a few minutes in static application, SBAS carrier phase observables should be given a lower weight.

CONCLUSION 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 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.

Presently, the EGNOS satellite orbit and clock parameters are of such a poor quality that precise differential positioning is limited to short baselines. We could, however, show that EGNOS and all the other SBAS contribute to precise carrier phase positioning although they provide just single-frequency ranging signals by now.

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

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