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Ambiguity resolution in precise point positioning with hourly data for global single receiver

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Abstract

Integer ambiguity resolution (IAR) can improve precise point positioning (PPP) performance significantly. IAR for PPP became a highlight topic in global positioning system (GPS) community in recent years. More and more researchers focus on this issue. Progress has been made in the latest years. In this paper, we aim at investigating and demonstrating the performance of a global zero-differenced (ZD) PPP IAR service for GPS users by providing routine ZD uncalibrated fractional offsets (UFOs) for wide-lane and narrow-lane. Data sets from all IGS stations collected on DOY 1, 100, 200 and 300 of 2010 are used to validate and demonstrate this global service. Static experiment results show that an accuracy better than 1 cm in horizontal and 1–2 cm in vertical could be achieved in ambiguity-fixed PPP solution with only hourly data. Compared with PPP float solution, an average improvement reaches 58.2% in east, 28.3% in north and 23.8% in vertical for all tested stations. Results of kinematic experiments show that the RMS of kinematic PPP solutions can be improved from 21.6, 16.6 and 37.7 mm to 12.2, 13.3 and 34.3 mm for the fixed solutions in the east, north and vertical components, respectively. Both static and kinematic experiments show that wide-lane and narrow-lane UFO products of all satellites can be generated and provided in a routine way accompanying satellite orbit and clock products for the PPP user anywhere around the world, to obtain accurate and reliable ambiguity-fixed PPP solutions.

Keywords: Zero-difference; Integer ambiguity resolution; Hourly data; Precise point positioning; Uncalibrated fractional offsets

1. Introduction

With the availability of precise GPS satellite orsbit and clock products which have been routinely provided by a number of analysis centers of the IGS, precise point positioning (PPP) could provide absolute positioning with centimeter accuracy, which is almost comparable with that of network solutions (Zumberge et al., 1997). GPS users can obtain a homogeneous positioning accuracy through PPP over a region, even globally employing a single receiver. Over the past years it has been widely applied in a number of applications such as crustal deformation monitoring (Azuá et al., 2002; Savage et al., 2004; Hammond and Thatcher, 2005; D'Agostino et al., 2005; Calais et al., 2006), near real-time GPS meteorology (Gendt et al., 2003; Rocken et al., 2005), orbit determination of low earth orbiting satellite (Bock et al., 2003; Zhu et al., 2004), and mobile object's trajectories recovery (Gao and Shen, 2002; Zhang and Andersen, 2006) etc. However, the unknown uncalibrated fractional offsets (UFOs) destroy the integer nature of zero-differenced (ZD) ambiguities in conventional PPP (Ge et al., 2008). The ambiguities have to be solved as float values. Thus, compared with network double difference solution, PPP suffers from poor accuracy for observations covering a short time interval, e.g., less than one hour. Even when extending the observation time to 24 h, the accuracy of the east component is still not comparable to a double difference solution (Ge et al., 2008).

Therefore, attempts have been made to fix ambiguities in point positioning. Gabor and Nerem (1999) firstly

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proposed a method to fix single-differenced (SD) integer ambiguities by using a single receiver. In the method, the daily wide-lane and narrow-lane SD UFOs between satellites are estimated and used for removing the fractional part of SD ambiguities to implement integer ambiguity resolution by using a single receiver in a simulated test. Recently, more investigations have been done on this issue, and demonstrated that fixing integer ambiguities in PPP can improve the solution quality to some extent. Ge et al. (2008) developed the method proposed by Gabor and Nerem with real GPS data. They demonstrate that daily wide-lane and every 15 min narrow-lane UFOs with high quality can be estimated from a global network of about 180 stations by averaging. In this way daily static PPP solution accuracy can be improved from 4.1, 3.1 and 8.3 mm to 2.8, 3.0 and 7.8 mm for IGS stations (Ge et al., 2008). Geng et al. (2009) further examined the IAR in PPP with hourly data in static case and 6-hour 1 Hz data in real-time kinematic case by using a European regional network. Their results show that the accuracy of a hourly PPP fixed solution in static case can be improved from 3.8, 1.5 and 2.8 cm to 0.5, 0.5, 1.4 cm (Geng et al., 2009) and the mean position accuracy in real-time kinematic case is improved from 6.0, 3.6 and 6.9 cm to 0.9, 0.9 and 3.0 cm for the East, North and Up components, respectively (Geng et al., 2010a). However, in Geng's study, the narrow-lane UFOs are determined within each full pass of a satellite pair over a dense regional network. This approach is suitable for practical use in a regional network, nevertheless, seems unsuitable for a larger scale or even global network as a full pass of a same satellite pair cannot be observed by all sites. They do not apply their approach to a global ambiguity-fixed PPP service. Therefore, employing sparse global tracking stations instead of a dense regional network to estimate UFOs for PPP fixed solution is not investigated yet. In this paper, we aim at investigating and analyzing the global hourly ambiguity-fixed PPP service by producing ZD wide-lane UFO and narrow-lane UFO products of all satellites accompanying precise satellite orbit and clock production. It is expected to become a routine procedure for PPP as relative positioning in the near future. For this purpose the satellite UFO files are likely to be produced by some agency such as IGS analysis centers to promote the PPP service for global GPS users.

