GLONASS Double Difference Ambiguity Resolution in Real-Time

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BIOGRAPHY

Udo Rossbach holds a degree in aeronautical engineering from the Technical University Aachen (Germany). From 1994 to 1998 he worked as a Research Associate at the Institute of Geodesy and Navigation of the University of Federal Armed Forces Munich, doing research on GLONASS and GPS/GLONASS combination. Since 1999 he is working as a systems engineer with IfEN GmbH. There he is involved in the development of GPS/GLONASS/EGNOS algorithms and software. Positioning with GLONASS is also the topic of his pending Ph.D. thesis.

ABSTRACT

Undoubtedly, the combined use of GPS and GLONASS brings along a number of advantages as compared to the use of either of the systems alone. However, the different signal frequencies of the GLONASS satellites give rise to problems in the determination of double difference integer ambiguities. This is the more concerning, since double difference carrier phase observations are preferably used for geodetic applications. Therefore, this topic is under investigation by different groups of scientists all over the world.

In brief, the problem with GLONASS double differences is that either the receiver clock errors do not cancel, or the ambiguities are no longer of integer nature. Proposed solutions to this problem include confining to single differences or scaling GLONASS carrier phase measurements to a common frequency.

This paper introduces an improved approach to tackle the problem of using GLONASS and GPS/GLONASS combinations for high-precision geodetic applications. It is suitable for real-time operation, especially also for Real-Time Kinematic (RTK) applications.

The approach is described in theory. Processing results are given, and its performance is evaluated.

INTRODUCTION

GPS undoubtedly has become the means of choice for high precision navigation and geodetic positioning worldwide. Using double difference carrier phase measurements, decimeter accuracy can easily be reached. When the integer ambiguities are fixed correctly, even centimeter accuracy is obtained.

There are, however, situations where a precise positioning solution cannot always be guaranteed using GPS. In areas with lots of obstructions, such as “urban canyons”, mountainous areas or woodland, there may be cases when less than four GPS satellites are in view. This is not enough for a positioning solution at all. And even if four satellites are in view, for fixing the integer ambiguities it is desirable to have as many measurements as possible. Generally, at least six satellites are required for this purpose.

To overcome this potential visibility problem, one possible solution is the combination of GPS with GLONASS. The Russian satellite navigation system is very similar to GPS, and the combined use of GPS and GLONASS therefore can be easily accomplished. Basically, the GLONASS satellites can be treated as additional GPS satellites. These additional satellites may not only solve the problem of not having enough satellites in view. Even in cases where enough GPS satellites can be observed, the additional GLONASS satellites may lead to a better satellite geometry and thus to a more precise positioning solution.

In a similar fashion, the addition of GLONASS satellites may improve Receiver-Autonomous Integrity Monitoring (RAIM).

These advantages are the reason why there is still a strong interest in the use of GLONASS and combined

GPS/GLONASS for (precise) positioning, despite the recent demise of the GLONASS constellation due to the ongoing economic problems in Russia. Even the discontinuing of S/A, which constituted the main disadvantage of GPS compared to GLONASS, did not affect the interest in GLONASS significantly.

However, when using double difference carrier phase measurements for precise positioning, one distinct feature of the GLONASS system gives rise to a different kind of problem. Due to the different signal frequencies of the GLONASS satellites, the receiver clock errors do not cancel in the double difference observation equation, when the equation is set up in units of cycles. Alternatively, when expressed in units of length, the carrier phase ambiguities lose their integer nature. This is a major complication, since double difference carrier phase measurements are preferred for precise positioning. This topic therefore is under investigation by different groups of scientists all over the world.

This paper describes a unique approach to deal with this problem and gives some first experiences. This approach bases on the algorithm as introduced in [6].

GLONASS DOUBLE DIFFERENCE CARRIER PHASES

The observation equation for a carrier phase observation at a user U to a satellite i in units of length can be written as:

$$\lambda^i \varphi_U^i = \rho_U^i + \lambda^i N_U^i - c\delta t^i + c\delta t_U + c\delta t_U^{Trop,i} - c\delta t_U^{Iono,i} + \varepsilon_U^i \quad (1)$$

with

λ^i	Signal carrier frequency of satellite i,
φ_U^i	Phase measurement from user U to satellite i,
ρ_U^i	Geometrical range between user U and satellite i,
N_U^i	Integer ambiguity between user U and satellite i,
c	Speed of light,
δt^i	Clock offset of satellite i,
δt_U	Clock offset of user receiver U,
$\delta t_U^{Trop,i}$	Tropospheric delay between user U and sat. i,
$\delta t_U^{Iono,i}$	Ionospheric advance between user U and sat. i,
ε_U^i	Noise of measurement from user U to satellite i.

The single difference carrier phase observation between user U and reference station R to satellite i then reads:

$$\lambda^i \Delta\varphi_{UR}^i = \Delta\rho_{UR}^i + \lambda^i \Delta N_{UR}^i + c\Delta\delta t_{UR} + c\Delta\delta t_{UR}^{Trop,i} - c\Delta\delta t_{UR}^{Iono,i} + \Delta\varepsilon_{UR}^i \quad (2)$$

with the abbreviation

$$\Delta *_{UR}^i = *_U^i - *_R^i$$

Forming double difference carrier phase observations between user U and reference station R to satellites i and j, the observation equation becomes:

$$\lambda^i \Delta\varphi_{UR}^i - \lambda^j \Delta\varphi_{UR}^j = \nabla\Delta\rho_{UR}^{ij} + \lambda^i \Delta N_{UR}^i - \lambda^j \Delta N_{UR}^j + c\nabla\Delta\delta t_{UR}^{Trop,ij} - c\nabla\Delta\delta t_{UR}^{Iono,ij} + \nabla\Delta\varepsilon_{UR}^{ij} \quad (3)$$

with the abbreviation

$$\nabla\Delta *_{UR}^{ij} = \Delta *_{UR}^i - \Delta *_{UR}^j$$

Given two satellites with identical signal frequencies and thus wavelengths $\lambda^i = \lambda^j = \lambda$, equation (3) simplifies to

$$\lambda\nabla\Delta\varphi_{UR}^{ij} = \nabla\Delta\rho_{UR}^{ij} + \lambda\nabla\Delta N_{UR}^{ij} + c\nabla\Delta\delta t_{UR}^{Tropo,ij} - c\nabla\Delta\delta t_{UR}^{Iono,ij} + \nabla\Delta\varepsilon_{UR}^{ij} \quad (4)$$

