Hourly Precise Point Positioning with Ambiguity Resolution

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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, integer ambiguity resolution for PPP at a single GPS station has been considered difficult, due to the non-zero and non-integer uncalibrated hardware delays (UHD) originating in the receivers and satellites. It is shown that if these UHD can be accurately determined with a regional network, for example the European Reference Frame (EUREF) Permanent GPS Network (EPN), then ambiguity resolution applied to a single station is possible. Seven days of data from 17 IGS stations located in Europe are used to implement hourly PPP with ambiguity resolution in this study. This reveals that the total 3D position accuracy is improved by up to 66% after ambiguity resolution. Moreover, the accuracies of the East, North and Up components are improved from 3.9 cm, 1.5 cm and 3.0 cm to 0.5 cm, 0.5 cm and 1.6 cm, respectively. When zenith tropospheric delays (ZTD) are fixed to daily estimates, the accuracies of Up components are improved further to 1.8 cm and 0.7 cm in the float and fixed solutions, respectively. Furthermore, when ZTD are estimated and the observation period is increased to two hours, the 3D accuracy of float solutions is improved from 5.1 cm to 3.0 cm with minimal improvement in the fixed solutions. In addition, the total accuracy of ZTD estimates is improved by up to 20% after PPP ambiguity resolution. It is suggested that operators of GPS networks and/or providers of PPP-based online GPS processing services on a national or regional scale could provide the required UHD estimates as an additional GPS product to allow users to resolve integer ambiguities in PPP using a single station.

KEYWORDS: Precise Point Positioning; Ambiguity resolution; Uncalibrated hardware delay; Hourly data

INTRODUCTION

Precise Point Positioning (PPP) (Zumberge et al 1997; Kouba et al 2001) has been recognized as an efficient tool that can be applied to engineering surveying and scientific research for its no need of any reference stations and as comparable precision as that of double-difference technique. Thus the quality of positioning results can still be guaranteed whilst both the cost and workload are reduced. It is well-known that PPP can provide mm-level accuracy for static stations over daily observation periods. However, high accurate positioning with sub-daily frequency, is often a necessity for many monitoring applications.

Unfortunately, so far it has been a great challenge for PPP to achieve sub-cm accuracy within short observation periods such as one hour. Usually, PPP can only reach sub-dm accuracy with hourly data in a static mode (Tétreault et al 2005; Ghoddousi-Fard et al 2006). It is well-known that ambiguity resolution can increase the redundancy of observations and remove the correlations between the ambiguity and position parameters, which improves the accuracy of the positioning results.

However, there were no methods to fix the ambiguity parameters at a single station to integers, which has been prohibiting further accuracy improvement in PPP, especially within short observation periods. In this study 'PPP ambiguity resolution' is used to represent 'ambiguity resolution at a single station' for briefness.

The main barrier that prevents PPP ambiguity resolution is the existence of non-zero and non-integer uncalibrated hardware delays (UHD) originated in receivers and satellites (Teunissen et al 1997; Gabor et al 1999; Ge et al 2007). They can hardly be separated from the integer ambiguity in a least squares adjustment. Thus, the PPP ambiguities are always recognized as real-valued parameters in most published literatures. Consequently, integer ambiguity resolution in PPP is considered impossible by many researchers.

Recently, several literatures have introduced some innovative methods to resolve ambiguities at a single station. Gabor et al (1999) reported perhaps the first trial to fix ambiguities at a single station, aiming at applying their method to PPP. They proposed a theoretical model, but the final ambiguity resolution failed because of the instability of narrow-lane (NL) UHD. Eight years later, Ge et al (2007) used a global network to assess the contribution of ambiguity resolution to the daily positioning quality in PPP. It was reported that 80% of independent ambiguities could be fixed to integers successfully and the accuracy of the East component was improved by around 30%. Laurichesse et al (2007) resolved the PPP ambiguities and reported that around 88% of the ambiguities within one day could be resolved successfully.

In this study, the authors aim at assessing the contribution of ambiguity resolution to PPP within short observation periods in a regional network. On account of PPP convergence issues, hourly data is used here as is usually done in tests of PPP online processing services (Tétreault et al 2005; Ghoddousi-Fard et al 2006). At first, the high efficiency of ambiguity resolution based on single stations is presented in hourly data processing. Finally, the improvement in both the accuracies of hourly position estimates and of hourly zenith tropospheric delay (ZTD) estimates after PPP ambiguity resolution is shown and discussed.

