

## Ambiguity fixing in real-time PPP – Determination of uncalibrated phase delays using a regional network



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### Abstract

In the last years real-time Precise Point Positioning (PPP) became a well-known GNSS positioning technique which is nowadays already used for various applications. Combining precise satellite positions and clock corrections with zero-difference observations from a dual-frequency GNSS receiver PPP is able to provide position solutions at decimeter to centimeter level. However, these corrections are insufficient to fix the ambiguities, which is why PPP still suffers from long initialization periods until the solution converges to the desired accuracy. This long convergence time is one of the most limiting factors of real-time PPP with regard to numerous applications. This contribution shall give an overview on the work performed in the research project PPPServe (funded by the Austrian Research Promotion Agency – FFG), which aimed at the development of appropriate algorithms for real-time PPP with special emphasis on the ambiguity resolution of zero-difference observations. It shall especially deal with the process and obstacles of calculating the so-called wide-lane and narrow-lane phase-delays which allow PPP-base ambiguity fixing in real-time. Furthermore, the achieved quality and the temporal stability of the estimated phase delays as well as the coordinate convergence period and coordinate quality achieved at the rover site will be discussed on basis of the most recent results.

**Keywords:** GNSS, Precise Point Positioning, ambiguity fixing, convergence time

### Kurzfassung

In den letzten Jahren hat sich die präzise Einzelpunktbestimmung (PPP) in Echtzeit zu einer namhaften Technologie für die Positionsbestimmung mit Hilfe von Globalen Navigationssatellitensystemen (GNSS) entwickelt, die heutzutage schon für diverse Anwendungen zum Einsatz kommt. Durch die Kombination undifferenzierter Beobachtungen eines Zweifrequenz GNSS Empfängers mit präziser Satellitenbahn- und Uhrinformationen ermöglicht PPP eine Positionsbestimmung im Zentimeter- bis Dezimeterbereich. Allerdings reichen diese Korrekturen nicht aus um die Mehrdeutigkeiten zu fixieren, weshalb PPP sehr lange Initialisierungszeiten benötigt, um die gewünschte Positionsgenauigkeit zu erreichen. Diese langen Konvergenzzeiten sind in Hinblick auf zahlreiche Anwendungen der größte limitierende Faktor von PPP. Dieser Beitrag soll einen Überblick über das Projekt PPPServe (gefördert durch die österreichische Forschungsförderungsgesellschaft – FFG) geben. Ziel dieses Projektes war die Entwicklung geeigneter Algorithmen für Echtzeit PPP mit dem Schwerpunkt der Mehrdeutigkeitslösung von undifferenzierten Beobachtungen. Dieser Beitrag beschäftigt sich im speziellen mit dem Prozess und den Problemen bei der Berechnung der sogenannten wide-lane und narrow-lane Phasenverzögerungen, welche eine Fixierung der Mehrdeutigkeiten in Echtzeit PPP erlauben. Des Weiteren werden die erreichte Genauigkeit und die temporale Stabilität der berechneten Phasenverzögerungen, sowie die Güte der am Rover ermittelten Position an Hand der aktuellsten Resultate diskutiert.

**Schlüsselwörter:** GNSS, Precise Point Positioning, Mehrdeutigkeitsfixierung, Konvergenzzeit

## 1. Introduction

### 1.1 Principles of PPP

Precise Point Positioning is a GNSS based positioning technique that utilizes undifferenced single- or dual-frequency code and phase observations from a single GNSS receiver. A precise position can be determined due to the compensation for orbit and clock inaccuracies by using precise orbit and clock corrections. The

concept of PPP was first introduced in the 1970s by R. R. Anderle, and was characterized as a single station positioning with fixed precise orbit solutions and Doppler satellite observations [1]. Nevertheless, GPS positioning was dominated by relative techniques until the late 1990's. First investigations using dual frequency data from a single GPS receiver for a few cm-positioning in post-processing mode have been published by [2].

