Ambiguity Resolution in Precise Point Positioning with Hourly Data

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Abstract: Precise Point Positioning (PPP) has become a recognized and powerful tool for scientific analysis of Global Positioning System (GPS) measurements. Until recently, ambiguity resolution at a single station has been considered difficult, due to the non-integer uncalibrated hardware delays (UHD) originating in receivers and satellites. Fortunately, recent studies show that if these UHD can be determined precisely with a network in advance, then ambiguity resolution at a single station is possible. In this study, the method proposed by Ge et al (2007) is adopted with a refinement in which the fractional parts of single-difference narrow-lane UHD for a satellite pair are determined within each full pass over a regional network. This study uses the European Reference Frame Permanent Network (EPN) to determine these UHD from Day 245 to 251 in 2007, and 27 IGS stations inside and outside the EPN are used to conduct ambiguity resolution in hourly PPP. It is found that the total hourly position accuracy is improved from 3.8 cm, 1.5 cm and 2.8 cm to 0.5 cm, 0.5 cm and 1.4 cm in East, North and Up, respectively, for the stations inside the EPN. For the stations outside the EPN, some of which are even over 2000 km away from the EPN, their total hourly East, North and Up position accuracies still achieve 0.6 cm, 0.6 cm and 2.0 cm, respectively, when the EPN-based UHD are applied to the ambiguity resolution at these stations. Therefore, it is feasible and beneficial for the operators of GPS networks, such as the providers of PPP-based online services, to provide these UHD estimates as an additional product to allow users to conduct ambiguity resolution in PPP.

Keywords: Ambiguity resolution; Precise Point Positioning; Hourly solution; Uncalibrated hardware delay

1 INTRODUCTION

In recent years, Precise Point Positioning (PPP) (Zumberge et al 1997; Kouba et al 2001) using Global Positioning System (GPS) measurements has been recognized as a valuable tool in a number of, for example, meteorological and geophysical applications (Bar-Sever et al 1998; Chen 2004; Kouba 2005). It is well-known that PPP can provide mm-level accuracy for static positioning over daily observation periods, however, many emerging applications require high accuracy (e.g. sub-cm) positioning with sub-daily frequency.

Unfortunately, so far it has been a great challenge for PPP to achieve sub-cm position accuracy within short observation periods such as a few hours. Usually only sub-dm accuracy is achievable with hourly data in static PPP (Tétreault et al 2005; Ghoddousi-Fard et al 2006). As a comparison, static relative positioning usually needs at least two to four hours of data to reach sub-cm accuracy in the horizontal plane and better than 2 cm accuracy in the vertical direction on short baselines (< 20 km) after ambiguity resolution (Eckl et al 2001; Soler et al 2006). Nevertheless, little progress has been made on ambiguity resolution at a single station, which has been prohibiting further accuracy improvement in PPP, especially within short observation periods. It should be noted that the ambiguity resolution in some PPP software is actually based on inter-station baselines, although PPP is applied to data processing (Webb et al 1997). For briefness, 'PPP ambiguity resolution' represents 'ambiguity resolution at a single station', and 'PPP ambiguities' represents 'ambiguities in the ionosphere-free combination observable' throughout this study.

The main barrier that prevents PPP ambiguity resolution is the non-zero and non-integer uncalibrated hardware delay (UHD) originating both in receivers and satellites, which are eliminated by double differencing in relative positioning. These offsets in the frequency oscillators are usually considered very stable or even constant (Gabor et al 1999; Ge et al 2007), and hence they cannot generally be separated from the integer ambiguities in a least squares adjustment. It should be noted that only the fractional parts of UHD are of importance for ambiguity resolution, but we still denote them as UHD.

