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A Novel Real-time Precise Positioning Service System: Global Precise Point Positioning With Regional Augmentation

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Abstract

Based on precise real time orbit and clock products from a global network, the standard Precise Point Positioning (PPP) computes user states, which requires a long initialization time in order to obtain a converged solution. Conversely, the Network Real-Time Kinematic (NRTK) positioning requires additional corrections from regional or local dense network for instantaneous ambiguity resolution and state solutions. Both standard PPP and NRTK modes have their own advantages and limitations.

A new approach is developed to generate undifferenced corrections in the observation domain from a regional network which can be disseminated station-by-station and applied to user observations for instantaneous ambiguity-fixing. In the proposed service, instantaneous ambiguity resolution is accessible for regions with these observation corrections as regional augmentation information, so that PPP and RTK are integrated into a unified service.

The paper presented the approach for generating the undifferenced corrections and the realization of the augmented system in detail. Results from an operational service are introduced as experimental validation.

Keywords: Precise Point Positioning, Ambiguity-Fixing, Regional Augmentation, Real-time service

1. Introduction

Based on the global real-time precise orbits and clock products, Precise Point Positioning (PPP) has been proved as very promising because of its cost-efficiency, global coverage and its accuracy that can meet the requirements of many applications [1, 2, 3, 6, 10, 15, 17]. However, the sparsely distributed global reference network does not provide sufficiently accurate atmosphere corrections (model) for fast ambiguity-fixing. Hence, ionospheric delays are usually eliminated through ionosphere-free combination and zenith tropospheric delays are estimated along with other state parameters. As a consequence PPP takes at least 30 minutes of initialisation time to obtain a converged solution.

Although recent developments in PPP ambiguity-fixing [5, 9, 13, 16] can significantly improve its performance, a successful fixing still needs more than 20 minutes because pseudo-range noises in the Melbourne-Wübbena (MW) combination needed for the wide-lane ambiguity-fixing can only be reduced by means of time average. Such a long convergence time is not acceptable for most users of the NRTK services where instantaneous ambiguity resolution and position solutions are achievable.

This situation could be improved if ranges of better quality or observations in additional frequency are available [7]. Constructing better ionospheric delay model using a dense network can also improve wide-lane ambiguity-fixing. Anyway, PPP is still unable to compete with NTRK positioning either in accuracy or in convergence time.

Conversely, a dedicated dense reference network is requested in the NRTK service. Current bias representation approaches use the observation residuals at the master (reference) station and the double-differenced (DD) residuals at other two or more reference stations to represent the spatial change of the biases [12, 18, 20, 21 22]. This requires a network solution of all reference stations, which is rather time-consuming. On the other hand using DD residuals as correction information makes the data communication rather complicate. Moreover, re-initialization is needed if user moves far away from the master station in use. All these preclude the possibility for a NRTK service to provide a unique and homogeneous service for very large regions such as China.

Therefore, both strategies have their own advantages and limitations. While they have been developed in parallel recently, one cannot be replaced by another in a foreseeable future.

In this paper, we present a new approach to estimate undifferenced (UD) integer ambiguities which can be used to derive the UD observation corrections at all frequencies. With these corrections the interpolated ones at the user-end can not only remove the biases at user stations, but also recover the integer nature of the ambiguity parameters. Thus, instantaneous ambiguity fixing is achievable at the user-end. Of the same importance, the information can be casted station-by-station via NTRIP (Networked Transport of RTCM via Internet Protocol, http://igs.bkg.bund.de/ntrip) and selected by the users for receiving and interpolating.

The data processing at the user side is very similar to current PPP and the only difference is whether the corrections based on the regional network are applied or not. This implies a new service system: global PPP with the regional augmentation. The new PPP service offers 10 cm accuracy globally after a convergence time of about 30 minutes or after successful ambiguity fixing, and instantaneous positioning at a few centimetres in the regions where augmentation information is available.

The approach for estimating UD integer ambiguities is presented at first. Then the structure and algorithm of the augmentation system is discussed in details. Afterwards, the validation of an operational service system is introduced and, finally, some conclusions are drawn accordingly.