Combining the precise satellite positions and clocks with observations from a dual-frequency GNSS receiver (to remove the first order effect of the ionosphere), PPP is able to provide position solutions at decimeter to centimeter level. The beauty of this zero-difference technique is that it does not require access to observations from one or more close reference stations accurately-surveyed. Furthermore it provides an absolute position instead of a relative location as RTK does. The only products required for PPP are precise orbit and clock data, based on measurements from reference stations from a relatively sparse station network (thousands of km apart would suffice). Nevertheless the PPP technique is still less popular than RTK, since it requires a longer convergence time to achieve maximum performances (in the order of tens of minutes). While in the last years a lot of post-processing services offering PPP arose, real-time PPP is still in an incipient development phase due to a lack of precise real-time products. Only a handful of organizations, e.g. the IGS real-time service, started offering real-time products.

One of the main challenges with PPP is the integer ambiguity resolution. Simple integer ambiguity fixing is prevented by the presence of uncalibrated phase delays (UPDs) originating from oscillator-induced time delays of the satellite and the receiver. Therefore in PPP usually a real-valued bias is estimated in place of the integer ambiguity. However the estimation of real-valued ambiguities requires a large convergence period which is the most significant factor limiting wider adoption of PPP. Accordingly, integer ambiguity resolution of undifferenced carrier phase observations is considered as one of the innovative issues for current GNSS research and applications [3].

**1.2 Problems preventing PPP integer ambiguity resolution**

In PPP the usual practice when processing dual frequency data is to build the ionosphere-free (IF) linear combination of the pseudo-range  $P_{k,1}^i$  and  $P_{k,2}^i$  and phase observations  $L_{k,1}^i$  and  $L_{k,2}^i$  in order to eliminate the effect of ionosphere. Assuming that the satellite clock and orbit errors are accounted for by using precise orbit and clock products and that the systematic errors are eliminated the ionosphere-free code and phase observation can be expressed as follows:

$$P_{k,3}^i = \frac{f_1^2 P_{k,1}^i - f_2^2 P_{k,2}^i}{f_1^2 - f_2^2} = \rho_k^i + c\delta t_k + \delta_{tro} + \varepsilon_{p,3} \quad (1)$$

$$L_{k,3}^i = \frac{f_1^2 L_{k,1}^i - f_2^2 L_{k,2}^i}{f_1^2 - f_2^2} = \rho_k^i + c\delta t_k + \delta_{tro} + \lambda_3 B_{k,3}^i + \varepsilon_{L,3} \quad (2)$$

where the subscript  $k$  refers to a receiver and subscript  $i$  to a satellite,  $f_1$  and  $f_2$  denote the carrier-frequencies of the pseudo-range and phase observations,  $\rho_k^i$  denotes the geometric distance between the satellite and the receiver,  $\delta t_k$  the receiver clock error scaled by the speed of light  $c$ ,  $\delta_{tro}$  the slant tropospheric delay,  $\lambda_3 B_{k,3}^i$  the IF ambiguity scaled by the corresponding wavelength  $\lambda_3$  and  $\varepsilon_{p,3}$  and  $\varepsilon_{L,3}$  denote the noise of the code and phase measurements, respectively. Taking the UPDs into account the IF ambiguity parameter  $B_{k,3}^i$  can be written in the following form:

$$B_{k,3}^i = N_{k,3}^i + \Delta\phi_3^i - \Delta\phi_{k,3} \quad (3)$$

with  $\Delta\phi_3^i$  and  $\Delta\phi_{k,3}$  being the transmitter and receiver specific UPDs and  $N_{k,3}^i$  being an integer number of wavelengths. Usually the UPDs or any linear combination of them are not integer values, thus prevent the fixing of ambiguities to integers.

Figure 1 illustrates an example of a typical PPP float solution. It shows the north, east and up position differences (with respect to the reference position) of a generated float solution of the IGS station Graz-Lustbühel using dual-frequency data and precise orbit and clock products. As it can be seen after some tens of minutes the horizontal position is within a few cm while the height difference is at approximately 1 dm.