Only in recent years has PPP ambiguity resolution gained significant progress. Gabor et al (1999) reported perhaps the first trial to resolve ambiguities at a single station. They tried to estimate the wide-lane (WL) and narrow-lane (NL) UHD within a network using single-difference (SD) ambiguities between satellites. It was found that the SD WL UHD were stable over several months, but the instability of SD NL UHD finally made the ambiguity resolution unsuccessful. Ge et al (2007) proposed a similar method, but absorbed the SD WL UHD into the SD NL UHD. Their method was assessed in a global network using daily data, in which 80% of independent SD ambiguities were resolved and the position accuracy in East was improved by around 30%. On the instability of SD NL UHD, Ge et al proposed that these should be estimated every 15 minutes. For comparison, Laurichesse et al (2007) mixed the zero-difference (ZD) NL UHD with the satellite clock estimates. Collins (2008) adopted a similar method to this, but based on a decoupled clock model. Laurichesse et al reported that around 88% of ZD NL ambiguities can be resolved using daily data. It is worth indicating that all above methods are based on ZD data processing, and that SD ambiguities, instead of being estimated directly, are composed of ZD ambiguity estimates.

This study assesses the contribution of ambiguity resolution to PPP within short observation periods. Because of convergence issues, hourly data is used which is also usually the case in tests of PPP online processing services (Tétreault et al 2005; Ghoddousi-Fard et al 2006). A refinement to the method of Ge et al is proposed for the computation of SD NL UHD, using a regional network, before the accuracy improvement of hourly position and zenith tropospheric delay (ZTD) estimates after PPP ambiguity resolution is shown and discussed.

2 PPP AMBIGUITY RESOLUTION

The innovative method for PPP ambiguity resolution proposed by Ge et al (2007) is illustrated in Figure 1. It can be seen that this method is divided into four sequential steps which are carried out separately within two modules. In the module of network solution, SD WL and NL UHD are determined based on the real-valued ambiguity estimates. Then in the module of single point solution, these UHD are used to recover the integer property of the PPP ambiguities. It should be emphasized that the accuracies of SD NL UHD affect the accuracies of position estimates in fixed solutions.

The biggest problem in PPP ambiguity resolution is the determination of the SD NL UHD. Due to their instability when they were estimated in a global network over 24 hours, Ge et al proposed to compute them every 15 minutes to retain a high estimation precision. By contrast, we propose that the SD NL UHD for a satellite pair can be determined precisely within each continuous tracking period by a regional network, i.e., each full pass by this satellite pair over the regional network. In this manner there are usually only two or three SD NL UHD estimates for a satellite pair within 24 hours.

To test this refinement, daily observations of approximately 80 stations from the European Reference Frame (EUREF) Permanent Network (EPN) (Bruyninx et al 2001) (Figure 2) covering Day 245 to 251 in 2007 were used to determine the SD WL and NL UHD. The final products of satellite orbits and clocks, ERP (Earth Rotation Parameters) and DCB (Differential Code Bias) from CODE (Centre of Orbit Determination in Europe) (Beutler et al 1999) were used. The IERS Conventions 2003 (McCarthy et al 2004) for station displacement, the absolute antenna phase centres, and the phase wind-up corrections were also considered. The elevation cut-off angle was set to seven degrees. The estimated parameters included the static positions, receiver clocks, ZTD, horizontal troposphere gradients and PPP ambiguities. It should be noted that all cross-correlation receivers were excluded for their relatively poor pseudo-range qualities (Ge et al 2007).

Figure 3 shows the estimates and the formal precisions (3σ) of all SD NL UHD with respect to satellite PRN01 on Day 245 in 2007. This figure illustrates that these estimates for a satellite pair can differ significantly within 24 hours. Most formal precisions (3σ) are less than 0.1 cycles. When these EPN-based SD NL UHD are applied to the EPN stations, 90.9% and 97.1% of all defined and independent SD NL ambiguities can be resolved, respectively, using a sequential bias fixing strategy (Dong et al 1989; Ge et al 2005) with a round-off criterion of 0.15 cycles. These validate the refined strategy for the determination of SD NL UHD using a regional network.