2. Retrieving the UD Corrections

The linearized observation equation of a GNSS phase measurement at a single frequency can be written as

$$\begin{aligned} l_u^i = \delta S_u^i + \delta I_u^i + \delta T_u^i + \delta t_u + f_u \\ -\delta t^i - f^i + n_u^i + \mathbf{u}_u^i \delta \mathbf{x}_u \end{aligned} \tag{1}$$

where l_u^i is the pre-fit residual or observed minus computed (OMC), δS_u^i is the remaining orbit bias, δI_u^i and δT_u^i are the ionospheric and tropospheric delays, δt_u and δt^i are the clock biases, n_u^i is the integer ambiguity, f_u and f^i are the uncalibrated phase delays (UPD), $\mathbf{u}_u^i$ is the unit vector from the receiver to the satellite, $\delta \mathbf{x}_u$ is the vector of the station coordinate corrections. Here super-index i is for satellites while sub-index u for receivers.

Except the terms for integer ambiguity and the station coordinate corrections, the others are either common for observations to the same satellite/receiver, for example UPDs and clocks for receivers and satellites, or their spatial changes can be approximately expressed with a linear function at each epoch. Similar to the bias representation in NRTK [8, 12], these constant and linear items can be represented by the values at a set of reference stations. As the stations coordinates can be determined precisely in advance for the reference stations, the only problem is how to obtain the ambiguities. We first discuss the bias representation with known UD integer ambiguities and later present a new approach to estimate the UD integer ambiguities.

2.1 Bias representation with known ambiguities

Assuming that integer ambiguities at all frequencies are known, for a reference station k with known coordinates we have the unambiguous residuals according to Eq. 1,

$$omc_k^i = \delta S_k^i - \delta t^i + \delta t_k + \delta I_k^i + \delta T_k^i + f_k - f^i \tag{2}$$

These residuals include ionospheric and tropospheric delays and UPDs for receiver and satellite pair, and biases for satellite orbits and clocks and receiver clock. The biases of clocks and UPDs are constant at a single epoch and the others can be represented by a linear function. Therefore, similar to NRTK applying the linear combination by Han and Rizos in [12] to the OMCs at the three reference stations surround the user stations, we have the following corrections:

$$\begin{aligned} \bar{l}_u^i = \sum_{k=1}^{3} \alpha_k (\delta S_k^i + \delta I_k^i + \delta T_k^i) \\ + \sum_{k=1}^{3} \alpha_k (\delta t_k + f_k) - \delta t^i - f^i \end{aligned} \tag{3}$$

with $\alpha_1 + \alpha_2 + \alpha_3 = 1$.

Introducing this correction into the user observation equation of Eq. 1, the remaining satellite clock biases and UPDs at satellite are completely cancelled, so that we have

$$\begin{aligned} l_u^i = \left[\left(\delta S_u^i + \delta I_u^i + \delta T_u^i \right) - \sum_{k=1}^{3} \alpha_k \left(\delta S_k^i + \delta I_k^i + \delta T_k^i \right) \right] \\ + \left(\delta t_u - \sum_{k=1}^{3} \alpha_k \delta t_k \right) + \left(f_u - \sum_{k=1}^{3} \alpha_k f_k \right) \\ + n_u^i + \mathbf{u}_u^i \delta \mathbf{x}_u \end{aligned} \tag{4}$$

The first term is very close to zero depending on the behaviour of the spatial change of orbit biases and atmosphere delays and the interstation distances. The second term is the receiver clock shifted by the linear combination of remaining receiver clock biases at the three reference stations which is a constant for all observed satellite at each epoch and can be absorbed by the receiver clock parameter. Similar to the second term, the third one is the receiver UPD shifted by the combined receiver UPDs of the reference stations. This constant can be absorbed by the receiver clock or the integer ambiguity parameters. The next is the integer ambiguity and the last one represents the station coordinate corrections. Then the observation equation is reduced accordingly as follows,

$$\begin{aligned} l_u^i &= \delta\bar{t}_u + n_u^i + \bar{f}_u + \mathbf{u}_u^i \delta\mathbf{x}_u \\ &= \delta\bar{t}_u + b_u^i + \mathbf{u}_u^i \delta\mathbf{x}_u \end{aligned} \tag{5}$$

where b_u^i includes the integer ambiguity and the shifted UPD of the user receiver. As the shifted UPD is a constant for all satellites, the SD ambiguity between satellites has still integer feature and can be fixed to integer too.

2.2 Estimation of the UD integer ambiguities

It is well noted that the UD integer ambiguities are unknown and they cannot even be estimated with a reasonable accuracy because of their high correlations with other parameters and the existence of UPDs. Instead of the true, we try to find out a set of integer UD ambiguities based on which observation corrections can be obtained for removing all the biases and recovering the integer nature of the ambiguities at the user-end, so that instantaneous ambiguity-fixing is available.