In Figure 2 the IF float ambiguity of PRN 15 corresponding to the PPP float solution presented before is shown. Due to the presence of

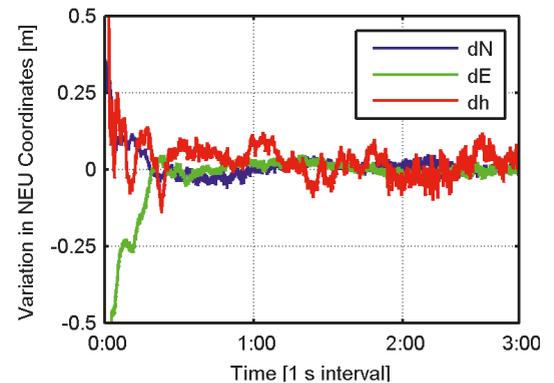


Fig. 1: Float solution of station GRAZ

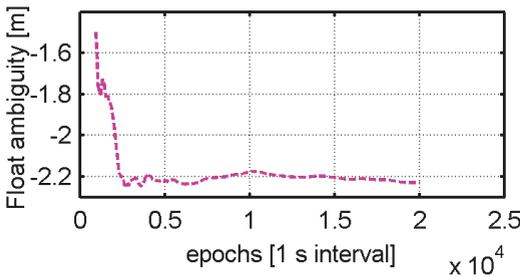


Fig. 2: Transient behavior of float ambiguity of PRN 15

the phase delays the ambiguity estimate lost its integer nature. As it is illustrated in the example the ambiguity parameters seems to be stable after an initialization time of 3000 epochs (interval of 1 s). This time is correlated to the initialization time of the position solution.

## 2. Project Work

To comply with the aforementioned challenge, the research project “Network based GNSS Phase Biases to enhance PPP Applications – A new Service Level of GNSS Reference Station Provider” (PPPServe) started in April 2012. The project aimed at the provision of UPDs which are the missing link at the user side to allow for real-time PPP based phase ambiguity resolution. The Technische Universität Wien, Forschungsgruppe Höhere Geodäsie (lead), the Graz University of Technology, former Institute of Navigation and the former Wien-Energie Stromnetz GmbH contributed to this project which has been successfully completed in November 2013.

### 2.1 Concept

During the last years several approaches to recover the integer nature of zero-difference phase ambiguities to perform integer PPP have been developed (see [4], [5], [6] and [7]). Thereby integer resolution is achieved by applying improved satellite products where the UPDs are separated from the integer ambiguities. The concept for the estimation of the UPDs which was developed in context of the project is based on an approach called “phase recovery from fractional parts” which was presented in a study of [6] for the first time. In this approach the undifferenced ambiguities are decomposed into wide-lane WL and narrow-lane NL ones. Thereby, a satellite-to-satellite single-difference (SD) is used to eliminate the receiver-dependent calibration biases. Within a network of reference stations the WL phase biases are determined from averaging the fractional parts of all WL-estimates using the Melbourne-Wübbena combination of

the measurements. The NL phase biases are similarly determined by averaging the fractional parts of all NL ambiguity estimates derived from the WL ambiguities and the IF observables. The estimated phase biases can then be applied to ambiguity estimates of single-receivers to recover their integer nature.

Based on the aforementioned approach a fully functional system consisting of a network-side and a user-side module was developed (see Figure 3). The network-side module allows for the estimation of WL and NL UPDs in relation to one chosen reference satellite using observations of a regional network of GPS stations. These corrections can be used by the user-module that applies the calculated UPDs in a modified PPP algorithm to enable integer ambiguity resolution on the basis of wide- and narrow-lane observables. Details on PPPServe and its general system overview can be found in [8].

### 2.2 Server-side algorithms

In the following especially the algorithms for the estimation of the WL and NL UPDs implemented in the network-side module will be presented. As previously mentioned the UPDs are decomposed into WL and NL ones, which are related to the ambiguity parameter of the IF linear combination  $B_{k,3}^i$  (see [9]) according to

$$\begin{aligned}
 B_3^{i,j} &= \frac{c}{f_1^2 - f_2^2} B_{NL}^{i,j} + \frac{cf_2}{f_1^2 - f_2^2} B_{WL}^{i,j} = \\
 &= \frac{c}{f_1^2 - f_2^2} \left( N_{NL}^{i,j} + \Delta\phi_{NL}^{i,j} \right) + \\
 &\quad + \frac{cf_2}{f_1^2 - f_2^2} \left( N_{WL}^{i,j} + \Delta\phi_{WL}^{i,j} \right).
 \end{aligned} \tag{4}$$