3 RESULTS AND DISCUSSION

3.1 DATA AND MODELS

To evaluate the benefits of PPP ambiguity resolution, 27 test stations from the IGS network (Figure 2) are selected to conduct hourly PPP from Day 245 to 251 in 2007. 12 of them are distributed evenly within the coverage of the EPN (i.e. inside-EPN stations), and the rest are scattered outside the EPN (i.e. outside-EPN stations) in roughly all directions. The models adopted at these stations are the same as those at the EPN stations except for horizontal troposphere gradients, which cannot be estimated precisely within a one-hour period. It should be noted that those solutions with data of less than half an hour or without sufficient satellites (less than five) during more than half an hour are removed. To assess the accuracy of the hourly position and ZTD estimates, their daily estimates are used as the ground truth instead of the EUREF estimates in order to avoid potential biases between our solutions and the EUREF ones (Teferle et al 2007). A 10 cm threshold is chosen in terms of the 3D position accuracy in published hourly PPP tests (Tétreault et al 2005; Ghoddousi-Fard et al 2006) to identify outlier solutions. For these, even correct ambiguity resolution cannot reduce the 3D position accuracy to less than 10 cm. These outlier solutions only amount to 0.8% in all hourly solutions.

PANDA (Positioning And Navigation Data Analyst) software (Liu et al 2003), developed at Wuhan University in China, is used for PPP ambiguity resolution. It is a versatile tool for the analysis of satellite positioning and navigation data, and currently serves as a fundamental platform for scientific studies in China.

3.2 STRATEGY OF AMBIGUITY SEARCH AND VALIDATION

The resolution of SD WL ambiguities follows the sequential bias fixing strategy. However, due to the strong correlation among the hourly PPP ambiguities, a search strategy based on the LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) method (Teunissen 1994) is applied to resolve the SD NL ambiguities.

Integer ambiguities at lower elevation angles are usually affected by higher noise levels and larger biases than those at higher elevation angles, which will increase the likelihood of incorrect ambiguity resolution. Hence, only the ZD PPP ambiguities with averaged elevation angles over 15 degrees are used to compose SD ambiguities. If an independent set of SD NL ambiguities cannot all be fixed to integers reliably, at most two of them will be excluded and the search is repeated until the validation tests are passed, unless all possible integer candidates are rejected.

One ambiguity validation test is based on the compatibility between the unit variances of the fixed and float solutions, which is $\frac{\sigma_{fixed}^2}{\sigma_{float}^2} < \zeta$ where σ_{float}^2 and σ_{fixed}^2 denote the unit variances of the float and fixed solutions, respectively, and ζ is a critical criterion. It is worth noting that if F_α (F-distribution with the confidence level α) is used as ζ as usual (Teunissen et al 1997), this test usually cannot be met in this study, even when correct integer candidates have been found. Under this circumstance, Teunissen et al (1997) suggested that more observations should be used. Nevertheless, it can be argued that F_α may be too conservative for this study. Thus ζ is set empirically to 1.8, but actually the averaged $\frac{\sigma_{fixed}^2}{\sigma_{float}^2}$ of all hourly solutions is smaller than 1.3.

The other test is the well-known ratio test (Euler et al 1990) in which the critical criterion is selected as 3, which is generally deemed as conservative in ambiguity validation (Han 1997). The ratio value is an index of the reliability of ambiguity resolution.

3.3 HOURLY PPP AT INSIDE-EPN STATIONS

Table 1 shows the fixing rate of independent SD ambiguities, the ratio value in PPP ambiguity resolution and the RMS of position and ZTD estimates with respect to the ground truth in the float and fixed solutions for each inside-EPN station during the seven days. It can be seen that the fixing rate of each station is larger than 96% and the total fixing rate of all stations is more than 98%. Moreover, all their ratio values are bigger than 30 with an average of over 40, which are much larger than the chosen critical criterion. Therefore, it is confirmed that the EPN-based UHD are quite effective for the ambiguity resolution at those inside-EPN stations.

