Real-time PPP with ambiguity resolution – Determination and Application of Uncalibrated Phase Delays

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BIOGRAPHIES

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Robert Weber is associate professor at the Department of Geodesy and Geoinformation, Vienna University of Technology, Austria. His main fields of research are Global Navigation Satellite Systems, geodetic Reference Systems, active GNSS reference station networks and applications of GNSS for geodynamics and meteorology. Robert Weber served within several activity fields of the IGS e.g. as the former chair of the GNSS Working Group. He is involved in several projects setting up regional GNSS reference networks, Network-RTK, Real-Time-PPP as well as GNSS Atmosphere Monitoring.

ABSTRACT

Currently, the precise point positioning (PPP) technique is a well-established GNSS processing method for post-processing applications, while real-time PPP is still a field of ongoing research. Meanwhile a new RTCM (Radio Technical Commission for Maritime Services) standard for exchanging PPP corrections has been released. This so-called state space representation (SSR) contains orbit and clock corrections for real-time PPP as well as differential code bias corrections (DCBs). Nevertheless the issue of ambiguity fixing within PPP is still not generally solved, which is why real-time PPP still suffers from long initialization phases until the solution converges to the desired accuracy. Several research institutions are working on services and solutions to enable PPP with ambiguity resolution (PPP-AR), which would ideally shorten the convergence time to a few seconds and therefore make PPP more attractive to a broader range of applications.
Motivated by the aforementioned challenge, an Austrian consortium has spent the last two years on the research project PPPserve, which aimed at the development of appropriate algorithms for real-time PPP with special emphasis on the ambiguity resolution of zero-difference observations.
A fully functional system was developed that consists of a network-side module, calculating satellite-based wide-lane (WL) and narrow-lane (NL) phase delays from a GPS station network, and a user-software that applies the calculated corrections in a modified PPP algorithm to enable integer ambiguity resolution on the basis of wide- and narrow-lane observables.
This paper gives an overview on the work performed in the research project PPPserve and especially deals with the design and algorithms implemented in the user client. The Uncalibrated Phase Delays (UPDs) are evaluated and problems and deficiencies of PPP with ambiguity resolution will be shown on the basis of the most recent results produced by the user client.

I. INTRODUCTION

In the last two decades precise point positioning (PPP) has become a well-known technique for GNSS-based positioning for a wide range of post-processing applications. By using code and phase measurements of a single GNSS station or rover, and by replacing the broadcast satellite information with precise orbit and clock information derived from global GNSS networks, highly precise positions can be obtained. The influence of the atmosphere has to be considered, as it cannot be eliminated by building observation differences as performed in difference-techniques such as RTK. Usually 99% of the ionospheric effect can be eliminated by using the ionosphere-free (IF) linear combination of dual-frequency observations. The tropospheric influence can be divided into a hydrostatic and a wet part. While the hydrostatic part can be modeled accurately, the remaining wet part is rather unpredictable and therefore should be estimated during the adjustment procedure to achieve utmost accuracies.

Meanwhile PPP is a well-established technique for post-processing applications, but also the demand for real-time PPP increased within the last years. Therefore, in 2012 the real-time working group of the International GNSS Service (IGS) started a pilot project to broadcast real-time precise orbits and clock correction streams. Nevertheless, real-time PPP is still in its starting phase and currently only a few applications make use of the technique. Recently, the so-called SSR-messages (State Space Representation) for orbit, clock and code-bias corrections were standardized in the RTCM format [1].

Unfortunately, these corrections are still not able to fix the problem of integer-ambiguity resolution in PPP (PPP-AR). This results to a significant extent from receiver and satellite-based Uncalibrated Phase Delays (UPDs) contaminating the estimated phase ambiguities. Therefore, common PPP approaches are based on estimating only real-valued ambiguities, which leads to long convergence times and limited accuracy for real-time PPP compared to relative techniques such as RTK. Currently, these problems are a major topic of many scientific investigations (see [2] and [3]) and may only be solved by almost instantaneous integer ambiguity resolution at zero-difference level.

Motivated by the aforementioned challenge, an Austrian consortium consisting of the Vienna University of Technology, the Graz University of Technology and the GNSS service provider Wiener Netze GmbH operating the national station network EPOSA have spent the last two years on the research project PPPserve, which was funded by the Austrian Research Promotion Agency (FFG). This project aimed at the development of appropriate algorithms for real-time PPP with special emphasis on the ambiguity resolution of zero-difference observations.

The results of our PPP-AR approach were rather promising and could show that the phase bias corrections calculated within PPPserve are suitable to recover the integer nature of the wide-lane (WL) and narrow-lane (NL) ambiguities. Also the application of biases and the PPP positioning algorithms installed at the rover site work quite well. Nevertheless, there is still potential to enhance the solution concerning convergence time and robustness. At the moment the solution requires at least some minutes to fix the first set of ambiguities (WL and NL) to integers. We are currently testing ways to minimize this remaining convergence time. Options to solve this problem are the calculation and use of more accurate initial rover coordinates or the introduction of regional information, such as atmospheric delays. This could happen in form of external values for the tropospheric delay to eliminate this parameter from the equation system. Concerning the robustness we are dealing with one major problem. Especially during the filter initialization period ambiguities are sometimes fixed to wrong integers. Currently we are investigating possibilities to prevent such events and are working on an adequate algorithm to detect such wrong fixed ambiguities very fast.

