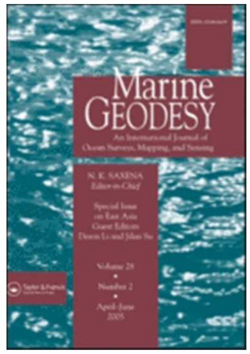


Performance of Real-time Precise Point Positioning (PPP)

Journal:	*Marine Geodesy*
Manuscript ID:	UMGD-2011-0041.R2
Manuscript Type:	Research paper
Keywords:	Absolute position < General Keywords, GPS < General Keywords, Global Ionosphere Map < Geodetic Theory & Applications

Performance of Real-time Precise Point Positioning (PPP)

Junping Chen[1], Haojun Li[1], Bin Wu[1], Yize Zhang[1,2], Jiexian Wang[2], Congwei Hu[2]

[1]Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, P.R. China
[2]Department of Surveying and Geo-informatics Engineering, Tongji University, Shanghai, 200092, P.R. China)

Corresponding author: Prof. Dr. Junping Chen
E-mail: junping.chen@shao.ac.cn
Tel: ++86(0)21-64386191 ext. 637
Fax: ++86(0)21-64386191 ext. 637
Address: 80, Nandan Road, 200030, Shanghai, P.R. China

E-mail of other authors:
Dr. Haojun Li: yanlhjch@126.com
Prof. Bin Wu: bwu@shao.ac.cn
Mr. Yize Zhang: zhyize@163.com
Prof. Jiexian Wang: wangjiexian@tongji.edu.cn
Prof. Congwei Hu: cwhu@tongji.edu.cn

The IGS Real-time Pilot Project (IGS-RTPP) provides real-time precise orbits and clocks, which support real-time positioning for single stations over large areas using the Precise Point Positioning (PPP) technique. This paper investigates the impact of real-time orbits, network configuration and analysis strategies on real-time PPP implementation and demonstrates the real-time PPP performance. One month of data from the IGS network is analyzed in a real-time simulation mode. Results reveal that: 1) In clock estimation, differential approaches are much more efficient than the zero-differenced approach; 2) The precision of IGS Ultra rapid (IGU) orbits could meet the IGS-RTPP requirement for precise clock estimation and PPP positioning; 3) Considering efficiency and precision, a network with 50 stations is recommended for the IGS-RTPP. It is demonstrated that the real-time satellite clock precision is 0.1 ns supporting hourly static PPP with a mean precision of 2-3 centimeters in the North component and 3-4 centimeters in the other components. Kinematic PPP assessed with onboard GPS data collected from a buoy provided mean coordinate precision of 2.2, 4.2, 6.1 cm in the North, East and Up directions, compared to the RTK solutions.

Key words: Wide-Area Positioning, IGU, IGS-RTPP, PPP

1. Introduction

GPS has been applied in marine applications, e.g., Watson et al. (2011) and Crétaux et al. (2011) use GPS buoys for the measurement of in-situ sea surface height to calibrate/validate absolute altimeter biases. In most of these applications, the method of real-time kinematic (RTK) positioning (e.g., Bock et al. 2000, Rizos 2003, Rocken et al. 2004) is normally used. The RTK technique requires the installation of reference stations to provide regional correction information. The major limitation of the state-of-art network RTK systems, including latter developments, e.g., VRS (Virtual Reference System), is its rather short reference station separation. Precise Point Positioning (PPP, Zumberge et al. 1997) has demonstrated to be a valuable technique for single station positioning over continental and even global scale (Kouba 2005; Geng et al. 2009). The positioning accuracy in static PPP based on the final products from the International GNSS Service (IGS, Dow et al. 2005) can reach a few millimeters with daily observations and a few centimeters with hourly observations (Geng et al. 2009). Kinematic PPP using IGS final products normally needs a convergence-period of 15~20 minutes after which the precision at cm level can be obtained.