In addition, Table 1 shows that the total RMS of the positions are improved significantly from 3.8 cm, 1.5 cm and 2.8 cm to 0.5 cm, 0.5 cm and 1.4 cm in East, North and Up, respectively, with a 3D total accuracy improvement of 68.3%. The horizontal accuracies of all stations are at the sub-cm level and most of them are below 5 mm. The accuracy in East reveals the most improvement of 86.7%, which was also found by Ge et al (2007). The vertical accuracies of most stations are better than 1.5 cm with a total improvement of 50.0%. The relatively lower improvement in Up is related to its relatively small correlation with the ambiguities (Blewitt 1989). In addition, the RMS of hourly ZTD estimates are reduced by 22.2% in total after ambiguity resolution. Based on these statistics, it is demonstrated that PPP ambiguity resolution contributes significantly to the accuracy improvement of hourly position estimates.

To analyse the efficiency of ambiguity resolution, the integer ambiguity estimates derived from daily processing are used as the ground truth to identify any incorrect ambiguity resolution. The solutions with rejected ambiguity resolution are also identified. The percentages of these two types of unacceptable solutions reach 0.85% and 0.40%, respectively. This failure rate (i.e. 1.25% in total) may be related to the quality of the observation data (e.g. severe multipath effects) and the satellite products (e.g. during satellite eclipsing periods). When the observation period is prolonged to two hours, the corresponding percentages are reduced significantly to 0.20% and 0.00%, respectively. Therefore, it can be deduced that at least two hours of observations are necessary to achieve a success rate of more than 99% in PPP ambiguity resolution.

In the accepted solutions, there are still some in which the position accuracies are impaired a little after even correct ambiguity resolution (i.e. degraded solutions). The degradation of 3D position accuracies may reach up to 3 cm for the inside-EPN stations. In total, the percentage of degraded solutions in all accepted ones is 0.97%. Even if the observation period is increased to two hours, this percentage is still up to 0.91%. However, if the hourly ZTD are fixed during the estimation to accurate a priori values derived from daily estimates, this percentage is reduced significantly to only 0.15%. This fact demonstrates that ZTD is a crucial factor affecting the occurrence of degraded solutions in hourly PPP ambiguity resolution.

3.4 HOURLY PPP AT OUTSIDE-EPN STATIONS

Table 2 presents the distance of each outside-EPN station to the nearest EPN station (i.e. to-EPN distance), their fixing rates of independent SD ambiguities, their ratio values, and their RMS of position estimates with respect to the ground truth in the float and fixed solutions during the seven days. In Table 2, the outside-EPN stations are arranged according to their to-EPN distances, the average of which is approximately 2000 km.

Table 2 illustrates that the fixing rates at the outside-EPN stations fall with the increase of their to-EPN distances. When these distances are less than 2000 km, almost all fixing rates are over 95%. When these distances increase up to 3000 km, the fixing rates are reduced below 95% but still more than 90%. However, when they are over 3000 km, the fixing rates fall below 90% and even 85%. This descent is an effect of the reduced fixing rates of SD NL ambiguities, which are associated with the unavailability of SD NL UHD at the outside-EPN stations. However, this pattern is not observed in their ratio values. It can be seen that almost all ratio values are smaller than 30, with an average of about 20, which is nearly half of that for the inside-EPN stations. This fact can be explained in terms of the degraded accuracies of SD NL UHD when they are applied to the outside-EPN stations.