This paper will give an overview on the work performed in the research project PPPserve and further will deal with the design and algorithms implemented in the user client. The quality of the estimated UPDs from PPPserve is compared with that of solutions of other analysis centers. Problems and deficiencies of PPP with ambiguity resolution will be shown on the basis of the most recent results produced by the user client. The coordinate convergence prior and after ambiguity fixing will be discussed. Further problems arising with integer fixing such as the occurrence, detection and the treatment of wrong integer fixes will also be discussed within this document. Concluding, the profit of integer-fixed PPP compared to the standard PPP approach will be analyzed.

II. PROBLEMS PREVENTING INTEGER-FIXED PPP

In most commercial GNSS PPP solutions the IF linear combination of dual frequency code- and phase measurements is used as observation equation for highly precise positioning. Single-frequency PPP in contrast cannot achieve these high accuracies of only few centimeters as the influence of the ionosphere has to be treated by using external ionosphere products. Unfortunately, the global TEC-maps (TEC = Total Electron Content) available from several organizations do have accuracies of only a few decimeters. Anyway, in the following only the dual-frequency case is treated.

After widely eliminating satellite orbit and clock errors by using external ephemerides products and strongly reducing the influence of the ionosphere by building the IF linear combination, the observation equations for code pseudoranges P_{IF} and phase pseudoranges $\lambda\Phi_{IF}$ (see [4]) read

$$\begin{aligned} P_{IF} &= \frac{f_1^2}{(f_1^2-f_2^2)}P_1 - \frac{f_2^2}{(f_1^2-f_2^2)}P_2 \\ &= \rho - cdt_r + \Delta_{trp} + \Delta_{other} \end{aligned} \tag{1}$$

$$\begin{aligned} \lambda\Phi_{IF} &= \frac{f_1^2}{(f_1^2-f_2^2)}\lambda_1\Phi_1 - \frac{f_2^2}{(f_1^2-f_2^2)}\lambda_2\Phi_2 \\ &= \rho - cdt_r + \Delta_{trp} + \lambda_{IF}b_{IF} + \Delta_{other} \end{aligned} \tag{2}$$

The term ρ denotes the geometric distance between the satellite and the receiver antenna containing their three-dimensional coordinates. The term c stands for the speed of light, dt_r is the receiver clock error and Δ_{trp} stands for the tropospheric delay. Δ_{other} contains all remaining smaller error influences, such as tidal effects, phase center offsets or noise. The phase equation contains in addition the ionosphere-free effective carrier-phase wavelength λ_{IF} (~10.7 cm) and the ambiguity parameter b_{IF}.

$$B_{IF} = \lambda_{IF}b_{IF} = \frac{f_1^2}{(f_1^2-f_2^2)}\lambda_1 b_1 - \frac{f_2^2}{(f_1^2-f_2^2)}\lambda_2 b_2 \tag{3}$$

with

$$b_i = n_i + \Delta\Phi_i^s + \Delta\Phi_{i,r} \tag{4}$$

This ambiguity parameter b_{IF} cannot be treated as integer number due to the following two reasons: On the one hand the presence of instrumental biases $\Delta\Phi_i$ in the satellites' and the receiver's hardware adulterates the ambiguities' integer nature. On the other hand the real-valued coefficients of the linear combination prohibit the separate access of the single ambiguities leading to the estimation of just one real-valued ambiguity term, the so-called float ambiguities.

Summarizing, we may interpret b_{IF} as the sum of real-valued initial phase biases originating in the receiver's and the satellite's hardware $\Delta\Phi^s$ and $\Delta\Phi_r$ plus the IF-combination of the integer number of cycles of the single frequency ambiguities n_{IF} .

Building observation differences as it is done in relative positioning techniques eliminates these instrumental biases, but as PPP is a zero-difference technique, we have to treat this problem in another way.

III. SYSTEM OVERVIEW

To comply with the aforementioned challenge, the project research project PPPserve was brought to life, aiming at the production, transmission and application of such instrumental phase biases in order to enable PPP-AR. During PPPserve a fully functional system was developed that consists of two major parts, visualized in Figure 1.

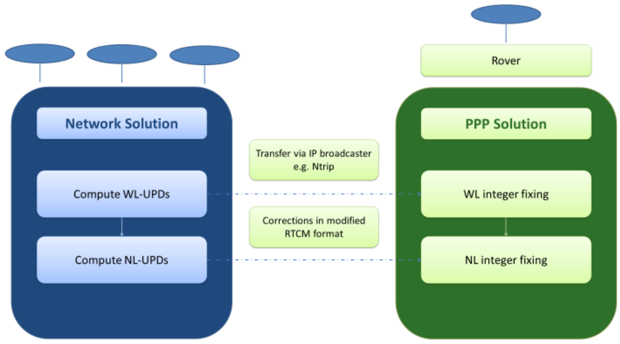

Figure 1: Scheme of PPPserve System

On the network-side a module was implemented, that calculates satellite-based WL and NL phase delays from GPS real-time observation data of a station network (obtained from IGS via BKG). The WL phase delays are quite stable over long periods, while the NL phase delays have to be re-established more often (every 15 minutes). Due to operational purposes they are in fact calculated and transmitted to the user every 30 seconds.