There are two approaches to obtain such kind of UD integer ambiguities. One approach maps the fixed DD-ambiguities from baseline or network solutions to UD integer ambiguities [11] and the other one estimates them from UD ambiguities of PPP solutions [14]. The former one does not need precise orbits and clocks and is more suitable for providing NRTK service over a large region while the latter is suitable for the augmentation of a global PPP service.

2.2.1 Approach based on fixed DD-ambiguities

For a reference network with *n* UD ambiguities denoted by $\mathbf{B}$, a set of independent DD ambiguities $\mathbf{N}$ of dimension *m* is usually defined for fixing,

$$\mathbf{N} = \mathbf{DB} \tag{6}$$

For any given integer vector $\mathbf{N}$ there could be numerous solutions for $\mathbf{B}$ because $\mathbf{D}$ is a rank-defected transformation due to $m < n$.

In data processing strategies working with UD observations, fixed DD ambiguities must be mapped into UD ambiguities in order to recover UD residuals of the fixed solutions. We can select $n-m$ UD ambiguities from $\mathbf{B}$ which are independent with the fixed DD ambiguities to construct a full-rank transformation [4]. Let the selected set $\mathbf{b}$ and $\mathbf{b} = \mathbf{GB}$ where each row of $\mathbf{G}$ has just one element of 1 and the others are all zero, we have the following full-rank transformation,

$$\begin{bmatrix} \mathbf{b} \\ \mathbf{N} \end{bmatrix} = \begin{bmatrix} \mathbf{G} \\ \mathbf{D} \end{bmatrix} \mathbf{B} \tag{7}$$

Then the solution of $\mathbf{B}$ can be written as

$$\mathbf{B} = \begin{bmatrix} \mathbf{G} \\ \mathbf{D} \end{bmatrix}^{-\mathbf{1}} \begin{bmatrix} \mathbf{b} \\ \mathbf{N} \end{bmatrix} \tag{8}$$

For any arbitrarily selected $\mathbf{b}$, we have a solution fulfilling the fixing condition of Eq. 6. So, ambiguities in $\mathbf{b}$ are referred as to the reference ambiguity in this study.

We first prove that the reference ambiguities $\mathbf{b}$ can be selected arbitrarily for a bias representation. Without loss of generality, we start with the observing scenario with three reference stations tracking three satellites which can be easily extended to the scenarios with more satellites and receivers. There are nine UD ambiguities b_k^i and from them four independent DD ambiguities can be defined. Therefore, five reference ambiguities must be selected in order to construct a full-rank transformation of Eq. 7.

We select the ambiguities of the first receiver and that of the first satellite as refence ambiguities and the four DD ambiguities are defined and fixed to $N_{1,2}^{1,2}$, $N_{1,3}^{1,2}$, $N_{1,2}^{1,3}$ and $N_{1,3}^{1,3}$. Through the backwards mapping of Eq. 8, the UD ambiguities can be derived and expressed with the reference ambiguities and the fixed DD ambiguities as

$$\begin{matrix} b_1^1 & b_2^1 & b_3^1 \\ b_1^2 & N_{1,2}^{1,2} - b_1^1 + b_1^2 + b_2^1 & N_{1,3}^{1,2} - b_1^1 + b_1^2 + b_3^1 \\ b_1^3 & N_{1,2}^{1,3} - b_1^1 + b_1^3 + b_2^1 & N_{1,3}^{1,3} - b_1^1 + b_1^3 + b_3^1 \end{matrix} \tag{9}$$

Now, if the reference ambiguities are biased by δb_i^j, the biases of all the mapped UD ambiguities are

$$\begin{bmatrix} \delta b_1^1 & \delta b_2^1 & \delta b_3^1 \\ \delta b_1^2 & -\delta b_1^1 + \delta b_1^2 + \delta b_2^1 & -\delta b_1^1 + \delta b_1^2 + \delta b_3^1 \\ \delta b_1^3 & -\delta b_1^1 + \delta b_1^3 + \delta b_2^1 & -\delta b_1^1 + \delta b_1^3 + \delta b_3^1 \end{bmatrix} \tag{10}$$