This is the common observation equation for double difference GPS carrier phase measurements.

But as soon as at least one GLONASS satellite is participating in the double difference observation, the wavelengths are no longer identical, and equation (3) can no longer be simplified in this way without losing the integer character of the ambiguity terms. Therefore, single difference terms remain in the double difference observation equation (3).

In the past, a number of different ways have been proposed to treat this problem.

Proposed solutions are to confine to floating ambiguities [3] or to confine single difference observations and obtain the clock offsets from pseudorange measurements [7]. However, the pseudorange measurements are less precise than the carrier phase measurements. Another proposal was to scale all GLONASS carrier phase observations to a common (center) frequency [4]. The proposed iterative ambiguity resolution [2] is not suitable for real-time applications such as e.g. RTK.

In [6] a method was described to form carrier phase double differences for different signal frequencies without losing the integer nature of the ambiguities. The core of this method is the introduction of an auxiliary signal with a wavelength, of which the wavelengths of the participating satellites are integer multiples. This method does not require much additional effort in processing the phase measurements. It is thus suitable for real-time applications and was therefore chosen as the basis for the GLONASS ambiguity resolution. It is briefly recapitulated in the following.

An expression of the double difference observation equation with integer ambiguities but without single difference terms in it can be found by introducing an auxiliary wavelength λ^*, of which both λ^i and λ^j are integer multiples:

$$\lambda^* = \frac{\lambda^i}{k^i} = \frac{\lambda^j}{k^j} = \frac{c}{k^i f^i}, \text{ with } k^i, k^j \in \Im \qquad (5)$$

Inserting this definition into equation (3) yields a modified double difference observation equation:

$$\begin{aligned} \lambda^* \nabla^{k^i,k^j} \Delta\varphi_{UR}^{ij} = & \\ & \nabla\Delta\rho_{UR}^{ij} + \lambda^* \nabla^{k^i,k^j} \Delta N_{UR}^{ij} \\ & + c\nabla\Delta\delta t_{UR}^{Trop,ij} - c\nabla\Delta\delta t_{UR}^{Iono,ij} + \nabla\Delta\varepsilon_{UR}^{ij} \end{aligned} \qquad (6)$$

with the abbreviation

$$\nabla^{a,b}\Delta *_{UR}^{ij} = a\Delta *_{UR}^{i} - b\Delta *_{UR}^{j}$$

The modified double difference ambiguities $\nabla^{k^i,k^j} \Delta N_{UR}^{ij}$ are still of integer type. They refer to the auxiliary signal with the wavelength λ^*.

The coefficients k^i, k^j must be chosen depending on the signal frequencies involved. For GLONASS satellites they depend on the frequency letters of the satellites involved. The L_1 and L_2 carrier frequencies of GLONASS satellite *i* are determined by the relations

$$f_{L1}^i = \left(2848 + n^i\right) \cdot \Delta f_{L1}$$

$$f_{L2}^i = \left(2848 + n^i\right) \cdot \Delta f_{L2}$$

with $\Delta f_{L1} = 0.5625$ MHz and $\Delta f_{L2} = 0.4375$ MHz and n^i being the frequency letter of satellite *i*.

In case of two GLONASS satellites, according to the definition (5), λ^* thus must be

$$\lambda^* = \frac{c}{k^i\left(2848 + n^i\right)\Delta f} = \frac{c}{k^j\left(2848 + n^j\right)\Delta f} \qquad (7)$$

This condition is fulfilled for the pair of coefficients $k^i = 2848 + n^j$, $k^j = 2848 + n^i$. Therefore, the GLONASS/GLONASS double differences become:

$$\begin{aligned} \lambda^* \nabla^{2848+n^j,2848+n^i} \Delta\varphi_{UR}^{ij} = & \\ & \nabla\Delta\rho_{UR}^{ij} + \lambda^* \nabla^{2848+n^j,2848+n^i} \Delta N_{UR}^{ij} \\ & + c\nabla\Delta\delta t_{UR}^{Trop,ij} - c\nabla\Delta\delta t_{UR}^{Iono,ij} + \nabla\Delta\varepsilon_{UR}^{ij} \end{aligned} \qquad (8)$$

with the auxiliary wavelength

$$\lambda^* = \frac{c}{\Delta f} \frac{1}{\left(2848 + n^i\right)\left(2848 + n^j\right)} \qquad (9)$$

These equations hold for both L_1 and L_2. Therefore, the respective indices were omitted.

For the double difference between a GPS and a GLONASS satellite the coefficients must be chosen as $k^i = 75 \cdot (2848 + n^i)$, $k^j = 210056$ for L_1 and $k^i = 35 \cdot (2848 + n^i)$, $k^j = 98208$ for L_2.

However, these auxiliary wavelengths are very small. For GLONASS/GLONASS double differences on L_1, this wavelength is about 65 µm, for GPS/GLONASS double differences it is even in the order of 0.9 µm. For L_2, the respective wavelengths are about 84 µm and 2.4 µm.