AMBIGUITY RESOLUTION AT A SINGLE STATION

This study implements the method proposed by Ge et al (2007) for PPP ambiguity resolution. Their method is divided into four steps in which the first two steps are conducted in network solutions, and the other two are accomplished at the user end. More details can be found in Ge et al (2007) and Geng et al (2008).

In this study, LAMBDA (Least-squares AMBiguity Decorrelation Adjustment) method (Teunissen 1994) is used to search for the optimal integer candidate of NL ambiguities, due to the strong correlation between them, especially when short period of data is used. LAMBDA method is capable of speeding up the search for the optimal integer ambiguity candidates through the decorrelation of the ambiguity parameters and the sequential conditional least squares estimation (De Jonge et al 1996).

For the ratio test that is used to validate the optimal integer candidates, the critical ratio value chosen in this study as a threshold is 3. The larger the ratio value is, the more reliable the integer candidates are.

DATA AND MODELS

Daily observations of approximately 80 stations from the European Reference Frame (EUREF) Permanent Network (EPN) (Bruyninx et al 2001) (Figure 1) covering a week from Day 245 to 251 in 2007 were used for the determination of the WL and NL UHD. The final satellite orbit and clock products from the Centre of Orbit Determination in Europe (CODE) (Beutler et al 1999) were fixed during PPP. Differential Code Biases (DCB), also provided by CODE, IERS Conventions 2003 (McCarthy et al 2004) for station displacement and absolute antenna phase centre variation were used for consistency with IGS standards. Phase wind-up corrections due to the relative movement between the antennas of receivers and satellites were also taken into account (Wu et al 1993). The elevation cut-off angle was set to seven degrees and elevation dependent weighting was applied. The estimated parameters included the static positions, receiver clocks, ZTD, horizontal troposphere gradients and PPP ambiguities. The sampling rate was 30 seconds. It should be noted that all cross-correlation (CC) receivers were excluded for their inconsistent pseudo-range qualities with those of other types of receivers (Ge et al 2007; Laurichesse et al 2007).

To evaluate the benefits of PPP ambiguity resolution within short observation periods, 17 stations from the European IGS network are selected to conduct hourly PPP from Day 245 to 251 in 2007 (Figure 1). It should be emphasized that these stations are not used for the determination of the UHD. They are evenly distributed over Europe and there are roughly 168 hourly solutions for each station. The models adopted for hourly PPP are the same as those for

EPN stations. However, horizontal troposphere gradients are not estimated in hourly PPP, for they cannot be determined well within the one-hour period. The parameters modelled are listed in Table 1.

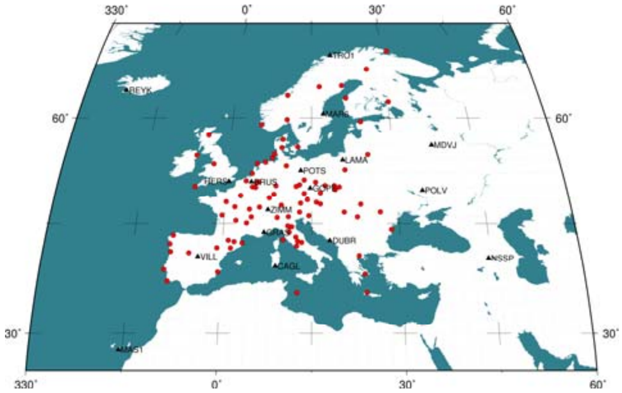

Fig. 1 Station distribution. The red circles denote the EPN stations used for the determination of fractional parts of uncalibrated hardware delays, whilst the black triangles denote the European IGS stations for testing the hourly PPP with ambiguity resolution

Table 1 Parameters Modelled in Hourly PPP

Parameters	Model & A Priori Constraint
Static position	1 meter for each component
Receiver clock	White noise, 9000 meters
ZTD	Constant within 1 hour, 20cm, Niell mapping function
Ambiguity	10000 cycles

To assess the accuracy improvement of the hourly position estimates after PPP ambiguity resolution, the daily position estimates are used as ground truth, and not the EUREF estimates, in order to avoid potential biases between the solutions of this study and the EUREF ones. It is well-known that PPP solutions can be affected by inconsistencies in the implementation of physical models in different software and by differences related to the adopted reference frames (Teferle et al 2007).