2. Method

The UFOs are usually derived from the estimated float ZD ambiguities. In Ge's approach all possible SD ambiguities are formed for each satellite pair. Their fractional parts should be statistically the same if the ZD ambiguities are estimated precisely, as further difference between any two of them forms a double-differenced (DD) ambiguity which should be very close to an integer. Taking the mean of the fractional part of the SD ambiguities of the same satellite pair over all the stations the SD UFO is estimated. Instead of estimating SD UFOs for all satellite pairs, we apply a new approach proposed by Li and Zhang (2012) to estimate the ZD UFOs in an integrated adjustment and with sequential integer ambiguity fixing in order to enhance the estimates. The approach can be applied to both wide-lane and narrow-lane if the corresponding ZD ambiguities are available.

Similar to Ge's method our method is composed of two modules based on ZD data processing. One is the ZD UFO estimation from a network for all satellites. The other is ZD ambiguity-fixed PPP solution for a single GPS receiver. In the network processing, wide-lane UFOs are first estimated with the float wide-lane ambiguities which are derived by the Melbourne–Wübbena combination (Melbourne, 1985; Wübbena, 1985). And then narrow-lane UFOs are determined with all involved narrow-lane ambiguity estimates, which are derived from the real-valued ionosphere-free ambiguities and the fixed wide-lane ambiguities. They are both estimated by the least square adjustment after the outliers have been detected and removed. In order to compute ZD UFOs of all satellites, one of the receiver's UFOs needs to be fixed, for example to be zero (Laurichesse and Mercier, 2007; Li and Zhang, 2012; Loyer et al,, 2012). At the PPP user end, the ZD phase observations can be corrected by these UFOs, and then the ZD ambiguity can be fixed to an integer. Fig.1 shows the flow of an ambiguity-fixed PPP service.

2.1. ZD UFOs estimation method

All GPS observations from a global IGS network are used to estimate the ZD UFOs for all GPS satellites. The

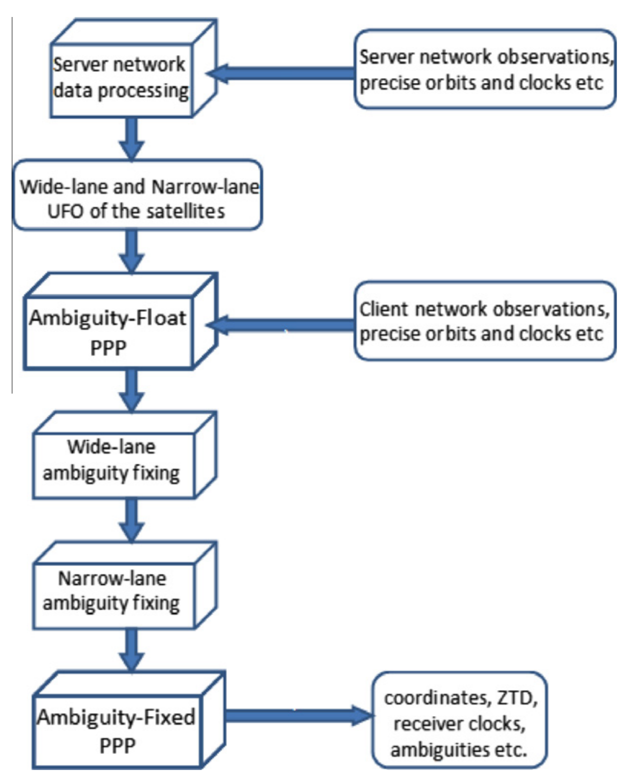

Fig. 1. Flow of ambiguity-fixed PPP service.

daily wide-lane UFOs can be estimated precisely from Melbourne–Wübbena combinations owing to its long wavelength feature and insensitivity to the errors of measurement. However, the narrow-lane UFOs are not as stable as the wide-lane ones because of its short wavelength. Thus, they must be estimated for short time interval in order to ensure enough precision (Ge et al., 2008; Geng et al., 2009). In Geng's investigation, a regional network is used to estimate the narrow-lane UFOs. Only parts of narrow-lane UFOs of satellites can be produced from a regional network. As the narrow-lane float ambiguity can be formed only when the ionosphere-free ambiguity is valid and the wide-lane ambiguity can be fixed, the numbers of available float narrow-lane ambiguities is much lower than that of the wide-lane ambiguities. In this paper, a global network of reference stations is involved so that narrow-lane UFO of all operable satellites could be estimated every 10 min.