AMBIGUITY RESOLUTION

The treatment of GLONASS double difference carrier phase measurements as described in the previous chapter was implemented in a GPS/GLONASS positioning software package. For the ambiguity search itself, the Euler-Landau method [1] was chosen. This is a fast way of searching ambiguities, suitable for real-time applications.

Due to the small wavelength of the GPS/GLONASS double differences, the ambiguities were deemed to be very difficult to fix correctly. Besides this, in GPS/GLONASS double differences effects of different receiver hardware biases for satellites of the two systems may be found [5]. Therefore, only GLONASS/GLONASS double differences are formed. In combined GPS/GLONASS scenarios, this means that two reference satellites are used, one for GPS and one for GLONASS.

The auxiliary wavelength for GLONASS/GLONASS double differences is much larger and might therefore be easier to fix. Still, it is far off from the wavelength of an original satellite signal. The idea was that with such small wavelengths, ambiguity fixing to integers will not be necessary, but fixing to thousands of cycles might be sufficient. The ratio of a typical GLONASS wavelength to a typical auxiliary wavelength is approximately 3000 for both L_1 and L_2.

Tests were made to verify the ambiguity resolution. Two Ashtech GG24 single-frequency GPS/GLONASS receivers had been set up at two known locations, approximately 450 m apart. One of them was situated on a concrete observation pillar. This was treated as the reference station. The other was regarded as the user whose position was to be determined. Data had been recorded at both stations with a data rate of 1 Hz. These data were processed off-line, but under real-time conditions. The main reason for this was to be able to test the effects of different parameter values. This is best done with identical data sets for the different processing runs, which is not possible in actual real-time.

Data analysis was done twofold: Separate positioning solutions were computed for GPS only and for the GPS/GLONASS combination. Due to the low number of GLONASS satellites, no GLONASS only solution was possible. These two solutions (GPS only and GPS+GLONASS) were compared.

As was noted before, the idea was to fix the GLONASS ambiguities (which refer to the auxiliary signal with the small wavelength) only to thousands of cycles. To test the effect of this quantization on the positioning solution, several processing runs were done with different values for the grid spacing, namely 500, 1000, 1500, 2000, 2500 and 3000, which is approximately the ratio of physical satellite wavelength to the auxiliary wavelength. The grid origin was also varied to include zero in one case or the rounded float solution in another case. For a grid spacing of 1000 e.g., this means that in the first case ambiguities 0, ±1000, ±2000, and so on were possible candidates for ambiguity resolution. In the second case, the rounded float solution $\overline{\nabla^{k^i,k^j}\Delta N_{UR}^{ij}}$ was a possible candidate, along with $\overline{\nabla^{k^i,k^j}\Delta N_{UR}^{ij}} \pm 1000$, $\overline{\nabla^{k^i,k^j}\Delta N_{UR}^{ij}} \pm 2000$, and so on. Of course, for the GPS double differences the grid spacing was 1 and the grid contained integer numbers in all cases.

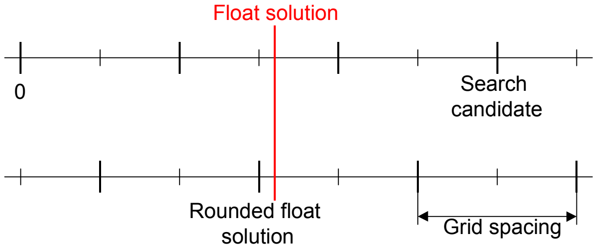

Figure 1: Organization of search space for GLONASS integer ambiguities.

Results of one of these tests are presented in the following. These results are from a half-hour data set, containing measurements from six GPS and three GLONASS satellites. Special importance was attached to fixing the ambiguities correctly. Thus, ambiguities were only fixed, when there was a significant difference between the residuals of the best and second-best combinations of integer ambiguities.

TEST RESULTS

The variation of grid spacing and origin for the GLONASS ambiguity search did not have any effect on the GPS ambiguities, of course. The impact on the GLONASS ambiguities was twofold. With the grid origin at zero, no successful ambiguity resolution could be achieved. Obviously in this case the examined grid points were too far off from the rounded ambiguity (where the minimum residual is located) to yield significantly different minimum residuals. Ambiguity resolution could only be achieved when the rounded float solution was included in the grid. In this case, however, the grid spacing did have no effect on the time when the ambiguities were finally fixed. Also, the found integer ambiguity was the rounded float solution, no matter what the grid spacing was.

On the other hand it was noticed that the GPS ambiguities were fixed to the rounded float solution, too. Thus, at the point of fixing the float solution was already such precise that a simple rounding would have sufficed, rather than a costly ambiguity search.

Figures 2 - 4 show the results of the positioning solution for latitude, longitude and height, respectively. Figure **5** shows the estimated ambiguity values. To obtain a more compact diagram, the value, to which the ambiguity finally was fixed, is subtracted from each ambiguity value.

A successful ambiguity fixing was achieved only very late into the data set. This is most probably due to multi-path effects. At least the site of the reference station is known to be apt to multi-path. But it can be noticed that ambiguity resolution for the combined solution was achieved earlier than for GPS alone. This is most clearly visible in figure 3. This effect of earlier ambiguity resolution in a combined solution is consistent with the findings of [3]. However, they confined to floating GLONASS ambiguities and fixed only the GPS ambiguities.