Following the availability of real-time precise GPS satellite orbit and clock products from the IGS Real-time Pilot Project (IGS-RTPP, Caissy 2006), the interest in the PPP technique for real-time kinematic positioning has increased as a potential next generation RTK methodology (Gao and Chen 2004). The PPP technique overcomes the station separation limitation of the RTK technique and therefore has valuable applications for user positioning and navigation over remote areas and ocean waters. Applying the PPP technique, the user needs only a single GPS receiver to obtain precise coordinates in real-time at any location of the globe. The accuracy of user positioning based on the PPP technique relies much on the measurements, where positioning with dual frequency observations is superior to single frequency observations, as ionosphere errors can be eliminated. Furthermore, the precision of satellite orbits and clocks are the remaining issues to deliver the required precision of PPP.

Ideally, IGS-RTPP will provide precise products supporting users around the globe with real-time PPP positioning capability, in which orbits are either from real-time estimation or IGS predictions and precise satellite clocks are estimated in real-time based on a reference network. This paper investigates key issues of the IGS-RTPP for the support of real-time PPP. In Section 2, we briefly introduce the current IGS-RTPP status. Section 3 discusses the impacts of real-time orbits, network configuration and analysis strategies on the real-time satellite clocks estimation and user static PPP positioning. In Section 4 we present Kinematic PPP results using onboard GPS data observed from a buoy. Finally, Section 5 summarizes the main findings and presents the conclusions.

2. Status of the IGS-RTPP

Since 2007, the IGS operates the IGS-RTPP. IGS-RTPP aims to acquire and distribute real-time data and products associated with GNSS satellite constellations. The primary products envisioned for the project are multi-frequency observation data and precise satellite clocks made available in real-time.

Under the IGS-RTPP collaboration, there are currently more than 100 stations providing real-time streams. Fig.1 shows a global network of about 90 stations, of which 50 stations (marked as green circles) provide real-time streams. The data from these stations is used to derive satellite clocks described in the following Sections. Fig. 1 shows also the mean latency of real-time streams recorded using the BNC client (Weber and Mervart 2008) in February 2010. The overall mean latency is around 1.5 seconds.

Figure. 1 Station distribution. The green circles denote the real-time network used in this paper for real-time clock determination. The mean observation latency of each station is plotted according to the scale. The red diamonds denote the selected IGS05 reference stations for the hourly PPP tests.

Currently, the IGS-RTPP has seven analysis centers (ACs) providing real-time clocks and two centers working on real-time clock combinations. The current precision of real-time satellite clocks is reported to be 0.2ns in RMS and 0.1ns in standard deviation.

3. Issues affecting IGS-RTPP products

Each IGS-RTPP analysis center differs in their analysis approaches, namely processing strategies, orbits and network configurations. This Section investigates the impacts of these variables on the estimated real-time products using real-time data for the month of February, 2010. In the data processing of the following sections, the 1 Hz streams from real-time stations are re-sampled at intervals of 30 seconds and archived in Rinex files (Gurtner, 1994). Data processing is performed using the LTW_BS software (Wang and Chen, 2011) developed at the Shanghai Astronomical Observatory (SHAO) and Tongji University, Shanghai.

3.1 Processing strategy

The IGS-RTPP intends to support real-time PPP, therefore, efficiency is a main requirement for each analysis center. The IGS-RTPP provides satellite clocks on an epoch-by-epoch basis, thus the processing efficiency depends much on the processing strategy implement in the analysis system. Different strategies are classified as the traditional zero-differenced (ZD), the epoch-differenced (ED, Ge et al. 2011; Chen et al. 2008, 2009) and the satellite- and epoch-differenced (SDED, Li et al. 2010) approaches. Based on the real-time network with 50 stations shown in Fig.1, Table 1 summarizes the mean processing time at each epoch and the clock precision for these three strategies. IGR orbits are used in the processing and real-time clocks are compared to the IGS final clocks; clock precision is represented by standard deviations (STD) with mean offsets removed. For user positioning and navigation, clock STD is more critical as a common offset in the satellite clocks will be absorbed by station clocks.