Different from the method proposed by Ge et al. (2008) in which the UFOs are estimated simply by averaging, a more robust method to estimate the UFOs by least square adjustment is used here. For all continuous arcs without cycle slip, the expressions for the float wide-lane and narrow-lane ambiguity can be written by the following equation (Laurichesse and Mercier, 2007; Li and Zhang, 2012; Loyer et al., 2012)

$$R_i^k = B_i^k - \tilde{N}_i^k = f_i - f^k \tag{1}$$

where R is the combined fractional part of uncalibrated phase delays for both receiver i and satellite k, B denotes float ZD ambiguities in the standard model, $\tilde{N}$ denotes the sum of the original integer ambiguity N and the integer part of the uncalibrated phase delays from satellites and receiver, f_i denotes receiver's UFO, f^k denotes satellite's UFO. To ensure consistency between all passes of a given station-satellite pair, some of the R_i^k values are shifted by $+1$ or -1 to keep them all close to each other.

Eq. (1) is suitable for both wide-lane and narrow-lane UFO estimation. Under the condition that all the integer ambiguities are exactly known and one UFO is fixed to zero, then the UFOs can be estimated by means of the least square adjustment. In order to avoid possible biased estimates due to, for example, large multipath effects, ZD ambiguities with an observation time shorter than 20 min are ignored. For the same reason, those with a STD larger than 0.2 cycles are also rejected.

2.2. ZD ambiguity resolution for PPP

As we know, the UFOs from satellite and receiver destroy the integer feature of ZD ambiguities. The UFOs should be corrected before fixing the ZD ambiguity to the integer. The satellite UFOs can be removed by making the ZD UFO corrections. Then the corrected ZD ambiguities should have very similar fractional parts if the satellites UFOs are eliminated; we take the mean fractional parts of all the corrected ambiguities as receiver UFO. After removing satellite and receiver UFOs, the ZD wide-lane ambiguity can be simply fixed by rounding to the nearest integer value. Due to the strong correlation between the hourly PPP ambiguities, a search strategy based on the LAMBDA (Teunissen, 1994) method is applied to solve the ZD narrow-lane ambiguity. In the ambiguity resolution procedure, we adopt the following strategies to improve the solution. Firstly, observations with elevation angle lower than 15° will be masked to prevent the impact of the noisy observations on the solution. Secondly, the observations for which the STD of ionosphere-free ambiguity or the wide-lane ambiguity is larger than 0.2 cycles will not be used. The well-known ratio test is applied to validate the ambiguities, and the critical criterion of the ratio value is set to 3 which is generally deemed as conservative option in ambiguity validation (Han, 1997).

3. Experiment scheme

In order to investigate and analyze the global hourly ambiguity-fixed PPP service in static and kinematic mode, observations on DOY 1, 100, 200 and 300 of 2010 from about 360 IGS stations are used to demonstrate the performance of such a PPP service. Fig. 2 shows the IGS tracking stations we used. Among them, the stations marked with black solid circle are denoted as 'Reference Stations' and used to estimate the ZD wide-lane and narrow-lane UFOs. It is noticed that not all reference stations would be finally used in the UFOs estimation, few of them may be rejected in the quality control process of the estimation. Five stations with blue diamond in each of six continents except Antarctica are selected as 'User Stations'. Except that observations of user stations in the kinematic experiment are with 5 s sampling rate, all the other data are with 30 s sampling rate. The daily observations from the 30 stations are separated into 24 pieces of hourly observations to validate the hourly ambiguity-fixed PPP service.

As reported in Wang and Gao (2009), for PPP float solution, the convergence time is typically fifteen minutes to half an hour or even longer, depending on the data quality (Wang and Gao, 2009). Geng et al. (2010b) show that over 20 min is needed to fix about 90% of the wide-lane ambiguities for low elevation angles. And for real-time IAR in which the accuracy requirement of UFO estimation can be relieved to 0.25 cycles, narrow-lane ambiguity resolution can be done once the wide-lane ambiguity resolution has been achieved (Geng et al., 2010b). Thus in the validation tests, the pieces less than 30 min would be removed.

In the experiment, final orbits and clocks, and the differential code biases generated by the Center for Orbit Determination in Europe (CODE) are used. We apply the absolute antenna phase centers, the phase wind-up corrections (Wu et al., 1993) and the station displacement conventions from the International Earth Rotation and Reference Systems Service (McCarthy and Petit, 2004).