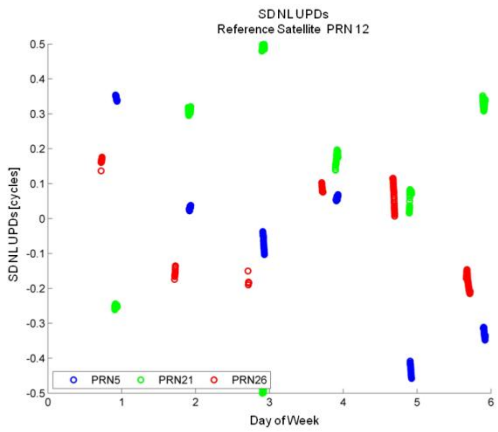

Figure 2: 3: Stability of SD NL UPDs

In Figure 2 the stability of an example of satellite-to-satellite differences (SD) of NL UPD estimates is shown. For the estimation we used one week of observations (GPS Week 1733) of 80 stations of the EUREF network and therefore we have daily solutions of the SD NL UPDs. As it can be seen most of the estimated SD NL UPDs are very stable during the time they are observed (once per day), but they are not stable over longer periods. Those differences are probably caused by remaining errors in the orbits and satellite clocks and errors introduced by the mapping function. One also has to keep in mind that one full NL cycle corresponds to about 10 cm, so the differences between the different "daily" solutions are in the range of a few centimetres only. Some of the daily solutions seem to drift. Those drifts may have their origin in un-modelled satellite specific errors. Since the effect is rather small no further investigation activities were conducted.

The phase delays calculated at the network-side are submitted to the rover by means of a real-time module either in a proprietary file-format or via an additional RTCM-message.

On the user-side the rover applies the received correction data in a modified PPP algorithm to correct the ambiguities and further to enable integer ambiguity resolution on the basis of WL and NL observables. In the course of PPPserve a user client software was implemented that encloses adequate algorithms for PPP with ambiguity resolution. By means of this client software the phase biases from the network solution were evaluated and tested together with data from other organizations researching on the same topic such as phase bias corrections calculated by the Centre National d'Études Spatiales (CNES) in Toulouse operating their PPP-wizard demonstrator system (see [3] and *www.ppp-wizard.net*).

Details on PPPserve and its general system overview can be found in [5].

IV. USER-SIDE ALGORITHMS

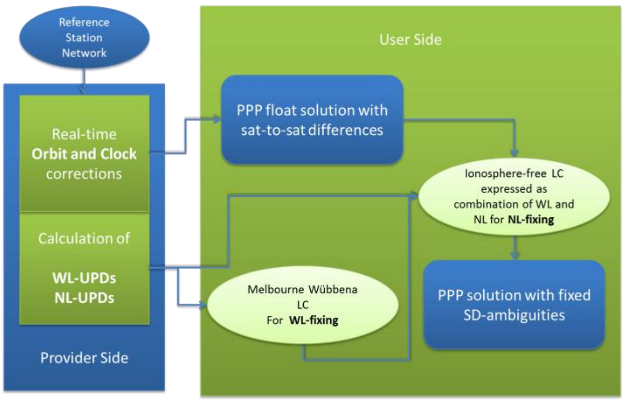

Figure 4: Scheme of PPP-AR user client

In the following especially the user-algorithms outlined in Figure 4 will be presented and problems occurring at the user-side will be addressed. Many publications already deal with the production of phase bias corrections at the network-side, while only few treat their application and effective problems occurring with the application of biases and integer fixing.

Float-solution

The first step of the presented PPP-AR algorithm is the calculation of a standard PPP float solution using the IF linear combination as described in (1) and (2). Thereby the parameters to be estimated are the three-dimensional coordinate components X, Y and Z, the receiver clock correction, the wet part of the zenith troposphere delay (the hydrostatic part was already modelled), and the ionosphere-free ambiguity part of all satellites in view.

As a near real-time solution is implemented, the observation epochs are processed successively, which is why an extended Kalman Filter is used to insert additional information on the dynamic behavior of the parameters. The coordinates are either introduced as constants with no process noise in the static case, or in kinematic mode the process noise is increased according to the supposed velocity of the movement. The estimated ambiguities also have the constraint that they do not change over time, as long as the receiver has no loss of lock. Therefore they are also treated as constant quantities in the filter. The receiver clock correction is modelled as white noise with a high process noise, and the troposphere parameter is assumed to be changing only a few mm per sqrt(hour).

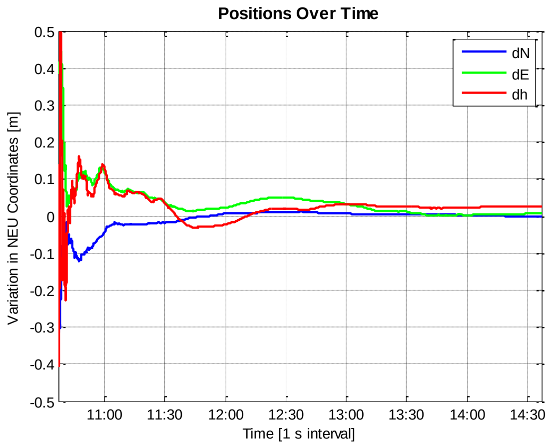

Figure 5: Float solution of GRAZ087.13O

Figure 5 shows an example PPP float solution of static data from station GRAZ Lustbühel compared to the known coordinates of this station, over approximately four hours of observation.
This figure shows a characteristic convergence behavior: After less than half an hour of observation the solution reaches sub-decimeter accuracy, while after three hours of observation almost no improvement can be seen. Generally, the PPP accuracy in horizontal coordinates is1-2 cm at best, while the height component is a bit worse as expected.

During PPP-AR processing the estimated float ambiguities $\lambda_{IF} b_{IF} = \hat{B}_{IF}$ (see equation (3)) are of special interest for the subsequent processing steps. They are extracted from the float-solution together with their covariance-matrix to serve as input for the ambiguity fixing process. Figure 6 and Figure 7 show that also the estimated float ambiguities do converge in accordance with the coordinate solution before the values become stable. The initial variations can make up two or more decimeters, which correspond to twice the narrow-lane wavelength or more. This can be rather problematic concerning ambiguity fixing in the early processing phase.