This equation is already given at the single difference level (differences between the satellites  $i$  and  $j$ ) in order to eliminate the receiver specific UPD. Subsequently, the index  $k$  has been omitted for simplification. The wide-lane part  $B_{WL}^{i,j} = N_{WL}^{i,j} + \Delta\phi_{WL}^{i,j}$  and the narrow-lane part  $B_{NL}^{i,j} = N_{NL}^{i,j} + \Delta\phi_{NL}^{i,j}$  both consist of the respective integer ambiguity  $N^{i,j}$  plus the corresponding satellite specific UPD  $\Delta\phi^{i,j}$  originating from oscillator-induced time delays of the satellite while the receiver specific UPD has been eliminated. The WL and NL UPDs cannot be estimated simultaneously therefore a stepwise estimation process is applied which will be described in the next paragraphs.

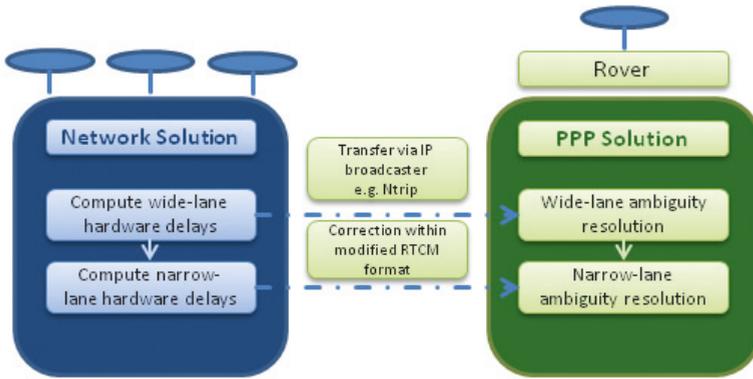


Fig. 3: Concept of the PPPServe System

**Determination of the reference satellite**

As mentioned above, the parameter estimation is based on the combination of SD observations. In order to be able to use the SD observations of all stations for the parameter estimation it is necessary to choose a common reference satellite. Therefore, a reference satellite must be selected prior to the estimation of the UPDs. Using only a regional network (Figure 4 illustrates the regional station network used by the PPPServe system) simplifies the selection of the reference satellites since the satellite is usually in the field of view at most of the stations. To keep it simple the satellite which is visible at most of the stations is chosen as reference satellite. Since data of a regional network is utilized the reference satellite has to be changed from time to time. Such a change also needs to be considered in the parameter estimation.

**Estimation of the wide-lane UPDs**

For the estimation of the WL UPDs the Melbourne Wübbena linear combination (MW) of all observations of the station network is built. The

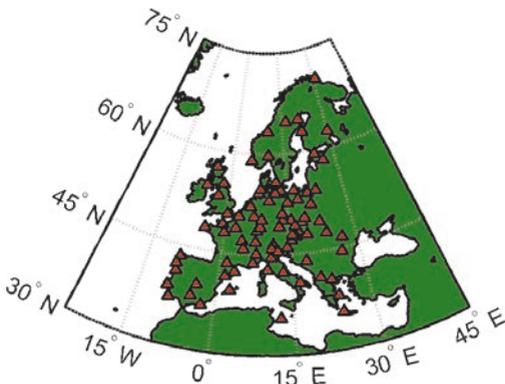


Fig. 4: Reference station network

MW combination is a linear combination of both, carrier phase (L1 and L2) and code (P1 and P2) observables. It eliminates the effect of the ionosphere, the geometry, the clocks and the troposphere and provides a noisy estimation of the wide-lane ambiguity according to the following equation:

$$L_{k,WL}^i = \lambda_{WL} (N_{k,WL}^i + \Delta\phi_{WL}^i - \Delta\phi_{k,WL}) + \varepsilon_{WL} \quad (5)$$

where  $\lambda_{WL}$  is the wavelength of the WL combination,  $N_{k,WL}^i$  is the integer WL ambiguity,  $\Delta\phi_{WL}^i$  and  $\Delta\phi_{k,WL}$  account for the satellite and receiver specific UPDs and  $\varepsilon_{WL}$  is the measurement noise, including carrier phase and code noise. A major disadvantage of the MW combination is the increased measurement noise which is highly dominated by the noise of the code measurements which is slightly reduced by calculating the moving average of the MW combination.