The ZTD and length of observation period are the two crucial factors influencing the accuracy of position estimates and the efficiency of ambiguity resolution. In this study, hourly solutions with ZTD estimated are denoted as solution type EST ZTD (1 HR). Meanwhile for comparison, hourly solutions with ZTD fixed to precise a priori estimates derived from daily processing are denoted as solution type FIX ZTD (1 HR). In addition, two-hourly PPP solutions with ZTD estimated are represented by solution type EST ZTD (2 HR). These three solution types use the same models during data processing. It should be noted that those solutions with data of less than half of the required duration or without enough satellites during most of the period (less than five) are removed.

PANDA (Positioning And Navigation Data Analyst) software (Liu et al 2003) which was originally developed at Wuhan University, China, is used for PPP ambiguity resolution. It is a versatile tool for the data analysis of satellite positioning and navigation systems and is now able to serve as a fundamental platform for scientific studies (Shi et al 2006). It has recently been equipped with a PPP ambiguity resolution module (Ge et al 2007).

EFFICIENCY OF AMBIGUITY RESOLUTION

High efficiency of PPP ambiguity resolution can validate the method demonstrated in this study and the reliability of the UHD. More than 97% of independent ambiguities of all stations for all three solution types are fixed to integers successfully, which confirms the reliability and accuracy of the WL and NL UHD determined based on the EPN when they are applied to European IGS stations. The fixing rates of both FIX ZTD (1 HR) and EST ZTD (2 HR) are slightly higher than that of EST ZTD (1 HR), which demonstrates that both ZTD and length of observation period influence the efficiency of ambiguity resolution.

Figure 2 presents the mean ratio values during the seven days for each station in the solution type EST ZTD (1 HR). It can be seen that all mean ratio values are bigger than 10, which shows that the ambiguity resolution in all test stations is fairly reliable. Furthermore, the mean ratio values of all stations are 35.4, 39.8 and 48.0 for EST ZTD (1 HR), FIX ZTD (1 HR) and EST ZTD (2 HR), respectively. This confirms that the reliability of ambiguity resolution can be improved when ZTD are fixed to precise a priori values derived from daily processing or when longer observation periods are used.

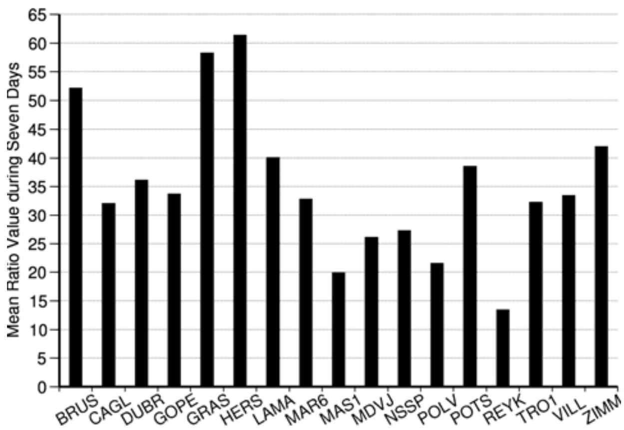

Fig. 2 Mean ratio values during seven days for each station

Figure 3 presents the percentages of solutions with successful, rejected and wrong ambiguity resolution in each station for EST ZTD (1 HR), FIX ZTD (1 HR) and EST ZTD (2 HR), respectively. In this study, successful solutions denote those in which the optimal integer candidates are correct when compared with those derived from daily processing. Rejected solutions denote those in which the validation tests fail without any ambiguities fixed to integers. Wrong solutions denote those in which some ambiguities are fixed to wrong integers. From Figure 3, the total percentages of successful solutions achieve more than 98% for these three solution types whilst those of rejected and wrong ones are all below 1%. Compared with the performance of EST ZTD (1 HR), when ZTD are fixed to precise a priori values, as is done in FIX ZTD (1 HR), the percentage of successful solutions is increased with those of rejected and wrong ones decreased. Furthermore, when ZTD are estimated and two hours of observations are used, as is depicted in EST ZTD (2 HR), further improvement is obtained.