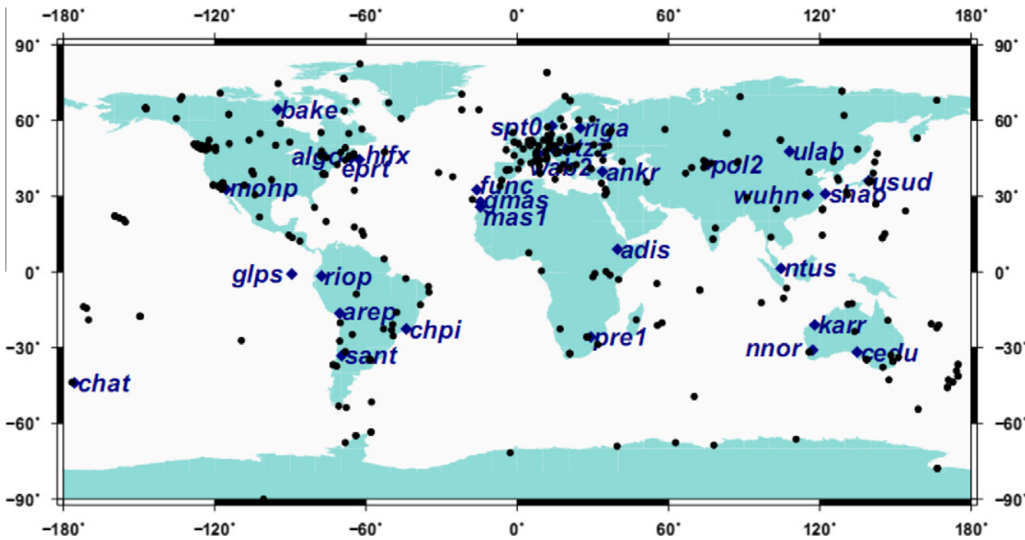

Fig. 2. Global reference station network and user station collocation. The blue diamonds denote the stations for testing the hourly ambiguity-fixed PPP service; the black solid circles denote the stations used for the UFOs estimation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Results and discussion

In the following sections, the quality of ZD UFO estimates, and the accuracy of hourly PPP fixed solution for 30 stations in both static and kinematic are presented.

4.1. Quality of ZD UFO estimation

Firstly, we compute the usage rate, i.e. the percentage of valid observations which are used to estimate UFOs to indicate the consistency of UFOs. Fig. 3 shows the usage rate of wide-lane float ambiguities used for UFOs estimation of each day. The min and max rate is 87.4%, 93.9% for DOY 1, 92.0%, 96.2% for DOY 100, 90.6%, 96.0% for DOY 200, and 86.8%, 95.8% for DOY 300. It is clear that most of them are higher than 90%. Higher usage rate means more redundancy in UFO estimation, which leads to more precise satellite wide-lane UFOs. With these valid wide-lane float ambiguities, the STDs of wide-lane UFO estimates are usually around 0.005 cycles. It should be mentioned that the quality of pseudo-range produced by cross-correlation receivers is relatively bad. The data from those stations equipped with cross-correlation receivers will not be used in UFOs estimation (Ge et al., 2008). In our investigation, if observations from those stations are excluded, the usage rate will be higher than we present here.

Fig. 4 shows the usage rate of the narrow-lane float ambiguities for the 85th ten-minute session of day 300. The total input narrow-lane float ambiguities are around 100 for each operable satellite. As a narrow-lane UFO is estimated every 10 min, and the narrow-lane float ambiguity is available only when the ionosphere-free ambiguity is valid and the wide-lane ambiguity can be fixed, the original input for narrow-lane UFO estimation is much less than that of wide-lane. It is found that the usage rate is generally around 80% and the min and max rate are 66.7% for G17, and 95.4% for G6. With these valid narrow-lane float ambiguities, the STDs of narrow-lane UFO estimates are usually around 0.03 cycles. Due to its short wavelength, the narrow-lane UFO estimates are easily affected or polluted by the residual un-modeled errors. Therefore the usage rate for the narrow-lane is usually lower than that for the wide-lane. Improving the quality of narrow-lane UFO

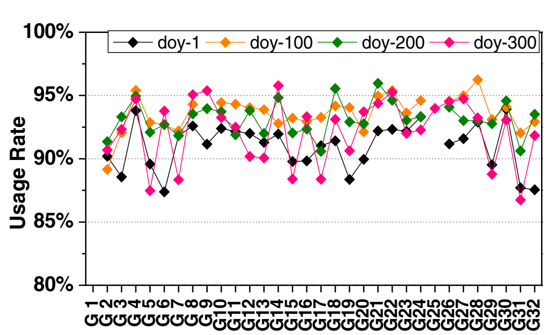

Fig. 3. The usage rate of wide-lane float ambiguity input for UFO estimation in day 1, 100, 200 and 300.

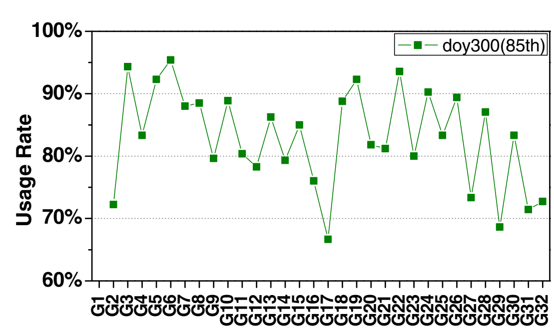

Fig. 4. The usage rate of narrow-lane float ambiguity input for UFO estimation in the 85th 10-minutes session of day 300.