Furthermore, as soon as the ambiguities are fixed the position is very close (within 2 mm for latitude/longitude and 6 mm for the height component) of the known user position. During the approximately 15 minutes until the end of the data set, no significant drift in the position can be observed. This is a strong hint for a correct ambiguity resolution. A closer look at the fixed ambiguities reveals identical values for the GPS ambiguities in the combined solution and the GPS only solution. The GPS observations were also processed with an independent software package. Here again, the ambiguities were fixed to the same integer values. So it is safe to assume that the fixing really was done correctly.

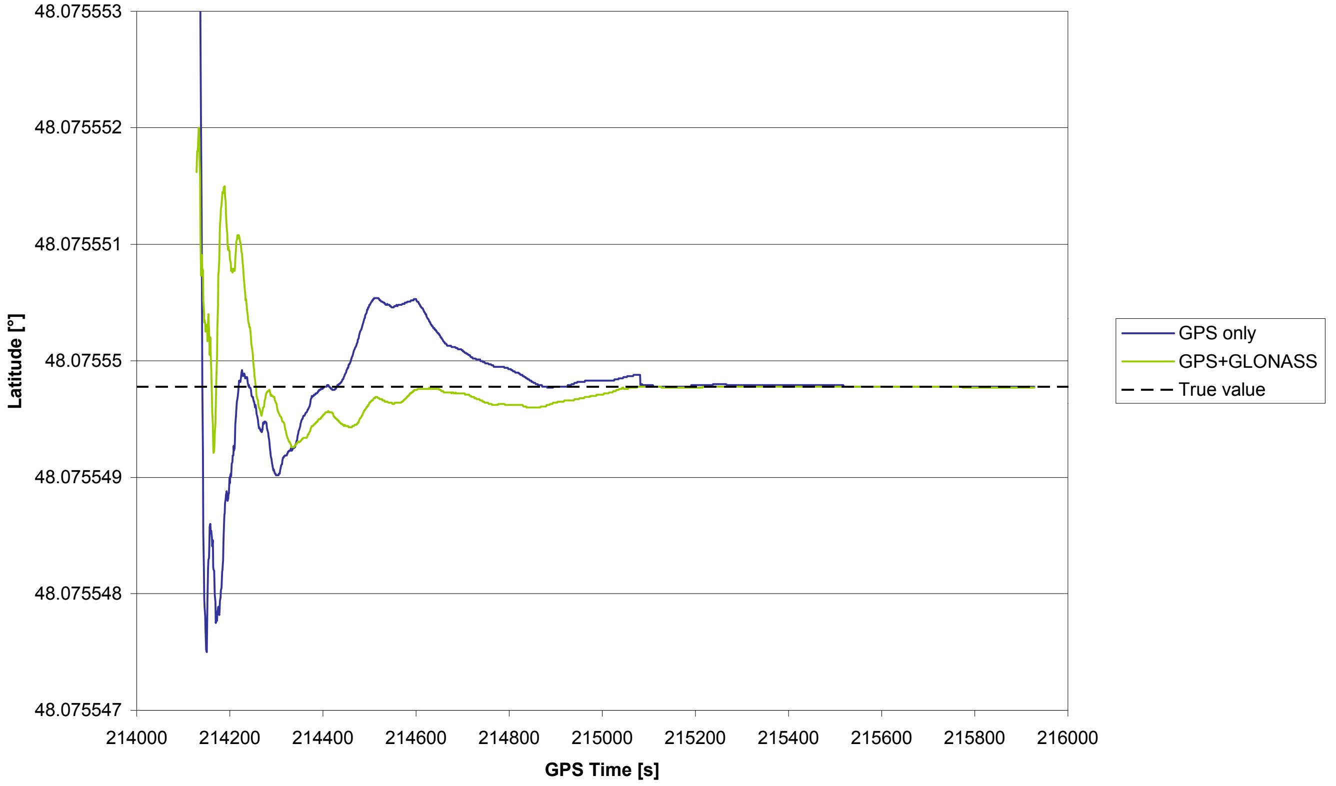

Figure 2: Latitudinal component of position solution.