In addition, the position accuracy improvement also suffers slightly from the accuracy degradation of SD NL UHD. In Table 2 the total RMS of the position estimates in East, North and Up are improved from 3.7 cm, 1.5 cm and 3.2 cm in the float solutions to 0.6 cm, 0.6 cm and 2.0 cm in the fixed solutions, with a total 3D accuracy improvement of 57.9% which is about 10% lower than that in Table 1. In comparison to the inside-EPN stations, the Up accuracy is affected more obviously than the horizontal ones by the accuracy degradation of SD NL UHD. Within the outside-EPN stations this impairs the position accuracies of the stations up to 3000 km from the EPN more than those of the other stations. Nevertheless, Table 2 still suggests that the EPN-based SD NL UHD are sufficiently applicable to the outside-EPN stations even when the to-EPN distance is up to 4000 km. It should be stressed that this performance is based on the use of the final products derived from global network observations in CODE.

Moreover, Table 2 shows that the position accuracies in the fixed solutions stand at nearly the same level, despite their varying to-EPN distances. Considering the same SD NL UHD are used at these stations, this implies that the SD NL UHD accuracies do not deteriorate rapidly with the increased to-EPN distances. Therefore, it can be argued that the SD NL UHD should be quite stable within an area covering several thousands of square km in both longitudinal and latitudinal directions. This finding, to some extent, justifies the refinement in the computation of SD NL UHD used in this study.

Furthermore, of particular interest is the question as to over what area extent the SD NL UHD are still sufficiently stable. This issue is related to the efficient computation of SD NL UHD, and the position accuracy in the fixed solutions. Clarifications may be made by investigating the relationship between the position accuracy in the fixed solutions and the accuracy of the SD NL UHD estimates. However, this is beyond the scope of this paper and will be studied in future.

4 CONCLUSIONS

This study discussed the recent progress achieved in PPP ambiguity resolution. The SD WL and SD NL UHD between satellites are determined from a network before SD WL and NL ambiguity resolution are carried out sequentially at a single station. It is proposed and demonstrated in this study that the SD NL UHD can be determined precisely within each full pass of a satellite pair over a regional network, rather than every 15 minutes. This refinement seems well suited for practical use in a regional network, and its suitability on a larger or even global scale will be investigated in future.

PPP ambiguity resolution is capable of improving the position accuracy to sub-cm level in the horizontal plane and better than 2 cm in the vertical direction even when only hourly observations are used. In addition, the accuracy of hourly ZTD estimates can also be improved by roughly 20%. Nevertheless, correct PPP ambiguity resolution cannot always bring about improved accuracy of the position estimates, this being closely associated with the estimation of ZTD.

From the comparison between the inside-EPN and the outside-EPN stations, the accuracies of SD NL UHD are slightly degraded if they are used outside the EPN. However, they are still applicable to the ambiguity resolution at the outside-EPN stations, and the position accuracy can still achieve the sub-cm level. More importantly, it can be deduced that the SD NL UHD should be quite stable within an area covering several thousands of square km. This finding may be useful when PPP ambiguity resolution is applied to a remote station which is far from any network.

Therefore, the presented technique has the potential to bring comprehensive new applications of PPP when accurate sub-daily or even hourly position estimates are required. With the envisioned availability of SD UHD as an additional GPS product on a regional scale, PPP ambiguity resolution seems a feasible endeavour which could be used in online PPP processing services.