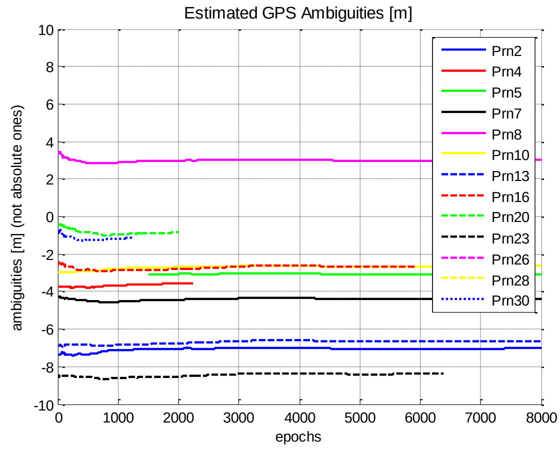

Figure 6: Float ambiguity estimates of GRAZ087.13O

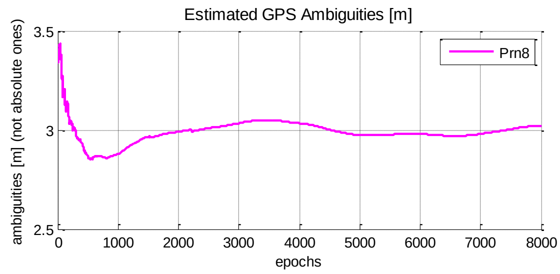

Figure 7: Float ambiguity estimate of PRN 8 of GRAZ087.13O

Reformulate IF-LC

As already mentioned before, the integer ambiguities of the single frequencies L1 and L2 cannot be accessed by using the representation described in equation (2). Therefore we have to switch to an alternative representation. The IF linear combination of the ambiguity parameter can be expressed as a combination of the so-called wide- and narrow-lane ambiguities (WL and NL) as follows:

$$\lambda_1 b_c^{ij} = \frac{f_1^2}{(f_1^2 - f_2^2)}\lambda_1 b_1^{ij} - \frac{f_2^2}{(f_1^2 - f_2^2)}\lambda_2 b_2^{ij} \tag{5}$$

$$\begin{aligned} b_c^{ij} &= \frac{f_1}{f_1 + f_2} b_n^{ij} + \frac{f_1 f_2}{f_1^2 - f_2^2} b_w^{ij} \\ &= \frac{f_1}{f_1 + f_2}\left(n_n^{ij} + \Delta\Phi_n^{ij}\right) + \frac{f_1 f_2}{f_1^2 - f_2^2}\left(n_w^{ij} + \Delta\Phi_w^{ij}\right) \end{aligned} \tag{6}$$

This representation contains satellite-to-satellite single-differences (between the satellites i and j) of ambiguities in order to get rid of the receiver specific bias parameters, which are different for every receiver antenna. A similar approach was proposed in [2].

In equation (6) the relation $\lambda_{IF} b_{IF}^{ij} = \lambda_1 b_c^{ij}$ connects the estimated ambiguity parameter from the ionosphere-free float solution in (2) with the reformulated ambiguity term. The wide-lane part $b_w^{ij} = (n_w^{ij} + \Delta\Phi_w^{ij})$ and the narrow-lane part $b_n^{ij} = (n_n^{ij} + \Delta\Phi_n^{ij})$ are both composed of the respective integer ambiguity n^{ij} plus the corresponding UPD $\Delta\Phi^{ij}$ originating from the satellites' hardware. The receiver's UPD has already cancelled in the course of the differencing between the two satellites and therefore is irrelevant for the integer ambiguity fixing procedure.

To solve and fix WL and NL integer ambiguities a stepwise fixing process is applied that is described in the next paragraphs.

WL-fixing

The great advantage of the new representation of the IF-LC ambiguity part in (6) is that the WL-ambiguity can now be calculated and fixed already in the pre-processing step, which leaves only the NL ambiguity part left as unknown term.

For the WL-fixing the Melbourne-Wübbena linear combinations of all satellites can be built epoch-wise. This combination was described by [6]and [7] and uses code and phase observations from two carriers (e.g. GPS L1 and L2) to calculate an observable with a huge wavelength of ~86 cm containing only the integer wide-lane ambiguity, a wide-lane receiver-emitter dependent UPD and noise. Depending on the satellites' elevation angle this noise level should be no more than 0.1 to 0.2 cycles. To support the user's integer PPP solution the emitter dependent WL-UPD is calculated by an analysis center (in PPPserve the TU Vienna is responsible for that task) from station network data and transmitted to the rover. The receiver dependent part can either be eliminated by building satellite-to-satellite differences as it is done here, or, if no differences are built, estimated from the WL-observables.

The drawback of building differences is that a reference satellite has to be chosen, from which all other satellites' ambiguity estimates are subtracted. This is generally no problem as long as the reference satellite signals have low noise and appropriate ephemeris data and WL-UPDs are available. All single-difference observables and ambiguity parameters are affected by the reference satellite's errors which further may cause wrong WL- and subsequently also NL-fixes.

Usually the WL-fixing procedure can be started only after one or two minutes of observations. The WL-calculation is done by means of a moving average over the collected Melbourne-Wübbena observations corrected for the WL-UPDs.