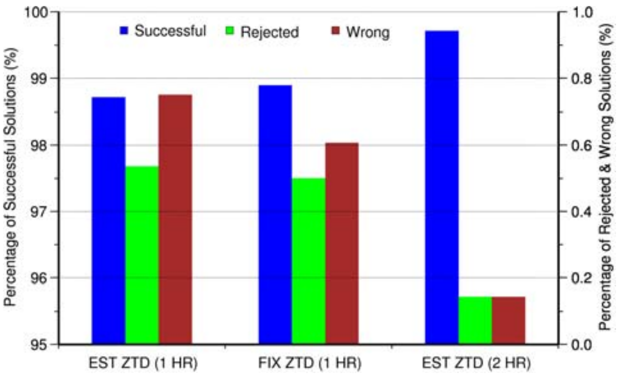

Fig. 3 Percentages of PPP solutions with successful (refers to left vertical axis), rejected and wrong (both refer to right vertical axis) ambiguity resolution in three solution types. Note the difference in the scale of the left and right vertical axis

It is worth noting that PPP solutions with rejected or wrong ambiguity resolution are all related to severely biased float position estimates with respect to the ground truth in this study. These biased PPP solutions may be caused by severe multipath effects or satellite eclipsing periods. The mean 3D RMS of the float position estimates in rejected solutions with respect to the ground truth are 27.2 cm, 15.6 cm and 13.7 cm and those in wrong solutions are 24.2 cm, 22.6 cm and 13.5 cm for EST ZTD (1 HR), FIX ZTD (1 HR) and EST ZTD (2 HR), respectively. Therefore, ambiguity estimates of these solutions may be biased, resulting in the failure of PPP ambiguity resolution.

ACCURACY IMPROVEMENT IN POSITION ESTIMATES

In the above successful solutions, there are cases in which the 3D RMS of both the float and fixed position estimates are larger than 10 cm. Again they might be related to multipath effects or satellite eclipsing periods. Hence, these solutions are removed as bad solutions and are not taken into account in the assessment of the contribution of PPP ambiguity resolution. A threshold of 10 cm is chosen on account of the usual accuracy of hourly float position estimates (Tétreault et al 2005; Ghoddousi-Fard et al 2006) and of five times the accuracy of the position estimates in the fixed solutions (Table 2).

Table 2 presents the RMS of the float and fixed position estimates with respect to the ground truth for seven days for each station for solution type EST ZTD (1 HR). It should be noted that only the accepted solutions are used to yield this table. It can be seen that after PPP ambiguity resolution the total RMS are improved by 87.2%, 66.7% and 46.7% in the East, North and Up components, respectively. The accuracies of the horizontal components even achieve sub-cm level. In total, the 3D RMS is improved from 5.1 cm to 1.7 cm, which is an improvement of 66.1%. It is demonstrated that PPP ambiguity resolution contributes significantly to accuracy improvements of position estimates within short observation periods.

Table 2 RMS of the float and fixed position estimates with respect to the daily estimates in the solution type EST ZTD (1 HR) (cm)

Station	Float solutions				Fixed solutions			
	E	N	U	3D	E	N	U	3D
BRUS	3.3	1.4	2.8	4.5	0.4	0.4	1.3	1.5
CAGL	4.8	1.9	4.0	6.5	1.0	0.8	2.0	2.4
DUBR	5.6	1.9	3.3	6.8	0.4	0.6	1.3	1.4
GOPE	4.5	1.8	2.9	5.7	0.3	0.4	1.5	1.6
GRAS	2.4	1.1	2.4	3.6	0.4	0.4	1.3	1.4
HERS	4.1	1.3	2.4	5.0	0.3	0.4	1.2	1.3
LAMA	3.8	1.5	2.6	4.8	0.7	0.6	1.4	1.7
MAR6	3.3	1.6	2.3	4.3	0.7	0.7	1.5	1.8
MAS1	5.4	1.4	4.6	7.2	0.5	0.6	2.5	2.6
MDVJ	3.1	1.2	2.2	4.0	0.4	0.7	1.6	1.8
NSSP	3.8	1.3	3.1	5.1	0.5	0.5	1.8	1.9
POLV	4.0	1.9	3.0	5.3	0.4	0.5	1.7	1.8
POTS	3.6	1.4	2.8	4.8	0.3	0.4	1.3	1.4
REYK	4.0	2.0	3.2	5.5	0.5	0.6	2.2	2.3
TRO1	1.5	1.1	1.8	2.6	0.3	0.3	1.2	1.3
VILL	4.1	1.5	3.4	5.6	0.4	0.5	1.5	1.6
ZIMM	3.1	1.2	2.4	4.1	0.4	0.4	1.2	1.3
Total	**3.9**	**1.5**	**3.0**	**5.1**	**0.5**	**0.5**	**1.6**	**1.7**