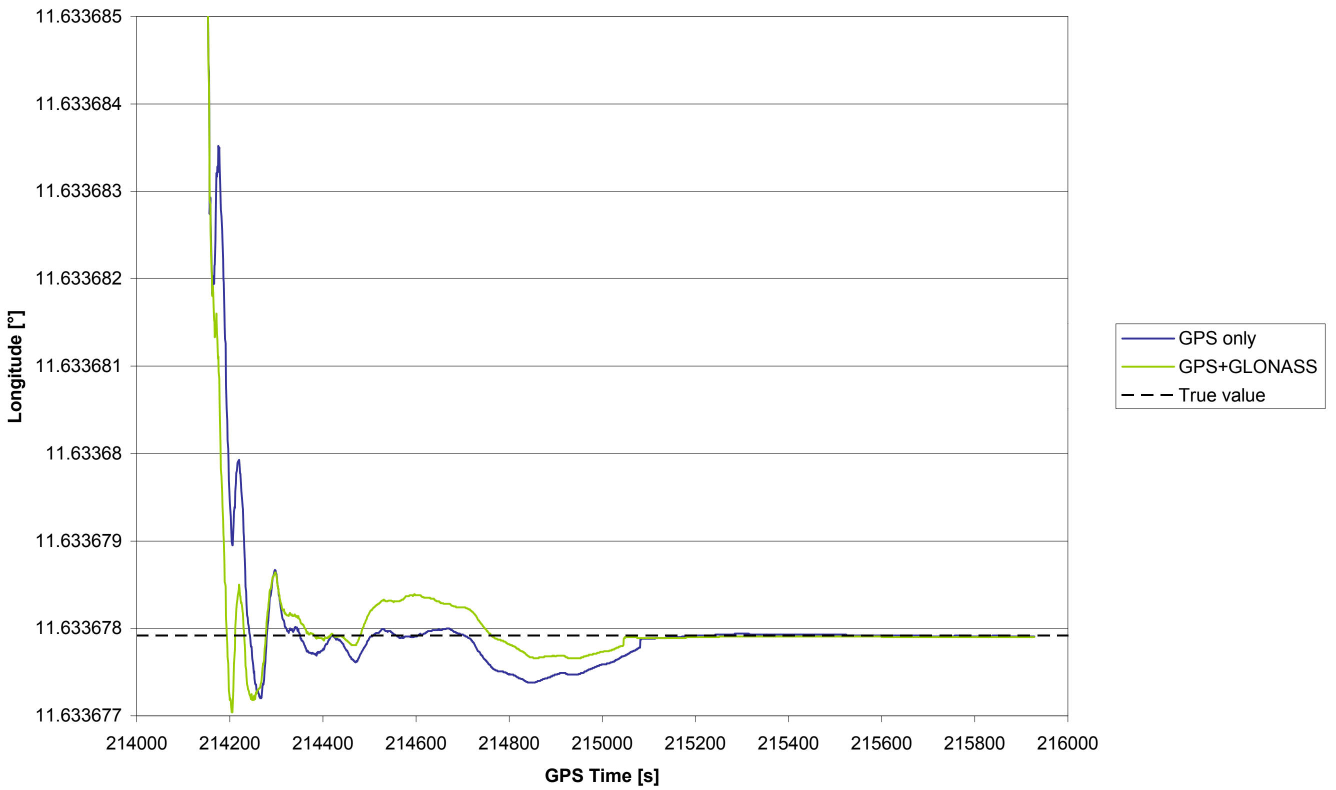

Figure 3: Longitudinal component of position solution.

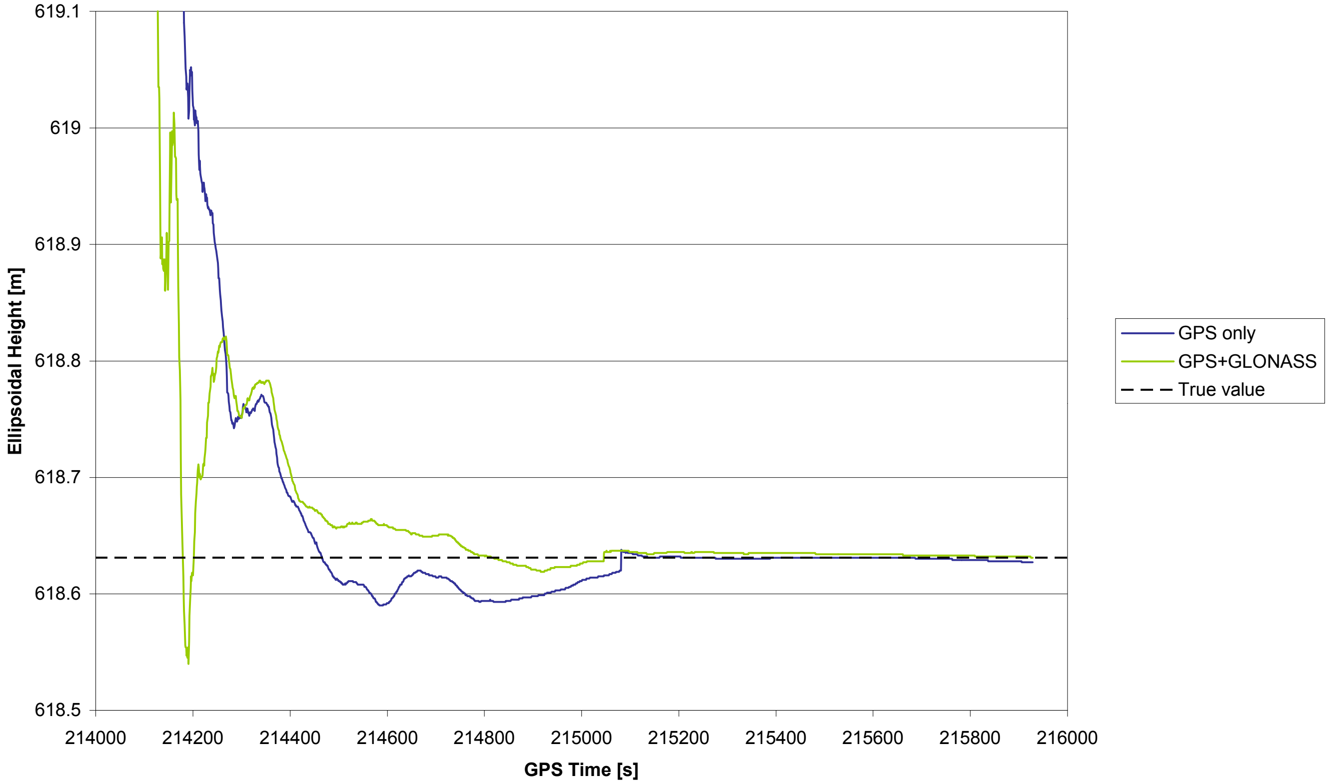

Figure 4: Height component of position solution.