Applying the linear interpolation of Eq. 3, we have the biases of the observation corrections at the user side,

$$\begin{bmatrix} \delta\bar{l}_u^1 \\ \delta\bar{l}_u^2 \\ \delta\bar{l}_u^3 \end{bmatrix} = \begin{bmatrix} \delta b_1^1 & \delta b_2^1 & \delta b_3^1 \\ \delta b_1^2 & -\delta b_1^1 + \delta b_1^2 + \delta b_2^1 & -\delta b_1^1 + \delta b_1^2 + \delta b_3^1 \\ \delta b_1^3 & -\delta b_1^1 + \delta b_1^3 + \delta b_2^1 & -\delta b_1^1 + \delta b_1^3 + \delta b_3^1 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix}$$

$$= \left(\sum_{i=1}^{3} \alpha_i \delta b_i^1 - \delta b_1^1 \right) \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} + \begin{bmatrix} \delta b_1^1 \\ \delta b_1^2 \\ \delta b_1^3 \end{bmatrix} \qquad (11)$$

The first term of the right-hand side is a constant for all satellites, and the elements of the second term are satellite-specific constants. Furthermore, both are constants over time and therefore will be absorbed by ambiguity parameters. So, we can conclude that arbitrary selection of reference UD-ambiguities has no effect on a bias representation.

The only problem caused by the arbitrary selection is that the SD-ambiguities in Eq. 5 are not any more integers because the satellite-specific biases in Eq. 11 could have different fractional parts. Fortunately, in this study **B** represents the UD integer ambiguities, as the fractional parts are already separated as UPDs. In other words, the true value of **B** is integers. Therefore, if integer values are selected for the reference ambiguities, their biases will still be integers. Consequently the second term in Eq.11 contains only integers.

Therefore biases in observations at user station can be removed and their SD-ambiguities are natural integers if integer values are selected for reference ambiguities.

2.2.2 Approach based on UD-ambiguities

If precise orbits and clocks are available, PPP can be performed for all regional reference stations with coordinates fixed to well-known values. We can derive the UD integer ambiguities directly from the UD ambiguities of such PPP solutions.

The real-valued ambiguities can be expressed by the integer ones and the (fractional) UPDs at a receiver and a satellite as

$$b_k^i = n_k^i + f_k - f^i \qquad (12)$$

For a reference network with *n* stations tracking *m* satellites we have the following observation equations,

$$\begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \\ \vdots \\ \vdots \\ \mathbf{b}_n \end{bmatrix} = \begin{bmatrix} \mathbf{I} & & & & \mathbf{R}_1 & \mathbf{S}_1 \\ & \mathbf{I} & \mathbf{0} & & \mathbf{R}_2 & \mathbf{S}_2 \\ & & \mathbf{I} & & \vdots & \vdots \\ & \mathbf{0} & & \mathbf{I} & \vdots & \vdots \\ & & & & \mathbf{I} \;\; \mathbf{R}_n & \mathbf{S}_n \end{bmatrix} \begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \vdots \\ \mathbf{n}_n \\ \mathbf{f_R} \\ \mathbf{f_S} \end{bmatrix}, \quad \mathbf{Q_{bb}} \qquad (13)$$

where $\mathbf{R}_i$ and $\mathbf{S}_i$ are the design matrix for UPD parameters at receivers and satellites, respectively. Each row of $\mathbf{R}_i$ or $\mathbf{S}_i$ has just one element of 1 instead of 0 as for all the others.

Obviously, we cannot solve for all parameters in Eq. 13 as the number of parameters is much larger than that of the equations. However, if we have reasonable initial values for the UPD parameters, then fixing ambiguities to their integers can be possible. The fixed integer ambiguities can be removed from Eq. 13. If all ambiguities can be fixed we have the following equation for the estimation of precise fractional UPDs,

$$\begin{bmatrix} \mathbf{b}_1 - \mathbf{n}_1 \\ \mathbf{b}_2 - \mathbf{n}_2 \\ \vdots \\ \vdots \\ \mathbf{b}_n - \mathbf{n}_n \end{bmatrix} = \begin{bmatrix} \mathbf{R_1} & \mathbf{S_1} \\ \mathbf{R_2} & \mathbf{S_2} \\ \vdots & \vdots \\ \vdots & \vdots \\ \mathbf{R_n} & \mathbf{S_n} \end{bmatrix} \begin{bmatrix} \mathbf{f_R} \\ \mathbf{f_S} \end{bmatrix} \qquad (14)$$

In practise, we perform the estimation iteratively. First we select a set of fractional initial values then try to fix ambiguities. After removing the integer parameters from the related equations, fractional UPDs are estimated again. This procedure is repeated until no more ambiguity can be fixed.