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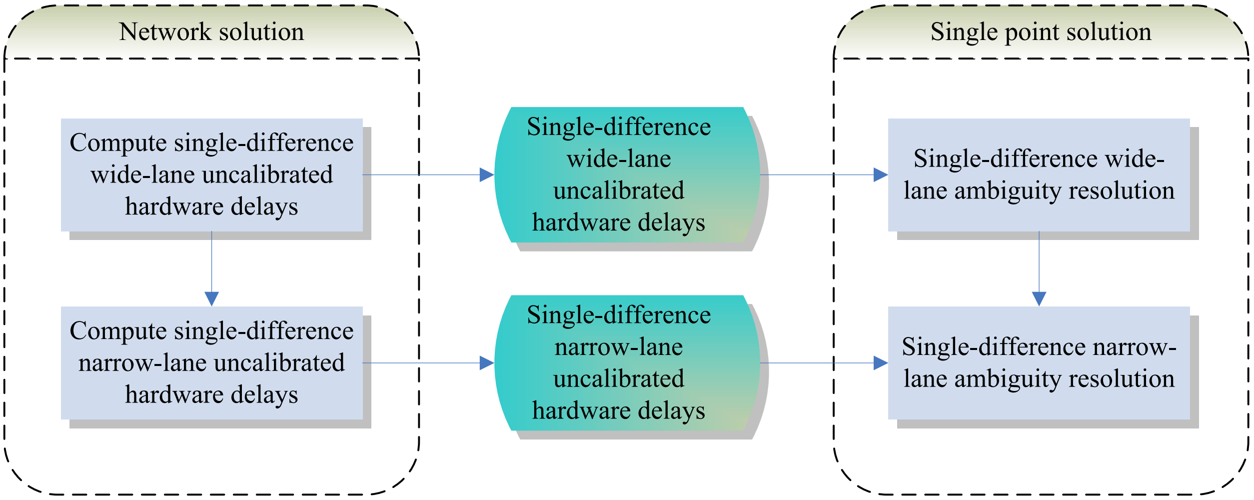