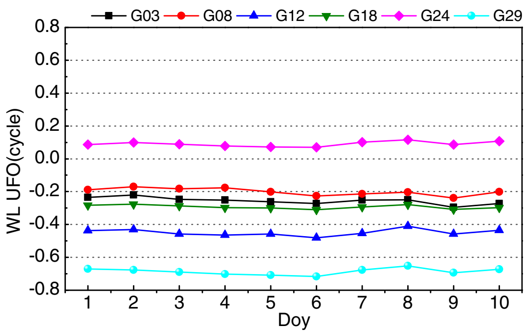

Fig. 5. The ZD wide-lane UFOs from doy 1 to doy 10, 2010.

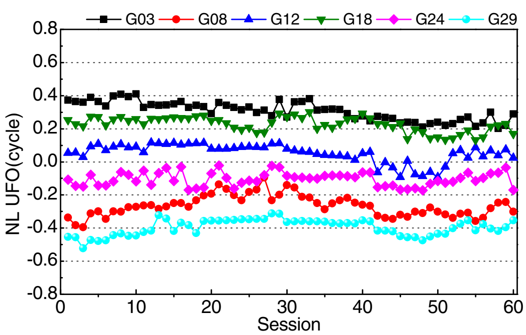

Fig. 6. The ZD narrow-lane UFOs from session 1 to session 60, doy 1, 2010.

estimations is important and should be investigated further because the accuracy of the narrow-lane UFOs estimation directly affects the position accuracy of PPP fixed solutions (Geng et al., 2009).

We also give the variability of the UFO as shown in Figs. 5 and 6. For each satellite, the ZD wide-lane UFOs of the beginning 10 days in 2010 agree with each other better than 0.1 cycles. They are rather stable and can be predicted for several days for real-time applications. Nevertheless, the ZD narrow-lane UFOs of the beginning 60 sessions clearly vary with time. And the change reaches up to 0.2 cycles for most satellites. Those narrow-lane UFOs are relatively stable in the short term so that they can only be predicted for a short time.

Applying these UFOs to PPP solution, the success rate of ambiguity fixed with the LAMBDA method at station

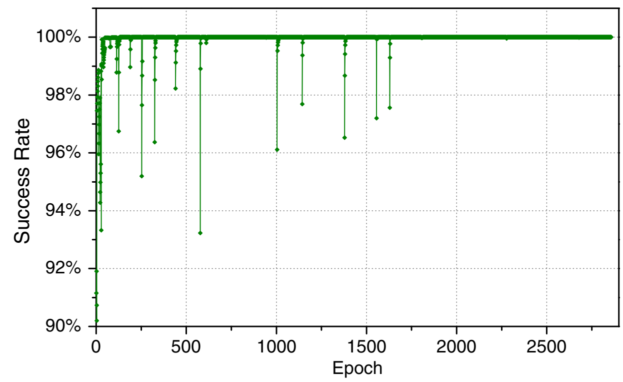

Fig. 7. The success rate of ambiguity fixing with LAMBDA method at station ANKR on DAY 1, 2010.

ANKR can be calculated and shown in Fig. 7. It clearly shows that the success rates are all higher than 90% and reach to 100% for most epoches. It can be concluded that reliable ambiguity resolution can be achieved after removing the UFOs from the ZD float ambiguities.

4.2. Static result comparison between float and fixed solution

We select 6 stations (NNOR locates in Oceania, MONP is from North America, GMAS from Africa, SANT from South America, ANKR from Europe and SHAO from Asia) from different continents where the density of network stations is different to compare the positioning accuracy of float and fixed solutions with hourly data. It should be noted that there are 24 hourly PPP solutions in each day for a station. We find the mean position errors for both fixed solution and float solution are closed to zero. That means no obvious systematic biases exist in fixed and float solutions. Therefore, we use the mean absolute bias of all sessions in east, north and up direction to indicate the positioning accuracy of the hourly PPP solutions. The magnitude of the mean absolute bias should reflect the scatter of PPP solutions. The accuracy comparison of float and fixed solution on DOY 1, 100, 200 and 300 is plotted in Fig. 8. The upper bar represents the difference of absolute biases between float and fixed PPP solution. It is noticed that significant improvements can be achieved by fixing

Table 1
The average positioning bias of float and fixed solution, and the accuracy improvement of fixed solution.