In the next step every possible SD observation is built at each station, by subtracting the observations of the difference satellites from the observation of the prior chosen reference satellite. Building the difference between two ZD MW observations (Eq. 5) and dividing the equation by the WL wavelength leads to the following equation with the receiver specific UPD being eliminated

$$B_{WL}^{i,j} = \frac{Lk_{WL}^{i,j}}{\lambda_{WL}} = N_{WL}^{i,j} + \Delta\phi_{WL}^{i,j} + 2 * \varepsilon_{WL} \quad (6)$$

where  $N_{WL}^{i,j}$  is the SD integer wide-lane ambiguity,  $\Delta\phi_{WL}^{i,j}$  is the satellite specific SD UPD and  $\varepsilon_{WL}$  is the measurement noise which is increased by a factor of two due to the built difference. Then, the positive fractional parts of all WL ambiguities observed are estimated. Finally the SD WL UPDs corrections are estimated by combining the corresponding fractional parts of the SD WL ambiguities using a Kalman filter.

The whole procedure is depicted by the following equation:

$$\delta\Delta\phi_{WL}^{i,j} = \text{Kal}\left(\text{Frac}\left(\hat{B}_{WL}^{i,j}\right)\right) \quad (7)$$

where  $\delta\Delta\phi_{WL}^{i,j}$  denotes the estimated SD WL UPD correction,  $\text{Frac}()$  is a function to return the fractional part,  $\text{Kal}()$  denotes the Kalman filter and  $\hat{B}_{WL}^{i,j}$  denotes the SD WL ambiguities observed at the stations. One must be aware that each UPD has an integer and a fractional part, wherein the integer part cannot be separated from the integer ambiguities anyway. Therefore it is only possible to estimate the fractional part of the UPDs. However, this is sufficient to restore the integer nature of the ambiguities.

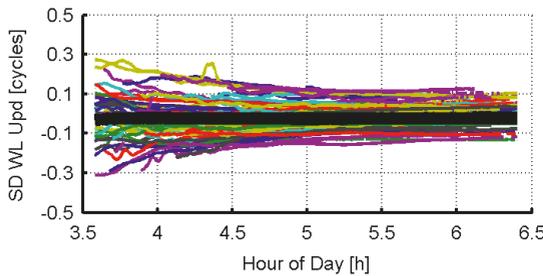


Fig. 5: SD WL UPD PRN19 – PRN32

In Figure 5 the input and output of the Kalman filter for the satellite pair PRN19 – PRN32 are shown. The fractional parts of the SD WL UPDs observed at the stations which serve as input are illustrated by the different colors. Since the network consists of more than 80 stations the same color appears several times. As it can be seen the fractional parts observed at the individual stations are very stable after a short initialization phase and the differences between them are in the range of about 0.3 cycles (one cycle corresponds to ~86 cm). In addition to the observations the UPD correction estimated as parameter of the Kalman filter is shown, which is illustrated by the slightly thicker black line.

### Estimation of the narrow-lane UPDs

Following the estimation of corrections for the SD WL UPDs the estimation for the SD NL UPDs is carried out. According to Eq. 4 an estimation of the SD NL UPD correction requires a solution of the SD IF float ambiguity  $B_3^{i,j}$  in the first place. The SD IF ambiguities are estimated together with the zenith tropospheric delay within a SD PPP solution at each station. All other errors are modeled or eliminated by building the ionosphere free linear combination and the difference between the observations of two satellites. Following this, the observed SD WL ambiguities are fixed using

the previously estimated SD WL UPD corrections according to

$$\hat{N}_{WL}^{i,j} = \hat{B}_{WL}^{i,j} - \delta\Delta\phi_{WL}^{i,j} \quad (8)$$