Fig. 1 Description of the procedure for ambiguity resolution at a single station

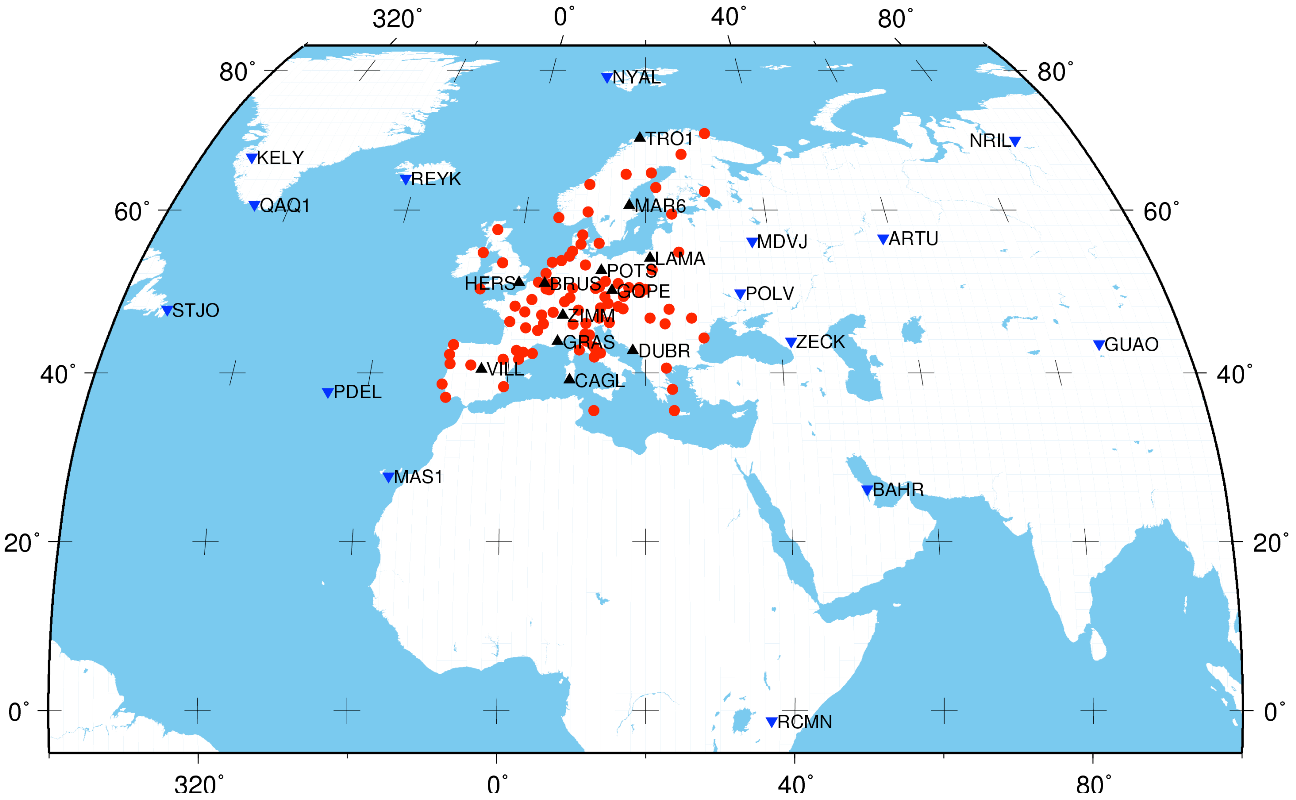

Fig. 2 Station distribution. The red circles denote the EPN stations used for the determination of uncalibrated hardware delays (UHD) whilst the triangles denote the IGS stations for testing the hourly PPP ambiguity resolution. The black triangles denote the stations inside the EPN while the inverted blue triangles denote the stations outside the EPN

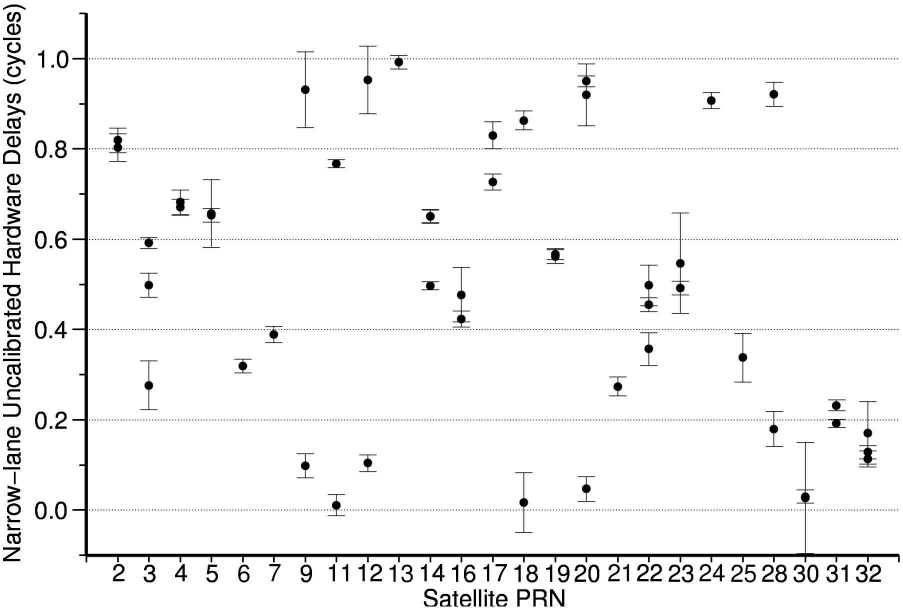

Fig. 3 SD NL UHD estimates for all satellites with respect to PRN01 on Day 245 in 2007. The solid dots denote the estimates whilst the error bars are their formal precision (3σ)

Table 1 Fixing rates and ratio values of independent SD ambiguities in PPP ambiguity resolution for all inside-EPN stations, and their RMS of position and ZTD estimates in the float and fixed solutions with respect to the daily estimates