Site	Float (mm)			Fix (mm)			Improvement (%)		
	E	N	U	E	N	U	E	N	U
NNOR (Oce)	22.7	9.1	26.8	9.2	6.8	18.9	59.7	25.6	29.6
MONP (Nor Ame)	21.3	9.4	27.5	6.8	5.2	18.4	68.2	44.3	33.2
GMAS (Afr)	19.7	8.3	29.2	6.6	5.6	22.9	66.4	32.1	21.4
SANT (Sou Ame)	23.2	9.4	29.0	11.4	6.7	23.6	51.1	29.0	18.7
ANKR (Eur)	24.0	13.4	28.5	6.3	7.5	18.6	73.9	44.3	34.5
SHAO (Asi)	26.0	12.7	29.7	12.1	8.9	22.0	53.6	30.3	25.8
MIN	–	–	–	–	–	–	51.1	29.0	18.7
MAX	–	–	–	–	–	–	73.9	44.3	34.5
MEAN	22.3	10.4	28.9	8.1	6.6	21.7	63.8	36.4	24.8

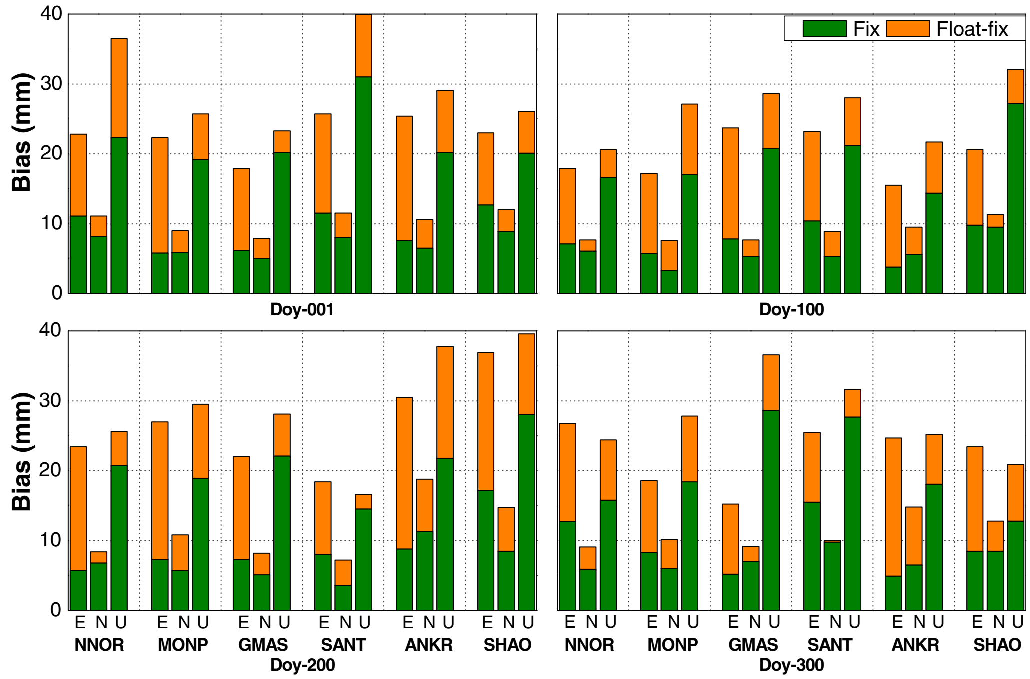

Fig. 8. The average positioning bias of float and fixed solution of six stations on DAY 1, 100, 200 and 300, in east, north and up respectively.

the ZD ambiguity in PPP, especially for the east component. An accuracy of better than 1 cm in horizontal and 2 cm in vertical could be achieved for the fixed solutions. Such accuracy can only be obtained with daily observations for float PPP. The four days' results of average positioning bias for each station are summarized and tabulated in Table 1. It is found that the mean positioning accuracy of all hourly solutions can be improved from (22.3, 10.4, 28.9) mm to (8.1, 6.6, 21.7) mm, the average improvement is 63.8%, 36.4% and 24.8% in the east, north and vertical components respectively. The accuracy of the east component is comparable with that of the north components in the fixed solution. Differently than for the horizontal components the improvement in the vertical is not significant. It can be explained that the vertical accuracy has small correlation with the ambiguities (Blewitt, 1989).

Furthermore, all 30 stations have been processed and the accuracy improvement benefit from fixed solution in east, north and up directions is shown in Figs. 9–11 respectively. Color scale denotes the percentage of improvement. The colors of most stations in Fig.9 are almost the same, showing a same level of 60% more or less improvement in east direction. In fact, except 36.9% for CHAT, 46.9% for NTUS, 48.5% for BAKE and 73.9% for ANKR, improvements for others stations are between 50.6% and 69.8%. Similarly, Fig.11 shows a same level of improvement