The fixing can be performed by simple integer rounding of the smoothed Melbourne-Wübbena observables, while the fixing decision is dependent on the proximity to the nearest integer values. A threshold of 0.25 cycles can be used due to the good wavelength/noise ratio of the Melbourne-Wübbena observables.

NL-fixing

Contrary to the WL-fixing procedure the NL-fixing has to be performed in the actual processing routine. Input for this step are besides WL-fixed ambiguities and NL-UPDs also the IF ambiguity estimates from the float solution of the current epoch. Further, the NL fixing step is more problematic than the WL fixing, as the NL UPDs are not that stable and the noise ratio of the NL-estimates is much higher compared to the WL-observables due to the narrow wavelength of ~10.7 cm.
The NL-estimates are computed by a reformulation of equation (5), where $\hat{B}_{IF}^{ij}$ is the float-ambiguity estimate in units of length. Similar to the WL procedure the receiver-specific UPD can be eliminated by building differences, while the satellite-specific UPD has to be calculated and forwarded to the user by the analysis center.

$$b_n^{ij} = n_n^{ij} + \Delta\Phi_n^{ij} = \frac{f_1 + f_2}{f_1}\frac{\hat{B}_{IF}^{ij}}{\lambda_1} - \frac{f_1}{f_1 - f_2}\left(n_w^{ij} + \Delta\Phi_w^{ij}\right) \tag{7}$$

Unfortunately, the float solution needs some time to converge which implies that also the float-ambiguity estimates may vary strongly in the beginning of the processing. Therefore it is rather difficult to find the right start epoch for the fixing process, by making a compromise between processing long enough to get stable ambiguity estimates and short enough to still profit from the fixed solution.

The fixing procedure itself is done as a partial ambiguity fixing using the LAMBDA-method (see [8]) for ambiguity subsets. Therefore the best ambiguities with respect to their variance are chosen to be fixed first. If this can be done successfully, more and more ambiguities are tried to be fixed, while already fixed ambiguities are checked every epoch and corrected or released if necessary. This permanent correction of ambiguities is required, because especially in the beginning of the processing wrong fixes do occur rather likely.

Fixed Adjustment

As soon as some NL-ambiguities are fixed to their integer value correctly, they can be used to enhance the coordinate solution. Therefore the fixed NL and WL ambiguities are used to reconstruct the ionosphere-free ambiguity (cf. equation (6)).
Now a second adjustment can be performed by using the known ambiguity information, and exploiting the full potential of the highly precise phase measurements. Therefore we chose an adjustment in kinematic mode, where the ambiguity information of the fixed ambiguities is inserted as pseudo-observation with extremely high weight to the equation system. Observations with unknown ambiguity values are still used in the adjustment in order to enable solutions with less than 3 fixes. The receiver clock estimates and the troposphere estimates are taken from the float solution and eliminated from the fixed adjustment.

In an iterative procedure more and more ambiguities are tried to be fixed and the solution becomes more stable and accurate.
Unfortunately, the detection of a wrong fix is not an easy task, since the only comparison measure is the noisy float ambiguity. Therefore, without the implementation of enhanced algorithms, the narrow-lane ambiguities can only be detected within a range of ±1-2 cycles in the early processing phase.

Detection and avoidance of wrong fixes

In the beginning of the processing, a simple limitation of the elevation cut-off angle can help to limit the number of wrong NL-fixes. This is due to the fact that signals of lower satellites experience a larger noise and larger errors originating from residual atmospheric effects. Therefore the elevation angle in the first epochs is limited to 30°. Lower satellites will be added later on in the processing.

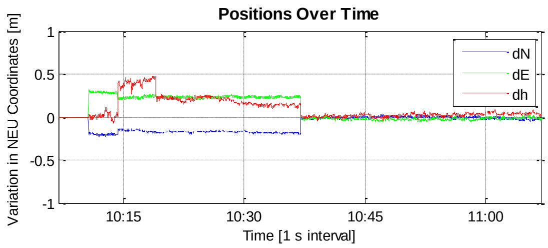

Figure 8: NEU solution, where cutoff-angle is set to 10° from the beginning of the processing

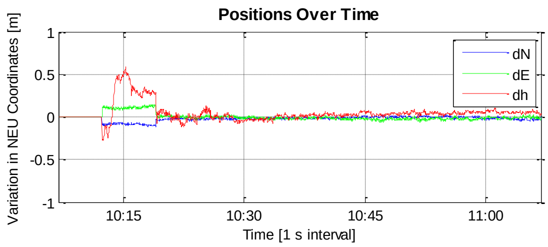

Figure 9: NEU solution, where cutoff-angle is 30° for processing times < 500 s, 15° for processing times < 1000 s and 10° after that time

Figure 8 shows a solution without this initial limitation of the cut-off angle. In the beginning of the processing many satellites can be fixed, but as it can be seen in Figure 10, the phase residuals show inconsistencies in the phase measurements resulting from incorrectly fixed NL-ambiguities. Figure 9 and Figure 11 show the same data, but now processed with an initial cutoff-angle of 30°. In the second solution the North, East and Up (NEU) coordinates as well as the phase residuals indicate better values for the ambiguity fixes. Fewer satellites are fixed, but more of them seem to be correct.