Station	**Fixing rate (%)**	**Ratio**	**Float solutions (cm)**					**Fixed solutions (cm)**				
			East	**North**	**Up**	**3D**	**ZTD**	**East**	**North**	**Up**	**3D**	**ZTD**
BRUS	98.4	52.2	3.3	1.4	2.8	4.5	0.55	0.4	0.4	1.3	1.5	0.40
CAGL	96.2	32.1	4.8	1.9	4.0	6.5	0.74	1.0	0.8	2.0	2.4	0.57
DUBR	98.2	36.2	5.6	1.9	3.3	6.8	0.49	0.4	0.6	1.3	1.4	0.36
GOPE	97.1	33.8	4.5	1.8	2.9	5.7	0.61	0.3	0.4	1.5	1.6	0.52
GRAS	98.9	58.3	2.4	1.1	2.4	3.6	0.48	0.4	0.4	1.3	1.4	0.39
HERS	99.7	61.4	4.1	1.3	2.4	5.0	0.49	0.3	0.4	1.2	1.3	0.35
LAMA	99.1	40.1	3.8	1.5	2.6	4.8	0.56	0.7	0.6	1.4	1.7	0.46
MAR6	98.6	32.9	3.3	1.6	2.3	4.3	0.49	0.7	0.7	1.5	1.8	0.42
POTS	99.0	38.6	3.6	1.4	2.8	4.8	0.50	0.3	0.4	1.3	1.4	0.41
TRO1	98.4	32.3	1.5	1.1	1.8	2.6	0.34	0.3	0.3	1.2	1.3	0.27
VILL	98.5	33.5	4.1	1.5	3.4	5.6	0.70	0.4	0.5	1.5	1.6	0.49
ZIMM	98.8	42.0	3.1	1.2	2.4	4.1	0.48	0.4	0.4	1.2	1.3	0.39
Total	**98.4**	**41.1**	**3.8**	**1.5**	**2.8**	**5.0**	**0.54**	**0.5**	**0.5**	**1.4**	**1.6**	**0.42**

Table 2 Distance of each outside-EPN station to the EPN, their fixing rates of independent SD ambiguities and ratio values in PPP ambiguity resolution, and their RMS of position estimates in the float and fixed solutions with respect to the daily estimates

Station	**Distance (km)**	**Fixing rate (%)**	**Ratio**	**Float solutions (cm)**				**Fixed solutions (cm)**			
				East	**North**	**Up**	**3D**	**East**	**North**	**Up**	**3D**
POLV	660.7	97.9	21.6	4.0	1.9	3.0	5.3	0.4	0.5	1.7	1.8
MDVJ	769.9	93.5	26.1	3.1	1.2	2.2	4.0	0.4	0.7	1.6	1.8
ZECK	1034.4	95.0	14.7	5.3	1.9	4.5	7.2	0.7	1.0	2.5	2.8
NYAL	1100.6	97.0	37.2	1.0	0.9	1.6	2.1	0.3	0.4	1.5	1.5
REYK	1208.4	97.0	13.5	4.0	2.0	3.2	5.5	0.5	0.6	2.2	2.3
MAS1	1222.3	96.6	19.9	5.4	1.4	4.6	7.2	0.5	0.6	2.5	2.6
PDEL	1421.6	98.5	22.6	3.8	1.5	3.6	5.5	0.6	0.5	1.9	2.1
ARTU	1724.5	95.8	20.8	3.7	2.0	3.2	5.3	0.5	0.6	1.6	1.8
NRIL	2116.4	93.7	24.8	1.7	1.6	2.2	3.2	0.5	0.5	1.7	1.8
QAQ1	2368.2	93.4	26.1	2.3	1.2	2.1	3.3	0.4	0.5	1.7	1.9
KELY	2554.2	94.5	20.8	1.9	1.2	2.3	3.2	0.7	0.6	1.7	1.9
BAHR	2708.5	91.6	17.3	4.5	1.3	4.7	6.6	0.9	0.6	2.5	2.7
STJO	3264.0	85.7	22.5	3.8	1.9	3.1	5.3	0.8	0.8	2.1	2.4
GUAO	4116.3	84.3	13.6	4.5	1.4	3.4	5.8	0.8	0.7	1.8	2.1
RCMN	4201.5	72.1	21.9	3.7	1.1	3.1	5.0	0.7	0.7	2.4	2.6
Total		**92.4**	**21.6**	**3.7**	**1.5**	**3.2**	**5.2**	**0.6**	**0.6**	**2.0**	**2.2**