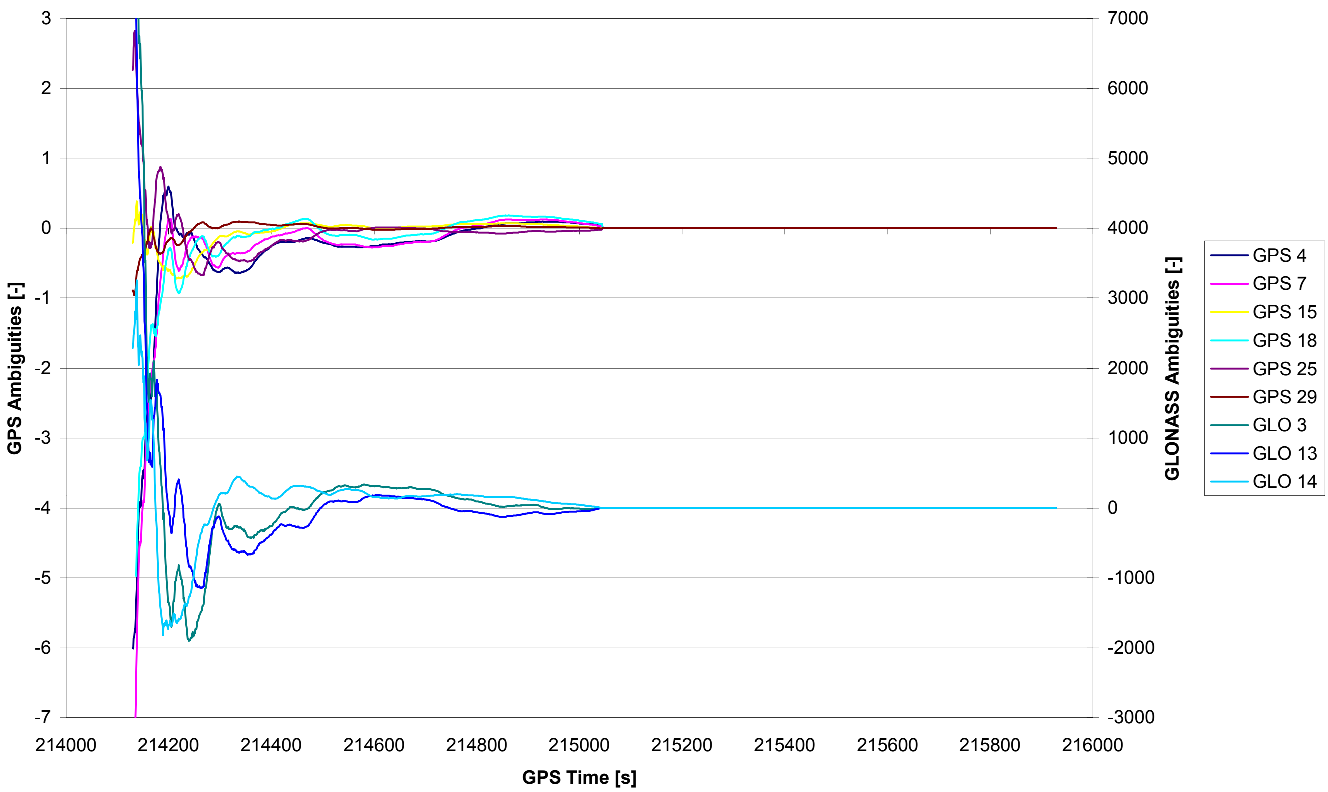

Figure 5: Difference of estimated double difference ambiguity values to finally fixed values, as obtained from the combined GPS/GLONASS solution.