In practice we do not have to fix all the ambiguities, but only fixed UD ambiguities can be used for the generating of UD observation corrections which will ensure both the precise bias representation and the integer ambiguity recovery at a user station.

Obviously, the estimated integer ambiguities can be biased because we cannot separate the integer part of UPDs from the integer ambiguities. Therefore, we use the fractional part of UPDs instead of UPDs themselves. As a result, the integer UD ambiguities could be biased by integers. It is easy to prove that these biases caused by ignoring integer parts of UPDs have no negative effects for the instantaneous ambiguity-fixing at a user station.

For the abovementioned observing scenario, assuming that the biases are δf , the resulted biases in the corrections at a user station are,

$$\begin{bmatrix} \bar{l}_u^1 \\ \bar{l}_u^2 \\ \bar{l}_u^3 \end{bmatrix} = \left(\begin{bmatrix} l_1^1 & l_2^1 & l_3^1 \\ l_1^2 & l_2^2 & l_3^2 \\ l_1^3 & l_2^3 & l_3^3 \end{bmatrix} - \begin{bmatrix} \delta f_1 - \delta f^1 & \delta f_2 - \delta f^1 & \delta f_3 - \delta f^1 \\ \delta f_1 - \delta f^2 & \delta f_2 - \delta f^2 & \delta f_3 - \delta f^2 \\ \delta f_1 - \delta f^3 & \delta f_2 - \delta f^3 & \delta f_3 - \delta f^3 \end{bmatrix} \right) \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{bmatrix} \qquad (15)$$

Eq. 15 can be easily reformatted into

$$\begin{bmatrix} \delta \bar{l}_u^1 \\ \delta \bar{l}_u^2 \\ \delta \bar{l}_u^3 \end{bmatrix} = \sum_{i=1}^{3} \alpha_i \delta f_i \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} \delta f^1 \\ \delta f^2 \\ \delta f^3 \end{bmatrix} \tag{16}$$

Similar to Eq. 11, we know the integer biases have no effects on both the representation and the integer recovering.

The two approaches are proven to be efficient for the estimating integer UD ambiguities to retrieve observation corrections at the reference stations. Additionally, these fulfill the requirements for a precise bias representation and the integer ambiguity recovery because of the constraint of the integer DD-ambiguities. Thanks to recent developments in a mobile communication, the UD corrections can be broadcast using NTRIP real-time streams station by station. A user can establish his communication with the caster to get the data of three nearby stations, so that the communication burden, which is a bottleneck in current NRTK systems, can be released significantly.

The network solution is no longer necessary because the integer ambiguities and the pre-fit residuals based on the same initials mainly for orbits and clocks can be derived in a baseline mode and even in a PPP mode. This allows NRTK or the regional augmentation to be extended for large areas with dense reference networks.

Finally, the client algorithm is exactly the same as the standard PPP with ambiguity-fixing except that the additional corrections interpolated from the pre-fit residuals at the three nearby stations must be applied. This means that PPP and NRTK can be integrated together.

3. The Augmentation System

Based on the approaches and algorithms for generating UD corrections from a regional network, we design a new precise positioning service: global PPP with the regional augmentation. Fig. 1 shows the structure of the augmented global PPP service.

The upper panel of Fig. 1 is the standard PPP with ambiguity-fixing where real-time precise orbits and clocks are estimated from a global reference network and UPDs and ionospheric model are reconstructed as additional information, so that both the standard PPP and PPP with ambiguity-fixing can be performed. The bottom panel shows the regional augmentation where UD observation corrections are generated for the instantaneous ambiguity-fixing at a user station.

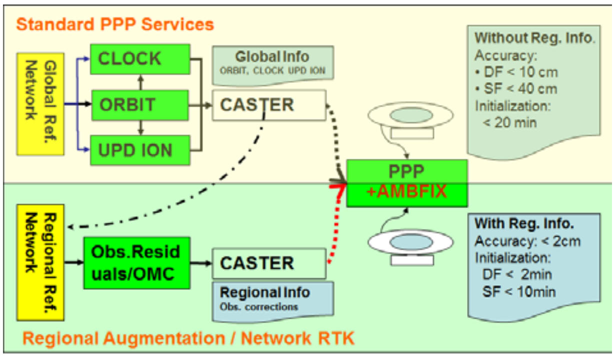

Figure 1 System structure of the global real-time precise positioning service based on Precise Point Positioning with the regional augmentation.