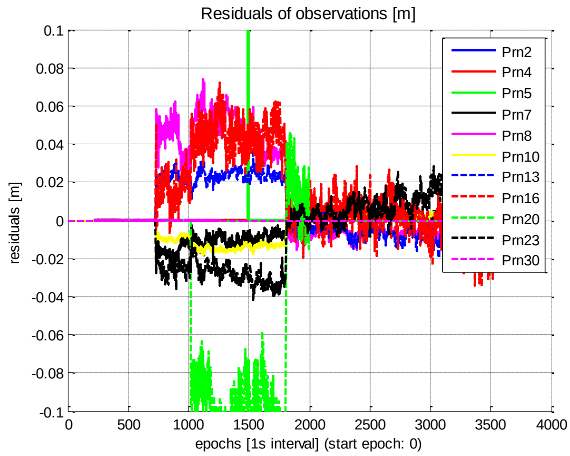

Figure 10: Phase residuals of solution, where cutoff-angle is set to 10° from the beginning of the processing

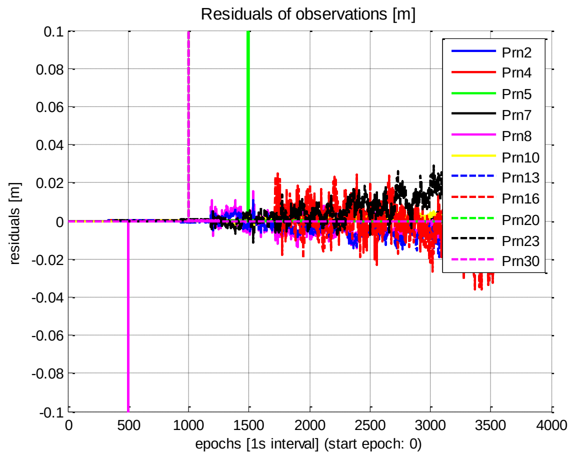

Figure 11: Phase residuals of solution, where cutoff-angle is 30° for processing times < 500 s, 15° for processing times < 1000 s and 10° after that time

By comparing Figure 10 and Figure 11 it becomes obvious, that the phase residuals give information about the correctness of fixed ambiguity values. If single phase residuals do have a significant offset from zero, incorrect fixes are very likely. Unfortunately, this does only work, after at least four NL-ambiguities have been fixed to integers. Further the residuals do not always indicate, which fixed NL-value is incorrect, especially when there is not only one but two or more wrong fixes.

Nevertheless, if the residuals' standard deviation does exceed a certain threshold (e.g. 0.5 cycles), an iterative procedure can be started, where fixed integers are shifted by ±1, until the residuals' standard deviation becomes a minimum. Currently, we are looking for efficient ways to implement such a procedure and use the analysis of residuals to find the incorrect fixes and enhance the solution.

At the moment the ambiguity fixing routine is repeated every epoch for all satellites in view to enable the correction of single ambiguities, based on the current proposed fixed values from the LAMBDA method. Unfortunately this only depends on the quality of the float estimates of the current epoch, while it would be desirable to find also other quality measures to verify the fixed solution.

V. RESULTS

In the following example results of PPP with ambiguity fixing of the IGS station Graz Lustbühel (GRAZ) and other Austrian GNSS stations are shown.

Effect of wrong fixes

In the following figures the result of a small experiment concerning the influence of wrong fixes on the coordinate solution are shown.

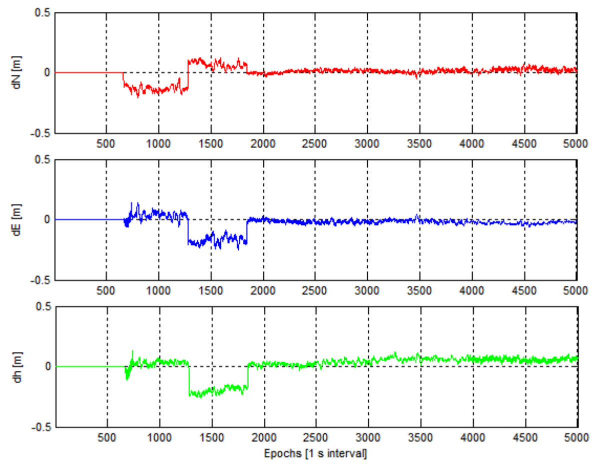

Figure 12: PPP solution with fixed ambiguities of GRAZ087.13O

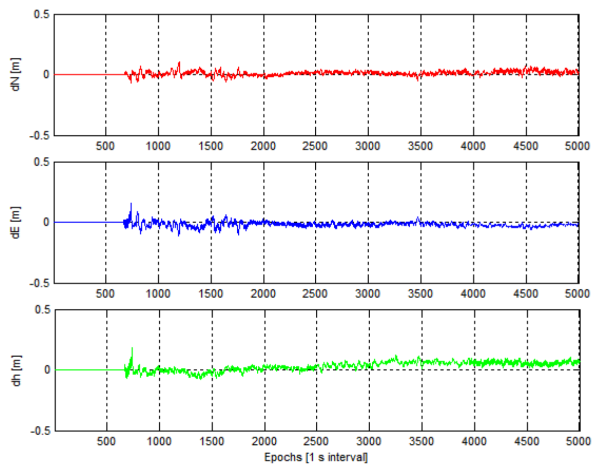

Figure 13: Manipulated fixed solution of GRAZ087.13O

During a part of our sample dataset, two wrongly fixed ambiguity values are detected and corrected to a better value (in this case only ±1). In the coordinate solution

(Figure 12) at that time an offset is clearly visible between epoch 1277 and epoch 1847, where the correction of the fixed NL-ambiguities happens.
Later on the solution was calculated again, and the wrong fixes for the two concerned satellites were corrected immediately. The result was a smooth coordinate solution from the beginning of the processing, which shows, that even small errors in fixes can dramatically worsen the result.