The fixing is performed by a simple integer rounding of the corrected SD WL ambiguities to the nearest integer using a threshold of 0.25 cycles as fixing decision. This relative high threshold can be used due to the good wavelength/noise ration of the smoothed MW observables. After a successful fix the SD NL ambiguities can be estimated by a reformulation of Eq. 4 and the substitution of Eq. 8 according to:

$$\begin{aligned} N_{NL}^{i,j} + \Delta\phi_{NL}^{i,j} + \frac{f_2}{c(f_1 - f_2)} \left( N_{WL}^{i,j} - \hat{N}_{WL}^{i,j} + \Delta\phi_{WL}^{i,j} \right) &= \\ &= \frac{1}{c(f_1 - f_2)} B_3^{i,j} - \frac{f_2}{c(f_1 - f_2)} \hat{N}_{WL}^{i,j}. \end{aligned} \quad (9)$$

The difference between  $N_{WL}^{i,j}$  and  $\hat{N}_{WL}^{i,j}$  must not be necessarily zero which is mainly caused by the integer part of the SD WL UPD  $\Delta\phi_{WL}^{i,j}$  and biases of the pseudo-range. Since both of the two terms are constant they can be merged into the SD NL UPD correction according to

$$\begin{aligned} \Delta\hat{\phi}_{NL}^{i,j} &= \Delta\phi_{NL}^{i,j} + \frac{f_2}{c * (f_1 - f_2)} \left( N_{WL}^{i,j} - \hat{N}_{WL}^{i,j} + \Delta\phi_{WL}^{i,j} \right) \\ B_{NL}^{i,j} &= N_{NL}^{i,j} + \Delta\hat{\phi}_{NL}^{i,j}. \end{aligned} \quad (10)$$

But this means that one has to keep consistency between the SD NL UPD correction and the related SD WL UPD correction. With the definition given in Eq. 10, Eq. 9 can be rewritten as

$$B_{NL}^{i,j} = \frac{1}{c(f_1 - f_2)} B_3^{i,j} + \frac{f_2}{c(f_1 - f_2)} \hat{N}_{WL}^{i,j} \quad (11)$$

with  $B_3^{i,j}$  being the real-valued carrier-phase ambiguity estimated within the SD PPP solution and  $\hat{N}_{WL}^{i,j}$  being the fixed SD WL ambiguity.

The estimation of the SD NL UPD corrections itself is carried out using the same procedure as for the estimation of the WL UPDs corrections. In a first place the positive fractional parts of the SD NL ambiguities are estimated which are subsequently combined in a Kalman filter. The main difference compared to the estimations of the WL UPDs is the stability of the NL UPDs. The NL UPDs corrections are less stable which is mainly due to the small wavelength of the NL combination which corresponds to ~10 cm as well as unmodelled effects introduced by remaining error sources (remaining troposphere and ionosphere, orbit and clock inaccuracies).

Figure 6 illustrates the input and output of the Kalman filter for the estimation of the SD NL

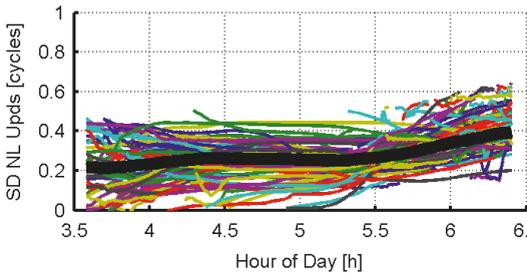


Fig. 6: SD NL UPD PRN19 – PRN32

UPD correction of the previously shown satellite pair (PRN19 – PRN32). As it can be seen the fractional parts of SD NL UPDs observed are in the range of a few tenths of a cycle only (one cycle corresponds to ~10 cm). So the solutions of the different stations are in the range of a few centimetres which leads to the conclusion that all necessary errors are modelled quite well. Another very interesting point is that the fractional parts observed are very stable. This is also true for the other SD NL UPDs. Therefore, a continuous estimate of the UPD correction is possible and no time-dependent change has to be considered in order to provide high quality biases.