The data flow is illustrated in Fig. 2. The server receives data from the caster on the top for both global and regional stations. The global data is employed to estimated orbits and clocks which are casted through the bottom caster to users. The global network and the precise orbits and clocks are used to estimate UPDs. For the augmentation, orbits and clocks and UPDs are used for performing PPP of the regional reference stations. From these solutions the integer UD ambiguities are estimated and the observation corrections are generated for L1 and L2 and casted to users on the station base. It should be mentioned that the ambiguity resolution at the regional reference stations is very critical, as only corrections with fixed ambiguities can be used as regional augmentation information.

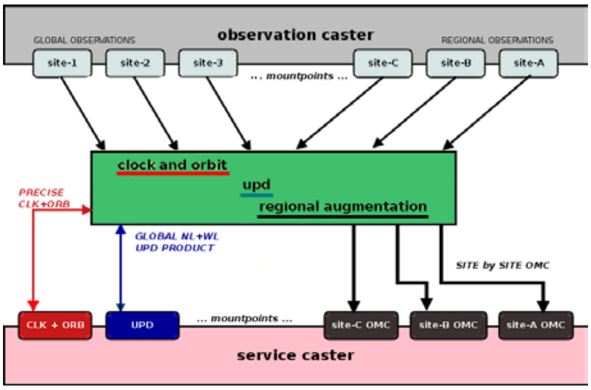

Figure 2 Data flow at the server side of the augmented global PPP service.

At the user stations, the mount-point table for the regional reference stations should be downloaded at the beginning and at least three nearby stations are selected according to the user location. The corrections are then received continuously, interpolated for the user location and applied to the related observation types. With the same orbit and clock products, the observations are modelled and PPP with ambiguity-fixing is performed. We use wide-lane and L1 phase and ionosphere-free range as independent observations for a better fixing performance. Additional ionospheric parameters with proper constraint can also be imposed in order to reduce the effect of the remaining ionospheric biases due to the large inter-station distance. The data flow at the user stations is illustrated in Fig. 3. The user can perform the standard PPP, PPP with ambiguity fixing and PPP with instantaneous ambiguity-fixing according to the information available.

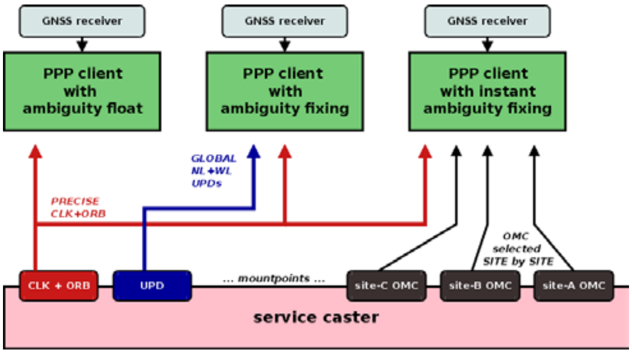

Figure 3 Data flow at the client side for standard PPP, PPP with ambiguity fixing and PPP with instantaneous ambiguity-fixing using regional augmentation information.

4. Validation

The EPOS-RT software [10] which is running at the GFZ' IGS real-time data analysis centre for providing real-time orbits and clocks, was adapted for the regional augmentation in a simulated real-time mode. Using this software the algorithms are validated with the SAPOS network [11]

Recently, new software in C/C++ was developed to overcome the disadvantage of the FORTRAN language in a real-time data handling. Now the system is running operationally to provide augmentation information for Germany with the SAPOS and GREF real-time stations in addition to the global PPP service provided by GFZ with the EPOS-RT software.

4.1 PPP with ambiguity resolution

We process about 80 IGS stream data in real-time for providing orbits and clocks. From the IGS real-time combination, the user range accuracy is about 0.1 ns or 3 cm. Routine PPP test by BKG shows that the agreement with ground true is better than 5 cm and 10 cm for horizontal and vertical components, respectively. UPDs for wide- and narrow-lane are also determined in real-time using the same network. Orbits and clocks and UPDs are broadcasted through the same caster via INTERNET.