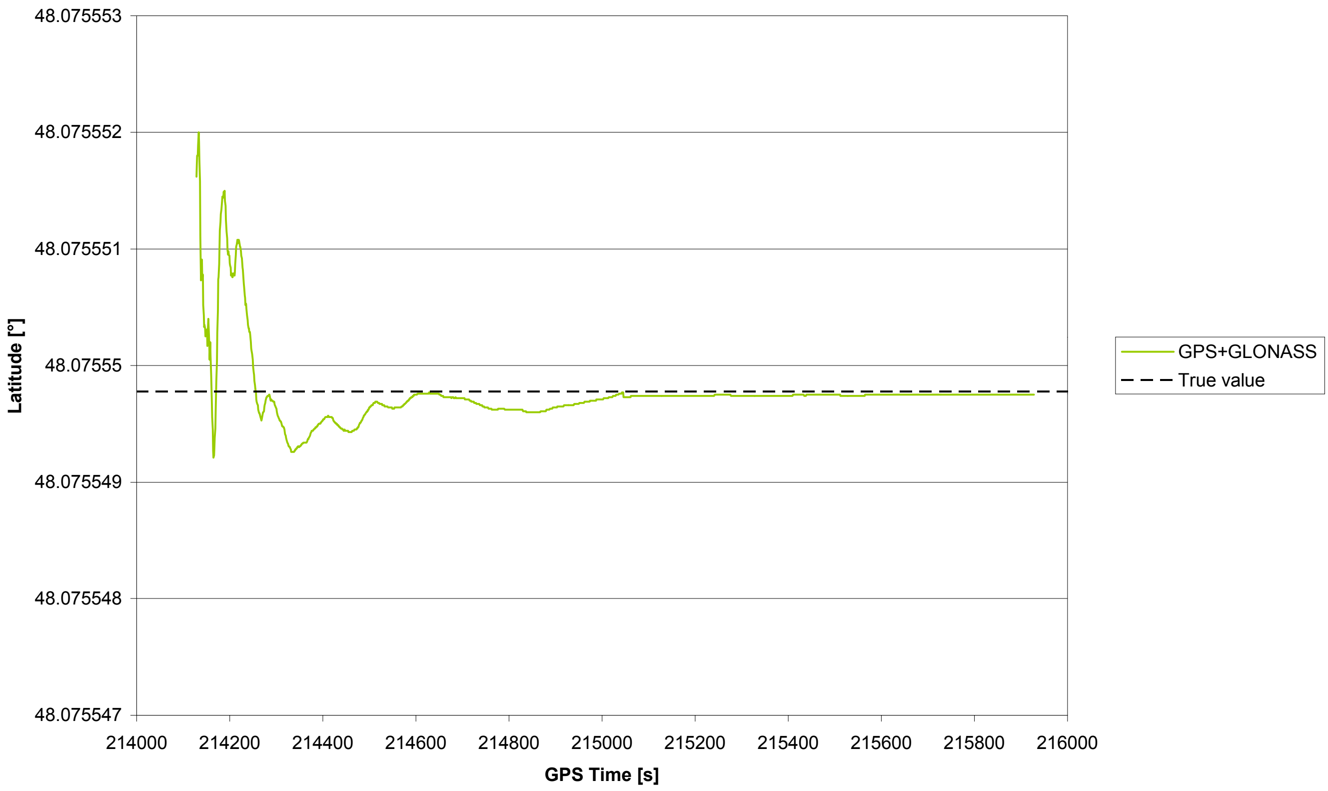

Figure 6: Latitudinal component of position solution, GLONASS ambiguities fixed incorrectly.

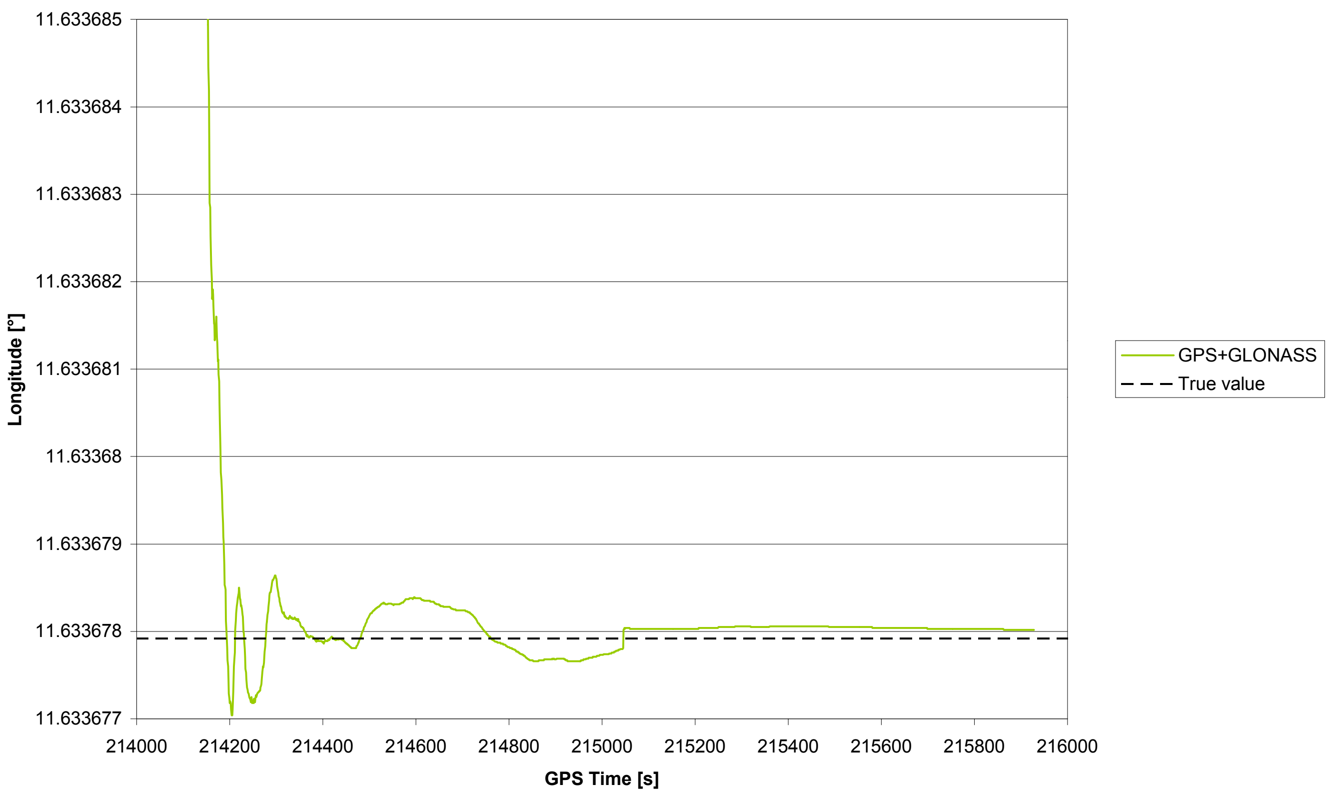

Figure 7: Longitudinal component of position solution, GLONASS ambiguities fixed incorrectly.