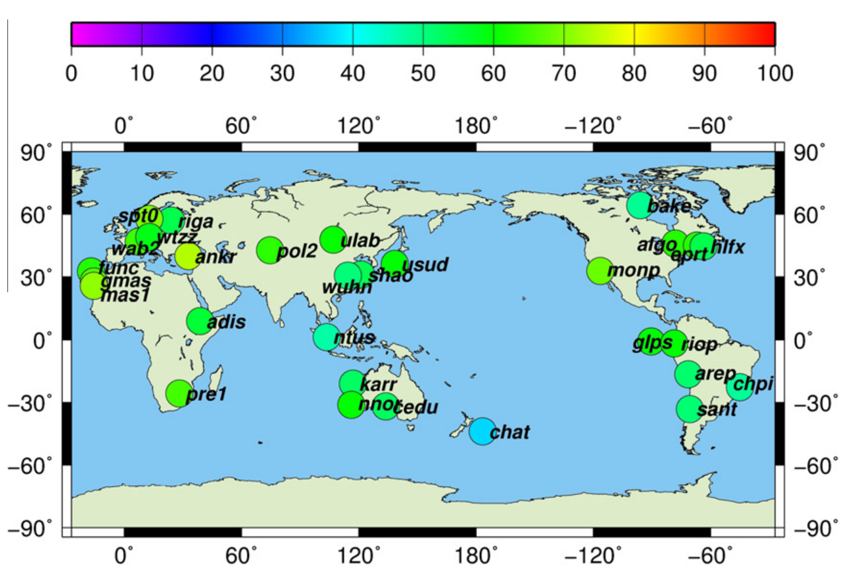

Fig. 9. The average accuracy improvement of global 30 stations in east direction.

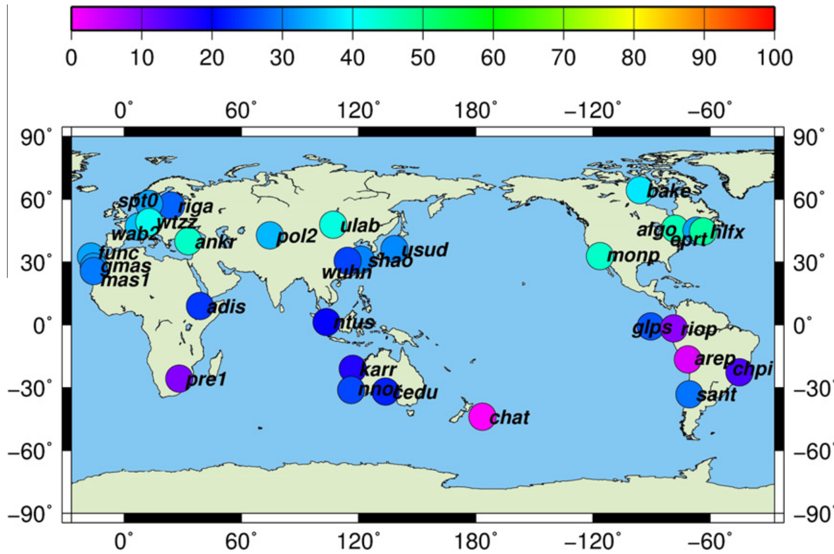

Fig. 10. The average accuracy improvement of global 30 stations in north direction.

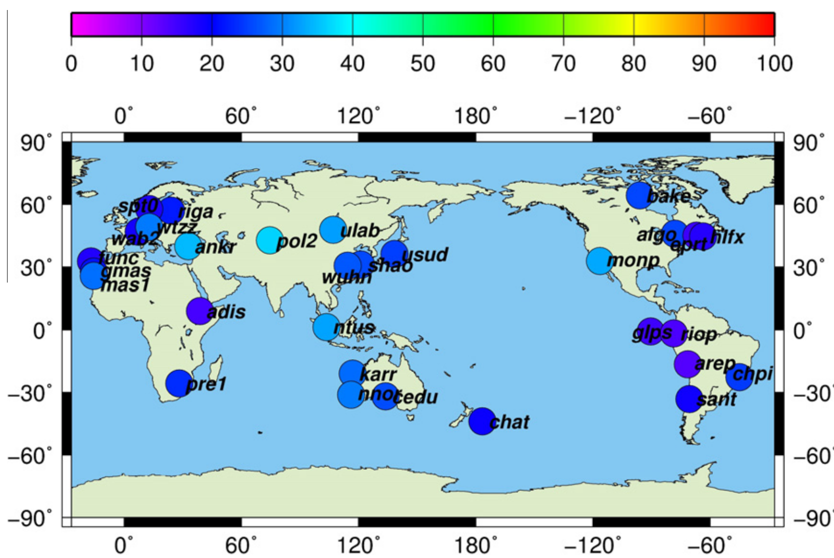

Fig. 11. The average accuracy improvement of global 30 stations in up direction.

in upward direction for most stations, improvement ranges from 15.1% to 35.5%. The improvement in north direction is not so much the same for different stations, as seen in Fig. 10. There are 4 stations i.e. CHAT, PRE1, AREQ and RIOP whose improvement is below 10%, while there are 6 stations whose improvement is over 40%. It may be explained that the position accuracy in north is reasonably higher than east and vertical for traditional float PPP solution. Finally, the average improvement for all stations is 58.2% in east, 28.3% in north and 23.8% in up, respectively.