With the UPDs, ambiguity-fixing can be performed and position accuracy can be improved significantly especially for the horizontal component. Fig. 4 is an example showing the impact of PPP ambiguity-fixing. Although the improvement is obvious, it takes about a few tens of minutes and the accuracy can still not meet the requirement of a large number of precise applications, for example, geodetic or engineering surveying. These can clearly be improved with regional augmentation information shown in the next sub-section.

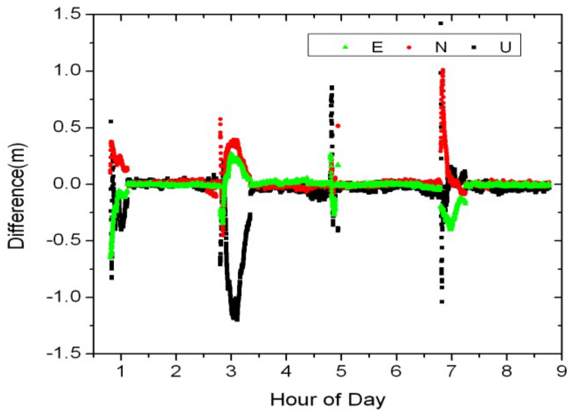

Figure 4 Impact of PPP ambiguity-fixing on position accuracy and convergence time. The estimator is restarted every two hours.

4.2 Regional augmentation with SAPOS network

Fig. 5 shows the distribution of the real-time stations of the SAPOS network. There are about 300 stations marked with small red dots. The real-time data is provided by the SAPOS authorities for this study. We selected 22 stations as regional augmentation stations indicated with large black dots. About 17 stations are chosen as user stations marked with green squares.

The regional reference stations are processed in PPP mode using products from the GFZ global precise positioning service. The UD observation corrections are generated using the strategies presented before. The corrections are broadcast station by station using different NTRIP mount-points and an internal format.

At each user station, GFZ real-time orbits and clocks are received and the augmentation corrections from three nearby regional reference stations are also used for instantaneous ambiguity-fixing. Wide-lane and L1 phases and ionosphere-free ranges are employed as independent observations in the parameter estimation by means of the sequential least square adjustment. The integer ambiguity resolution is attempted epoch-wise and wide- and L1 ambiguities are fixed simultaneously using the LAMBDA method by Teunissen in [19]. For the selected user stations, the estimator is restarted every minute to obtain the statistics about how long it takes for a successful fixing and how accurate the position of the fixed solution could be.

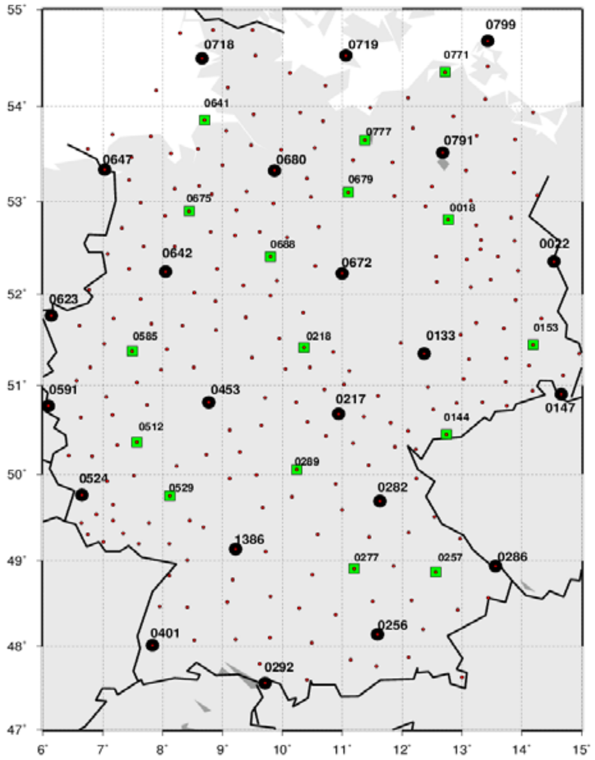

Figure 5 The German reference network and the SAPOS stations. Each small red dot indicates a real-time station of the SAPOS network. Large black dots indicate the selected regional reference stations and the large squares are for user stations.

Fig. 6 shows the statistics of the observation time needed for successful ambiguity fixing of about 5000 test solutions. For about 75% solution, the ambiguity can be fixed just with one epoch of data. On average, data of two epochs of a five-second sampling rate are needed for a reliable ambiguity-fixing. We also noticed there are a few solutions where ambiguities cannot be fixed within predefined restarting time of 1 minute. Further investigation should be carried out for possible improvement.