Sometimes the position accuracy may be impaired to some extent even after successful ambiguity resolution. In this study, these solutions are denoted as degraded solutions and the decrement of position accuracy is denoted as degraded accuracy. It should be clarified that when this decrement of position accuracy is less than 1cm or both the 3D accuracies of float and fixed position estimates are better than 2cm, this solution is not considered as significant or a real degraded one. These threshold values are chosen in terms of the approximately 2-cm accuracy of the position estimates in the fixed solutions in Table 2.

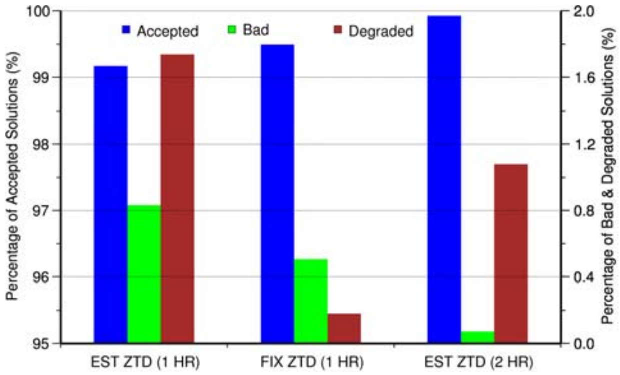

Fig. 4 Percentages of the accepted (left vertical axis), bad and degraded (both right vertical axis) solutions in the successful solutions in three solution types. Note the difference in the scale of the left and right vertical axis

Figure 4 shows the percentage of the accepted, bad and degraded solutions in the above successful solutions for each station in EST ZTD (1 HR), FIX ZTD (1 HR) and EST ZTD (2 HR), respectively, together with the mean and maximum degraded accuracies, which are all smaller than 5 cm. The total percentages of accepted solutions are all more than 99% for these three solution types whilst those of bad solutions are all less than 1%. Compared with the performance of EST ZTD (1 HR), when ZTD are fixed to precise a priori values, as is done in FIX ZTD (1 HR), the percentage of accepted solutions is increased with that of bad ones decreased. Furthermore, when ZTD are estimated and two hours of observations are used, as is depicted in EST ZTD (2 HR), further improvement is obtained. Regarding degraded solutions, on the contrast, FIX ZTD (1 HR) contributes much more than EST ZTD (2 HR) to reducing the percentage of degraded solutions. Moreover, in both solution types EST ZTD (1 HR) and EST ZTD (2 HR), the accuracies of vertical components are sure to be affected much more than those of horizontal ones in all degraded solutions. These confirm that ZTD is a crucial factor affecting the occurrence of degraded solutions.

Table 3 presented the total accuracy improvements of the position estimates after ambiguity resolution for the three solution types. Compared with the performance of EST ZTD (1 HR), when ZTD are fixed to precise a priori values, the accuracies of the Up components are improved from 3.0 cm to 1.8 cm in float solutions and from 1.6 cm to 0.7 cm in fixed solutions. However, the horizontal components reveal minimal improvements in both float and fixed solutions. Furthermore, when ZTD are estimated and the observation period is increased to two hours, all three components achieve significant improvement with the 3D RMS even being improved by 41.2% in the float solutions. However, only minimal improvement can be observed in the fixed solutions.