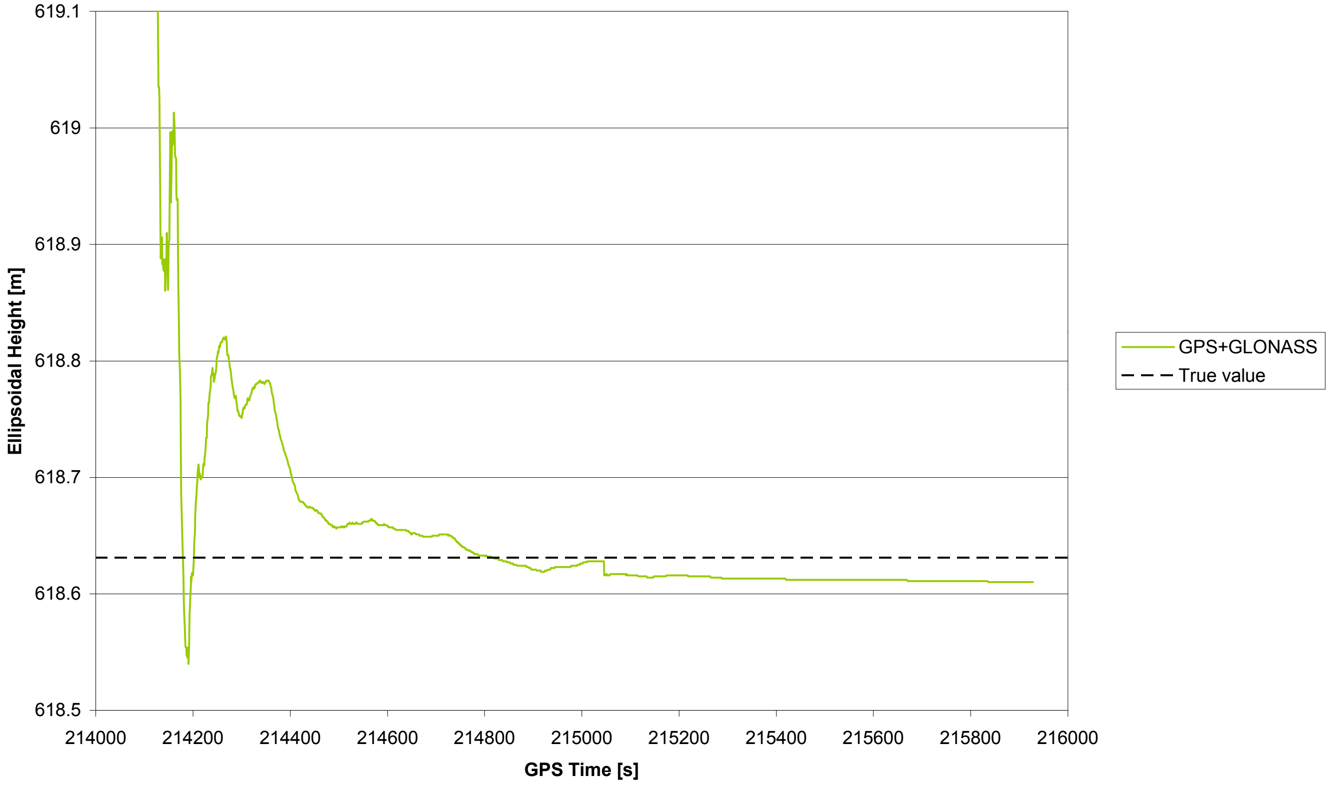

Figure 8: Height component of position solution, GLONASS ambiguities fixed incorrectly.

Undoubtedly a correct fixing would have been possible already much earlier than it actually happened in the tests. As can be seen from figure **5**, the floating ambiguities very soon are within ±1 cycle for GPS respectively ±2000 auxiliary cycles for the GLONASS double difference ambiguities.

To evaluate the effect of an incorrect GLONASS ambiguity fix, all GLONASS double difference ambiguities were deliberately offset by 500 (auxiliary) cycles as soon as they were successfully fixed to integer. This equals approximately 1/6 of a physical wavelength. This value was chosen because it also corresponds to the maximum possible distance between the floating ambiguity and the nearest candidate for fixing in the case of fixing to thousands of cycles. The results of the positioning solution under these circumstances are shown in figures 6 - 8.

The computed positioning solutions now show a noticeable offset from the known position. This offset is approximately 5 mm in latitude and 9 mm in longitude. With initially 15 mm it is most visible in the height component. The height component also shows a noticeable drift away from the true position. However, with approximately 6 mm over the 15-minute period until the end of the data set, this drift is not significant enough to clearly indicate an incorrect ambiguity fix. The same drift can be found in the positioning solution using the unbiased GLONASS double difference ambiguities.

CONCLUSIONS

A method for fixing GLONASS/GLONASS double difference carrier phase ambiguities has been introduced. It is based on an auxiliary signal with a wavelength, of which the original wavelengths of the satellites involved are integer multiples. Contrary to previously introduced algorithms, which could only be used in post-processing, this method does not require much additional treatment of the GLONASS double difference carrier phase measurements. It is therefore also suitable for real-time operation, even though it was not operated this way for the tests shown. Thus, it may be used in RTK applications as well.

This method has been applied to the GLONASS observations in a combined GPS/GLONASS scenario. It was shown that in the combined scenario a successful ambiguity resolution was possible earlier than in a GPS only scenario. The fixed integer ambiguities for both GPS and GLONASS double differences must be assumed to be correct.

With the integer ambiguities resolved, accuracy below one centimeter could be achieved. These results are comparable to positioning solutions from GPS only with fixed integer ambiguities.

Even with a deliberate offset of 500 cycles (of the auxiliary signal) on all fixed GLONASS double difference integer ambiguities, a position accuracy of less than 3 cm was achieved.

Instead of extending the costly ambiguity search to GLONASS, it might be sufficient to round the transformed GLONASS double difference carrier phase ambiguities to the nearest integer. But this still has to be investigated further. Anyway, the fixed value must be within less than 500 cycles of the auxiliary wavelength to obtain centimeter accuracy of the position solution. This may suggest that simple rounding may be possible in case the floating ambiguity is significantly less than 500 cycles away from the true value. But then criteria must be developed to determine, whether the floating ambiguity is sufficiently close to the true value or not.

For the results presented in this paper, a correct resolution of the integer ambiguities was preferred over a fast resolution. This is why ambiguities have been fixed rather late. Even though it is not shown here, an earlier fix is possible without obtaining any different results.

Despite the current depletion of the GLONASS constellation, the interest in GLONASS to be used in positioning is still strong. This includes high precision positioning using carrier phase measurements. With a successful resolution of GLONASS double difference integer ambiguities in real-time, it is possible to open access to GLONASS also for RTK and other applications, where high precision in real-time is required.

ACKNOWLEDGMENTS

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