As soon as the integer ambiguities are successfully fixed, the coordinates at the epoch is taken as the fixed solution for assessing the positioning accuracy of the augmentation system. The fixed solutions are compared with the precise coordinates estimated in a static mode in advance. Fig. 7 shows the distribution of the differences in east, north and vertical directions, respectively. The horizontal components have a RMS smaller than 15 mm and vertical less than 30 mm.

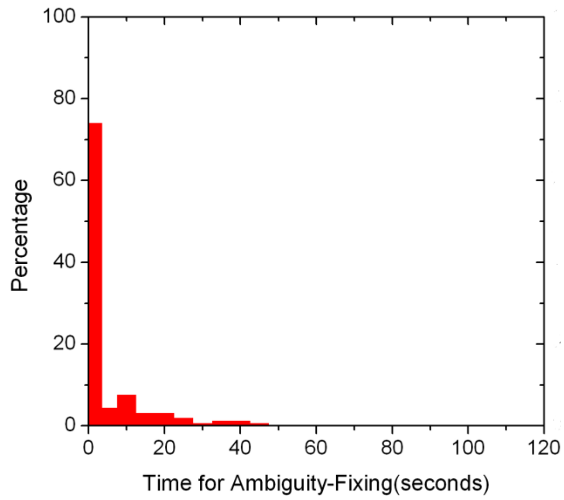

Figure 6 Observing time needed for ambiguity-fixing. 75% can be fixed within one epoch and on average two epoch data is needed.

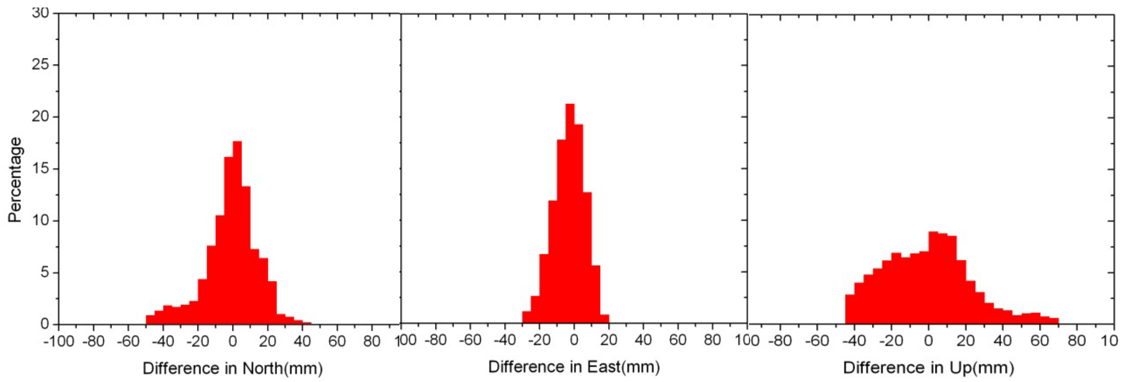

Figure 7 Distribution of position differences of the solutions with fixed ambiguities and the precise coordinates estimated in static mode.

5. Conclusions

We have presented a new approach to estimate the integer UD ambiguities from fixed DD-ambiguities or real-valued ambiguities from PPP solutions. With the derived UD integer ambiguities at L1 and L2, UD observation corrections can be retrieved and applied to user receiver for the instantaneous ambiguity-fixing. In this way PPP with regional augmentation information can replace current NRTK.

The UD correction information can be casted station-by-station like the IGS real-time data streams, and users can select the streams automatically according to their positions. This will significantly reduce the communication and management burden at the server side.

Network solution for the reference stations is not necessary any more. Only fixed ambiguities are required which can be estimated in PPP, baseline or sub-network modes. This characteristic will enable the new strategy to be applied to very large and dense reference networks for providing a homogeneous positioning service.

Based on the new strategy, a new real-time precise positioning service system, the real-time global precise positioning service with regional augmentation, is recommended. Without regional augmentation about 5-10 cm position accuracy will be achieved after 30 min and 5 cm accuracy after the ambiguity-fixing. With the regional augmentation 1-2 cm accuracy will be available within 1-2 min using dual-frequency receivers and 1-3 cm within 10-20 minutes using single-frequency receivers.

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