**2.3 Stability of the UPD corrections**

Within this section the stability of the WL and NL UPD corrections will be discussed on the basis of one week of processed data. For the estimation observations of 80 stations of the EUREF network (see Figure 4) in GPS Week 1733 in combination with precise orbit and clock products from the IGS (see [10]) were used. Processing one week of data allows for the analysis of the stability of the WL and NL UPD corrections which is of interest for the estimation process itself and the update rate for transferring the UPDs to the user.

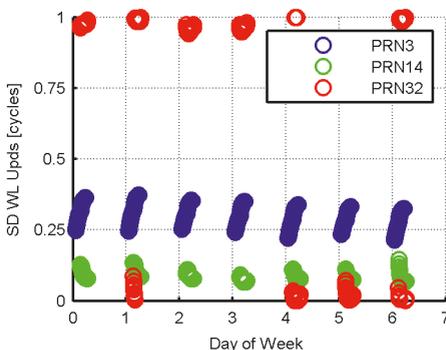


Fig. 7: Stability of SD WL UPDs

**Stability of the SD WL UPD corrections**

In Figure 7 the SD WL UPD corrections of three satellites (PRN13, PRN14 and PRN32) with respect to the reference satellite PRN19 are shown over the period of one week.

As it can be seen the estimated SD WL UPD corrections are not only stable during the time they are observed (usually once per day), they are also stable over much longer periods. This is also true for the solution of PRN32 even though it seems to jump. The reason for these artificial jumps is that the fractional parts of an ambiguity which is in the range of an integer, can exhibit differences of one full cycle. However, differences of one full cycle have no influence on the ambiguity fixing. In consideration of an operational service there would be two possibilities to process the SD WL UPD corrections: The first option would be to post process the UPDs with a delay of one day. The second one would be to estimate them in real-time together with the SD NL UPDs. The first option has the advantage of reduced computational burden. On the other hand, due to the high stability of corrections, it is more than sufficient to estimate them only every 15 minutes which does not need a lot of computer power.

**Stability of the SD NL UPD corrections**

The results of the SD NL UPD shown previously indicate that the corrections are very stable during the time they are observed. Now it is of special interest if they are also stable over longer periods. In Figure 8 the corrections of three satellites (PRN13, PRN14 and PRN32) with respect to the reference satellite PRN19 are shown over the period of one week.

As it can be seen the estimated corrections are almost stable during the time they are observed (once per day), but contrary to the SD WL UPD corrections they are not stable over longer peri-

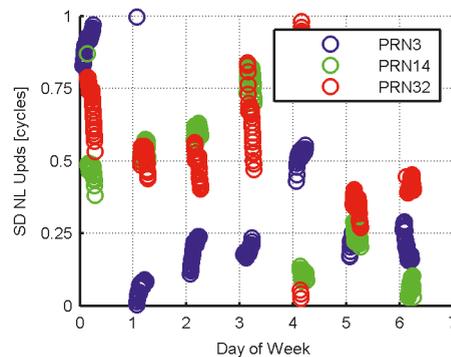


Fig. 8: Stability of SD NL UPDs

ods. Those differences are probably caused by remaining errors in the orbits and satellite clocks and errors introduced by the mapping function. One has to keep in mind that one full NL cycle corresponds to only 10cm, so the differences between the different “daily” solutions are in the range of a few centimetres only. Furthermore two daily solutions of the estimated SD NL UPDs of PRN32 seem to drift. Those drifts may have their origin in unmodelled satellite specific errors. Due to those drifts the NL UPD corrections require a higher estimation rate compared to the WL UPDs. Since the differences are in the region of a few centimetres only a rate 10 to 30 seconds is still enough.

### 3. Application of the UPD corrections

In order to test the quality and reliability of the estimated corrections they were tested and evaluated using the user-side module developed at the TU Graz, where the corrections are applied to recover the integer nature of the WL and NL ambiguities. The fixed integer ambiguities can be re-introduced in the PPP solution. In case of successfully established and applied corrections the convergence of the coordinate solution should be extremely short. In other words the applied corrections should allow for an ambiguity fixing in zero-difference mode after introducing only a few epochs of observations.