Table 3 Total RMS of float and fixed position estimates with respect to the daily estimates in EST ZTD (1HR), FIX ZTD (1 HR) and EST ZTD (2 HR) (cm)

Solution type	Float solutions			Fixed solutions		
	E	N	U	E	N	U
EST ZTD (1 HR)	3.9	1.5	3.0	0.5	0.5	1.6
FIX ZTD (1 HR)	3.7	1.5	1.8	0.5	0.6	0.7
EST ZTD (2 HR)	2.1	0.9	1.9	0.4	0.4	1.1

ACCURACY IMPROVEMENT IN ZTD ESTIMATES

With a significant improvement in the position estimates after ambiguity resolution, the accuracies of ZTD estimates are also improved even within short observation periods. In the following comparison, the daily ZTD estimates after ambiguity resolution are chosen as the ground truth. Figure 5 shows the RMS of the ZTD estimates with respect to the ground truth in float and fixed solutions for solution type EST ZTD (1 HR). It should be noted that only the ZTD estimates of the accepted hourly solutions are used. It can be seen that there is an improvement in the ZTD estimates for each station after ambiguity resolution with the total RMS for all stations reduced from 5.9 mm to 4.7 mm, indicating an improvement of 20.3%.

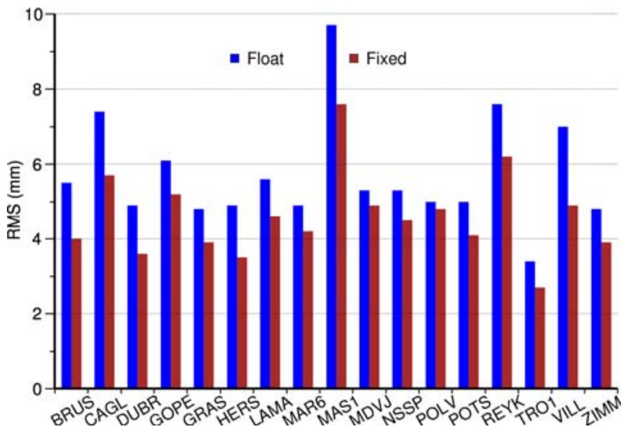

Fig. 5 Total RMS of hourly ZTD estimates with respect to the daily ZTD estimates for the float and fixed hourly PPP solutions (mm)

CONCLUSIONS

This study discussed recent progress made in PPP ambiguity resolution. The wide-lane (WL) and narrow-lane (NL) uncalibrated hardware delay (UHD) are determined from a network before the WL and NL ambiguity resolution are carried out sequentially for the testing stations that are selected from 17 European IGS stations.

When these UHD are applied to these testing stations for hourly PPP solutions, around 98% of independent ambiguities can be resolved. Due to the short observation periods used, there are still ambiguity resolutions which are rejected or even wrong in the hourly solution when ZTD are estimated, although their percentages are only 0.5% and 0.8%, respectively. When ZTD are fixed to precise a priori values derived from daily processing, these can be reduced further. Furthermore, when ZTD are estimated and the observation period is increased to two hours, both percentages are reduced significantly to about 0.1%. Meanwhile, the percentage of bad solutions is also reduced from 0.8% to 0.1%.

It has been shown that ambiguity resolution at a single station can improve the 3D position accuracy by 66.1% in hourly PPP. The horizontal accuracy even achieves sub-cm level whilst the vertical accuracy is better than 2 cm. When ZTD are fixed to daily estimates, the overall vertical total accuracy is improved by 40.0% in float solutions and 56.3% in fixed solutions, respectively, but with a minimal improvement in the horizontal accuracy. Furthermore, when ZTD are estimated and two hours of data are used, only the float solutions can reach a significant accuracy improvement of about 41.2%. In addition, ZTD estimates achieve an accuracy improvement of roughly 20.3% with hourly data after PPP ambiguity resolution.

However, ambiguity resolution at a single station cannot always guarantee an accuracy improvement even though the integer candidates are correct. This is related to the high correlation between ZTD and the Up component of the position estimates. When ZTD are fixed to those derived from daily processing, the occurrence of degraded solutions is reduced to a great extent from 1.8% to 0.5% in successful hourly solutions.