Figure 14 shows the fixed NL-ambiguities of the same solution. One can say that as soon as three ambiguities (depending on the satellite geometry sometimes four) are fixed correctly, the PPP-AR solution is rather stable and also accurate. Compared to the behavior of float solutions the coordinates do not have to converge and there is no deficiency in the east component.

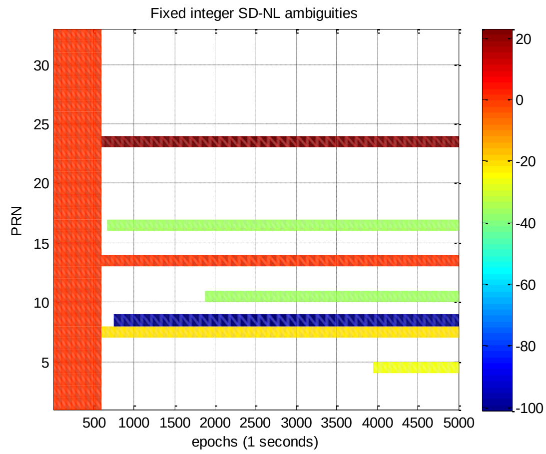

Figure 14: Fixed NL-ambiguities for solution GRAZ087.13O

The fixing procedure in our test scenario started after 600 seconds, while four fixes (excluding the reference satellite PRN13) could be made after 750 seconds. In most of our scenarios between 10 and 30 minutes of observation were necessary to successfully fix the first ambiguities. This is still a long time compared to RTK-techniques.

Optimizing Convergence Time

A shorter convergence time of the float solution would also shorten the elapsed time to the first fix. One option to accelerate the convergence is to get better initial coordinates, which is not an easy task for arbitrary receiver positions. Nevertheless by using reference station data, the receiver position is accurately known and therefore the effect on convergence can be tested easily.

The same observation data was calculated several times by putting different constraints on the approximate initial position coordinates. The different solutions were calculated with approximate coordinates with an initial standard deviation of 1 m, 5 cm and 1 cm. The reference coordinates themselves were not changed, only their assumed accuracy.

In all versions the routines for the ambiguity fixing were started in epoch 200 (after 200 seconds), which is long in time before the solution usually converges. Figure 15, Figure 16 and Figure 17 show example results of solutions with the same data, but different constraints to the approximate coordinates. Here, the solution with 1 m initial coordinate constraint needs 37 min minutes to produce valid fixed coordinates, the solution with 5 cm initial coordinate constraint needs 12 minutes and the solution with 1 cm constraint needs only 4 minutes for the optimum fixed-solution.

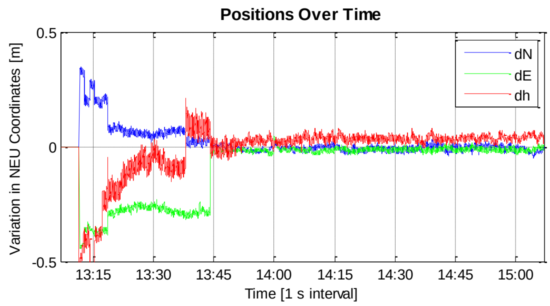

Figure 15: PPP-AR solution (coordinates constrained to 1 m)

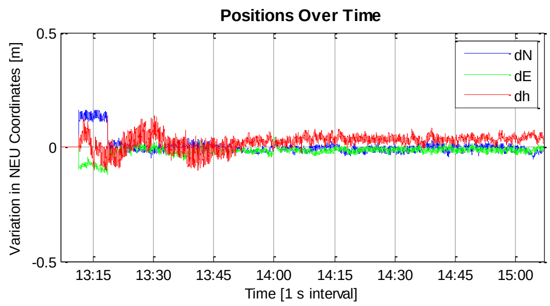

Figure 16: PPP-AR solution (coordinates constrained to 5 cm)

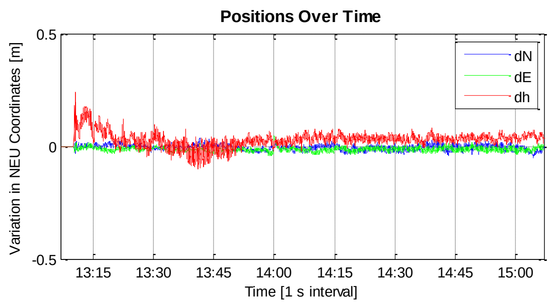

Figure 17: PPP-AR solution (coordinates constrained to 1 cm)

To get a better overview on the convergence behavior in dependency of the initial coordinate constraints, a table with convergence time, corresponding to the time an appropriate fixed solution can be established, is given in the following.
Table 1 shows the time to an appropriate PPP-AR solution from the beginning of the calculation in minutes. This solution was calculated with UPDs calculated at

CNES, while for the solutions in Table 2 UPDs from TU Vienna were used. The convergence is defined by a minimum of three fixed satellites and coordinate errors smaller than 5 cm in the horizontal plane and 10 cm in height.