4.3. Kinematic result comparison between float and fixed solution

In this part, we just demonstrate kinematic solutions by using static data of an IGS station to simulate the kinematic case since the true position is known. Fig.12 shows the positioning bias of forward filtering kinematic float solutions for station ALGO with 5 s sampling rate on DOY 1 of 2010. Fig.13 shows the coordinate bias for the ambiguity fixed solution for a time interval of 2 h. In those two figures, the first hour includes the initialization process while the second hour is the results after the solution has completely converged. It can be seen that the fixed solution can shorten the convergence time to centimeter level significantly comparing with the float solution. We check the initialization time to centimeter level and find that 1425 s are needed for fixed solutions, 2350 s for float solutions. In addition, it is clear that the bias in the horizontal component of the fixed solution is also reduced and smoother than for the float solution, especially for the east component. Overall, comparing the results of the

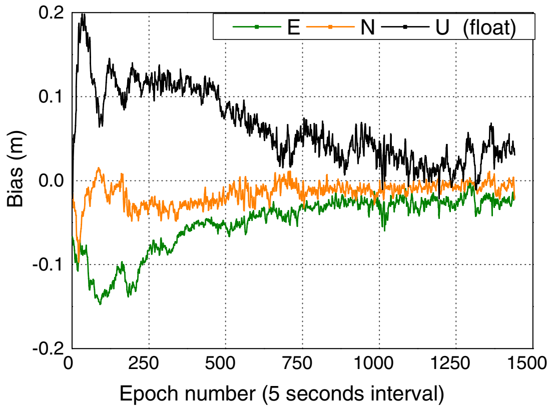

Fig. 12. Bias of kinematic float solutions.

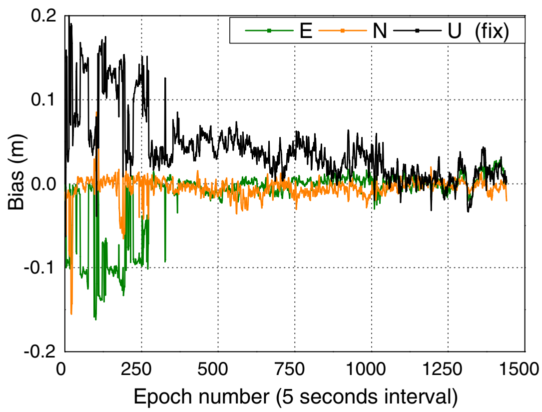

Fig. 13. Bias of kinematic fixed solutions.

Table 2
RMS of positioning bias of float and fixed solution on six stations in DOY 1 after initialization.

RMS	Float (mm)			Fixed (mm)		
	E	N	U	E	N	U
NNOR (Oce)	24.0	16.7	56.0	13.0	15.1	42.5
ALGO(Nor Ame)	23.2	21.9	37.6	11.6	13.1	28.6
ADIS (Afr)	24.1	12.0	32.9	12.4	10.5	38.9
SANT(Sou Ame)	22.9	14.5	46.0	14.8	13.3	40.6
SPT0 (Eur)	13.3	11.9	19.6	7.8	10.4	21.8
SHAO (Asi)	21.8	22.5	34.0	13.5	17.4	33.4
MEAN	21.6	16.6	37.7	12.2	13.3	34.3

second hour in Fig.12 and Fig.13, we can conclude that fixing the ambiguity contributes significantly to improving the positioning accuracy in kinematic PPP.

Furthermore, Table 2 summarizes the RMS of bias of kinematic position estimates with one hour observation at six stations from different continent in DOY 1 of 2010. These statistics are computed by using the position estimates of the second hour. The mean positioning accuracy can be improved from 21.6 mm, 16.6 mm and 37.7 mm for the float solution to 12.2 mm, 13.3 mm and 34.3 mm for the fixed PPP solution in the east, north and vertical component respectively.

5. Conclusions

In this paper, comprehensive experiments demonstrate that ZD UFOs can be estimated reasonably well in an adjustment procedure. Applying these ZD UFOs to correct the ZD carrier phase observations allows to recover the integer ZD ambiguities, and then more accurate PPP solution can be achieved with hourly dataset by fixing the ambiguity to integer. 30 stations from different continents except Antarctica are taken as PPP user stations. Observations on DOY 1, 100, 200 and 300 in 2010 are processed to test the global hourly ambiguity-fixed PPP service in both static and kinematic mode. Static results show that an accuracy of better than 1 cm in horizontal and about 1–2 cm in vertical could be achieved for the fixed solution. Comparing with the float solution, the accuracy of the fixed solution can be improved on average by 58%, 28%, and 24% in east, north and vertical component respectively. A kinematic experiment also shows that the positioning accuracy can be improved from 21.6 mm, 16.6 mm and 37.7 mm to 12.2 mm, 13.3 mm and 34.3 mm in the east, north and vertical component by fixing the ambiguities. It is confirmed that the daily wide-lane UFO and ten-minute-arc narrow-lane UFO products of all satellites together with satellite orbit and clock products can be generated in a standardized format for global PPP users to provide hourly centimeter-level positioning service. It should be noticed that the experiments above are conducted under normal ionosphere conditions. If severe ionospheric disturbance is present, the hourly ambiguity-fixed PPP solution probably does not work, more investigation should be done about this issue in the future.

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