The performance of hourly PPP solutions demonstrates the significant contribution of ambiguity resolution at a single station. This fact may lead to comprehensive new applications of PPP in engineering and the Earth science when accurate and precise sub-daily or even hourly update frequencies for position and ZTD estimates are required.

With the envisioned availability of the UHD on regional or global scale as an additional GPS product, next to the already available satellite orbits and clocks, PPP with ambiguity resolution at a single station seems a feasible endeavour. These UHD products could be provided by the operators of GPS networks or online PPP processing services on a regional or national scale.

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REFERENCES

Beutler G, Rothacher M, Schaer S, Springer T, Kouba J, Neilan RE (1999) The international GPS service (IGS): an interdisciplinary service in support of earth sciences. Adv Space Res 23(4):631-635

Bruyninx C, Becker M, Stangl G (2001) Regional densification of the IGS in Europe using the EUREF permanent GPS network (EPN). Physics and Chemistry of the Earth Part A. 26(6-8):531-538

De Jonge P, Tiberius C (1996) The LAMBDA method for integer ambiguity estimation: implementation aspects. LGR-Series No.12, Delft University of Technology

Gabor MJ, Nerem RS (1999) GPS carrier phase ambiguity resolution using satellite-satellite single difference. In: Proceedings of ION GPS 99, Sept. 14-17, Nashville, TN, USA

Ge M, Gendt G, Rothacher M, Shi C, Liu J (2007) Resolution of GPS carrier-phase ambiguities in precise point positioning (PPP) with daily observations. Journal of Geodesy. Doi:10.1007/s00190-007-0187-4

Geng J, Meng X, Teferle N, Dodson A, Ge M, Shi C, Liu J (2008) Performance of hourly precise point positioning with ambiguity resolution. In: Proceedings of ION GPS 2008, Sept. 16-19, Savannah, Georgia, USA

Ghoddousi-Fard R, Dare P (2006) Online GPS processing services: an initial study. GPS solutions. 10(1):12-20

Kouba J, Héroux P (2001) Precise point positioning using IGS orbit and clock products. GPS solutions. 5(2):12-28

Laurichesse D, Mercier F (2007) Integer ambiguity resolution on undifferenced GPS phase measurements and its application to PPP. In: Proceedings of ION GNSS 2007, Sept. 25-28, Fort Worth, TX, USA

Liu J, Ge M (2003) PANDA software and its preliminary result of positioning and orbit determination. Journal of Nature Science of Wuhan University. 8(2B):603-609

McCarthy DD, Petit G (2004) IERS Conventions (2003). IERS technical note No. 32

Niell AE (1996) Global mapping functions for the atmospheric delay at radio wavelengths. Journal of Geophysical Research. 101(B2):3227-3246

Shi C, Geng J, Liu J, Ge M (2006) Integrated adjustment of LEO and GPS with PANDA in Precision Orbit Determination. In: Proceedings of ION GNSS 2006, Sept. 26-29, Fort Worth, TX, USA

Teferle FN, Orliac EJ, Bingley RM (2007) An assessment of Bernese GPS software precise point positioning using IGS final products for global site velocities. GPS solutions. 11(3):205-213

Tétreault P, Kouba J, Héroux P, Legree P (2005) CSRS-PPP: an internet service for GPS user access to the Canadian Spatial Reference Frame. Geomatica. 59(1):17-28

Teunissen PJG (1994) A new method for fast carrier phase ambiguity estimation. Proceedings IEEE Position, Location and Navigation Symposium, Las Vegas, NV, April 11-15, pp: 562-573

Teunissen PJG, Kleusberg A (1997) GPS for Geodesy (2nd Edition). Springer-Verlag, Berlin, Heidelberg, New York

Wessel P, Smith WHF (1998) New, improved version of generic mapping tools released. EOS Trans, AGU 79(47):579

Wu JT, Wu SC, Hajj GA, Bertiger WI, Lichten SM (1993) Effects of antenna orientation on GPS carrier phase. Manuscripta Geodaetica. 18(2):91-98

Zumberge JF, Heflin MB, Jefferson DC, Watkins MM, Webb FH (1997) Precise point positioning for the efficient and robust analysis of GPS data from large networks. Journal of Geophysical Research. 102(B3):5005-5017