To show the convergence a PPP solution with ambiguity fixing was calculated. Therefore observation data of the IGS station Graz Lustbühel (GRAZ) from DOY 87 in 2013 was used together with the precise orbit and clock products of the IGS.

As soon as the 4th narrow-lane ambiguity value is fixed to an integer – in the example illustrated in Figure 9 this happens after a couple of minutes – the horizontal position solution stays extremely stable in the surrounding of  $\pm 2$ cm of

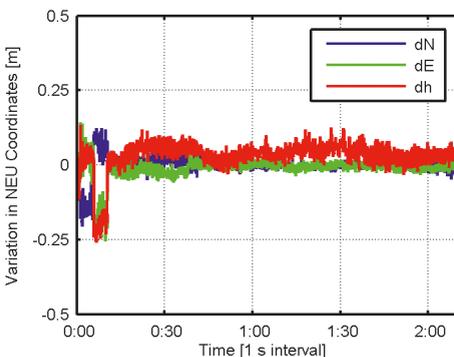


Fig. 9: PPP solution with ambiguity fixing

the reference coordinates. In contrast to common float PPP solutions the east-component is as accurate as the north-component – this arises from the fact, that now the ambiguities are no unknowns anymore. In general it can be stated that the period required to fix the first four NL ambiguities strongly depends on the quality of corrections as well as on the satellite constellation geometry and on the quality of the approximate coordinates. Under favorable conditions the convergence time is dramatically reduced to a couple of minutes. A much more detailed investigation on the application of the corrections at the user-side module can be found in [11].

### 4. Conclusion and Outlook

This paper shows that a fully functional system enabling integer PPP was developed within the context of the project PPPServe, which is consisting of a network-side and a user-side module. The network-side module allows for the estimation of PPP-corrections to phase observables, which, on the other hand, help to recover the integer nature of WL and NL ambiguities and therefore enable ambiguity resolution at the user-side.

The WL UPD corrections are estimated using the MW combination. Due to the noise introduced by the code observations the single MW observations have to be smoothed by building the mean value over the epochs. The estimation of the WL UPD corrections is carried out using a Kalman filter. Summarizing, the WL UPD corrections are very stable over several days, which would even allow for estimating them in post processing.

The NL UPD corrections are estimated on basis of the estimated IF float and fixed integer WL ambiguities. The IF float ambiguities are generated using a standard PPP solution and the WL ambiguities are fixed to integers by means of the WL UPD corrections. The estimation of the NL UPD corrections is also carried out using a Kalman filter. Due to the relatively short wavelength of the NL combination, unmodelled remaining errors in the orbits and satellite clocks and errors introduced by the mapping function, strongly effect their estimation. This effect may lead to jumps between the different daily solutions.

Nevertheless, it could be shown that the estimated UPD corrections allow for a PPP solution with ambiguity fixing at the user-side, which is extremely precise and stable as soon as only few integer ambiguities can be fixed correctly. Under favorable conditions the convergence time is dramatically reduced to a couple of minutes.

Further, especially the east component of the coordinate solution can be strongly improved compared to a PPP float solution.

Even though the work shown in this paper was only a proof of concept, a PPP service offering UPD corrections is realizable. Possible applications for such a service are:

- Using it in areas where no RTK service is available
- Static and kinematic applications with accuracy requirements of 5–20 cm, taking into account possible long convergence times
- Independent monitoring of the stability of reference stations using PPP

Nevertheless in order to reach the performance of consolidated RTK systems PPP still faces the following challenges:

- In terms of the convergence time PPP still cannot compete with established RTK services. Contrary to RTK the convergence time strongly depends on the initial conditions
- In order to reach the same quality as RTK regional error models are required. Such models can only be derived from regional network data
- Currently there are no industry message standards that would allow for the transmission of all corrections required for PPP with ambiguity fixing. It should be noted that those standards are currently established

Nevertheless, it is expected that the number of PPP solutions will strongly increase in the next couple of years.

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