Table 1: Convergence behavior of fixed coordinate solutions (different start epochs) of station GRAZ on DOY088 2014 (used UPDs by CNES) dependent on initial coordinates and their standard deviations, convergence time is given in minutes

	2	3	4	5	6	7	8	mean	median
1 cm	3,35	3,35	5,98	52,67	16,67	--	18,32	16,72	11,33
5 cm	46,72	52,60	32,67	25,22	70,43	19,65	30,00	39,61	32,67
1 m	44,43	53,03	32,50	29,25	69,68	19,28	30,00	39,74	32,50

Table 2: Convergence behavior of fixed coordinate solutions (different start epochs) of station GRAZ on DOY088 2014 (used UPDs by TU Vienna) dependent on initial coordinates and their standard deviations, convergence time is given in minutes

	2	3	4	5	6	7	8	mean	median
1 cm	7,53	3,35	16,67	4,38	10,58	20,00	31,67	13,45	10,58
5 cm	46,53	18,33	26,67	12,27	15,00	17,67	32,13	24,09	18,33
1 m	47,35	27,60	28,33	9,93	29,17	14,15	32,25	26,97	28,33

Both solutions in Table 1 and Table 2 are comparable, even though both UPD calculations have their outliers. The convergence with 1 m coordinate constraints is equivalent to completely unknown initial coordinates and converges between 20 and 40 minutes. Introducing better initial coordinates slightly accelerates the convergence, even though a significant improvement is only possible with initial rover positions known better than 5 cm. Unfortunately, it is rather unrealistic for real scenarios to have initial coordinates better than 10 cm.

Another possibility to accelerate convergence may be the use of external troposphere data, so that the remaining wet troposphere does not have to be estimated in the adjustment procedure.

Various solutions

Finally, fixed solutions of several GNSS stations of the EPOSA reference station network in Austria are shown, all using the satellite single-difference UPDs calculated by TU Vienna for DOY087 in 2013 (see Figure 18 - Figure 20).

All these solutions reach the dm-level in horizontal coordinates within less than half an hour. The height component usually is a bit worse, which may be caused by the typical GNSS geometry and un-modelled remaining atmospheric effects. Nevertheless, some integer NL-ambiguities cannot be fixed correctly in the first place and are corrected later on during the processing.

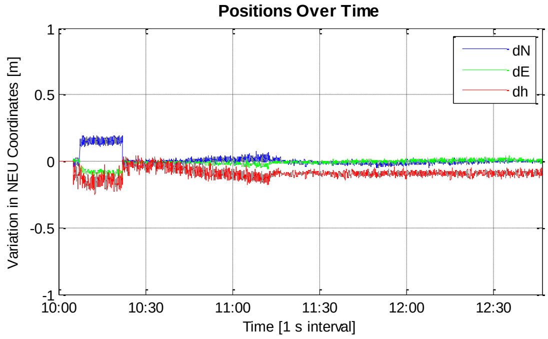

Figure 18: PPP-AR solution for EPOSA station GRAZ

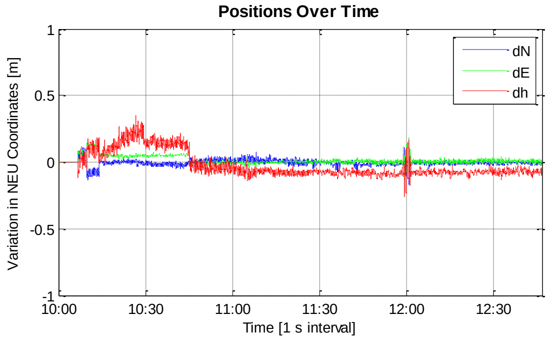

Figure 19: PPP-AR solution for EPOSA station BADE

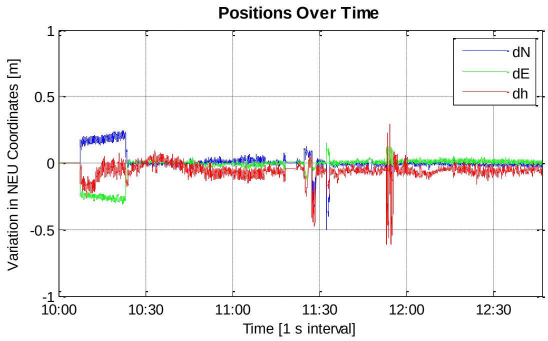

Figure 20: PPP-AR solution for EPOSA station DALA

VI. CONCLUSIONS AND OUTLOOK

This paper shows that ambiguity fixing using the software produced in this research works when external UPD corrections (in this research from CNES and TU Vienna) are available. These UPDs are different for each GNSS satellite and each GNSS receiver. Satellite specific UPDs can be calculated in a network solution while receiver-specific UPDs can be eliminated by building sat-to-sat differences as it was done in the presented research. Knowing these biases, the ionosphere-free ambiguity term can be reformulated and WL- and NL-ambiguities can be fixed, whereas the WL-fixing is done independently from the PPP-solution, while the NL-ambiguities are calculated on the basis of the estimated IF-ambiguities. Unfortunately, these estimated IF-ambiguities need some time to converge, meaning that

they vary for some dm in the beginning of the PPP-processing until they stay constant in the magnitude of one NL-cycle. Therefore it is especially tricky to fix NL-ambiguities before the float solution converges and to exploit the full potential of an ambiguity fixed PPP solution in order to comply the demands of (near) real-time applications. False fixes are likely to occur in the first 30 minutes of the solution. That still is a rather long time for initialization, which has to become shorter to compete with other GNSS-techniques as RTK.
Nevertheless, as soon as the ambiguities are correctly fixed, the PPP-AR solution is extremely precise and stable.

Even though the fixed solutions are more precise (especially in the east-component) than float solutions commonly are, the actual convergence time is still too long for many real-time applications.
Therefore, future investigations may focus on better and more stable algorithms to, on the one hand, fix ambiguities earlier and, on the other hand, detect wrong fixes earlier, knowing that the correctness of the solution is mirrored in the phase ambiguities of the ambiguity-fixed solution.

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