Table 1 Average epoch processing time and clock precision using the SDED, ED and ZD approach

Strategy	SDED	ED	ZD
Time (sec.)	0.10	0.23	3.37
STD (ns)	**0.10**	**0.12**	**0.11**

From Table 1 we see that the ZD approach takes more than 3 seconds to process one epoch for a network with 50 stations, which means that given the current computing power, users could get the precise products with a minimal delay of 4 seconds. The SDED and ED approaches are tens of times faster than the ZD approach. From the processing efficiency point of view, differential approaches could be more suitable in providing instantaneous precise satellite clocks. We notice that all three strategies achieve comparable precision at 0.1 ns which is at the same level as current official IGS-RTPP products. PPP positioning results using satellites clocks from the SDED, ED and ZD approaches show also similar positioning accuracy.

3.2 Orbits influence

Currently, most IGS-RTPP ACs fix the IGU orbits (predicted part) in their real-time analysis instead of estimating orbits. The IGU orbits are updated every 6 hours with a delay of 3 hours, where the predicted IGU orbits have a precision of few cm for the first 6 hours (Dousa, 2010). To study the impact of the latency and precision of current IGU orbits on the real-time satellite clock estimation, the same data set as in Section 3.1 is used. Data analysis is performed in a simulated epoch-wise real-time mode with real-time data streamed from IGS Rinex files. Satellite clocks are then estimated with the ED strategy by fixing IGU orbits.

In the tests, real-time orbits with different latency and update interval are used and the resulting satellite clocks are compared to the IGS final products. Table 2 shows the clock precision using different orbits, where IGU_00_03-09h, for example, is the IGU orbits issued for 00 GPST with a delay of 3 hours and its predictions from 03 hour to 09 hour are used. The mean STDs of the estimated clocks are at 0.1 ns level when prediction periods are shorter than 9 hours, which is the optimal period over which the official IGU orbits are applicable. With the orbit prediction extents to 24 hour, the precision of real-time clocks degrades to 0.2 ns. We observe also different biases using different orbits, which is actually the ED clocks offsets at the first epoch (Ge et al. 2011) that are be absorbed by user clocks in positioning. From the results of Table 2, we suggest that the precision of IGU orbits based on current updating strategy is sufficient for the IGS-RTPP.

Table 2 Clock precision under different orbits, comparing to the IGS Final clock

Orbits	IGU_00_00-03h	IGU_00_01-04h	IGU_00_03-09h	IGU_00_00-24h	IGR
Bias(ns)	**1.23**	**0.54**	**-0.25**	**1.41**	**1.20**

STD(ns)	**0.10**	**0.10**	**0.11**	**0.20**	**0.12**

3.3 Network influence

Real-time satellite clocks are the products provided to the users for PPP positioning. Within the IGS-RTPP, the number of IGS stations providing real-time streams is increasing, which could improve the real-time clock estimation. However it increases also the demand for data processing, especially computing time. In the following, we investigated the impact of network size on the precision of estimated satellite clocks and on the resulting PPP positioning.

The network described in section 2 and the orbit IGU_00_03-09h are used for each day of the month. Satellite clocks are estimated epoch by epoch using data from selected networks with a different number of globally distributed stations (from 85 to 20 as shown Table 3, where the network with 50 stations is the same as in Section 3.1 and 3.2).

Table 3 compares the estimated clocks to the IGS Final clocks. For cases with the number of stations ≥ 30, the mean biases are almost the same as the same orbits are used while the processing the different networks. The mean STDs of the estimated clocks are at the 0.1 ns level which suggests that using a network with ≥ 30 globally distributed stations is sufficient to support current IGS-RTPP requirement. In the case with 20 stations, one satellite could not be tracked for the first few hours, which introduced significant differences as shown in Table 3. In a real-time environment there are many cases of long delays or stream losses, therefore we recommend that a network with 50 stations is more suitable.

Table 3 Clock precision with different network sizes, compared to the IGS Final clock

Num.	**85**	**70**	**50**	**30**	**20**
Bias(ns)	**-0.25**	**-0.25**	**-0.25**	**-0.24**	**-0.34**
STD(ns)	**0.10**	**0.10**	**0.11**	**0.11**	**0.17**

To validate the above recommendation, we performed hourly static PPP for a subset of 41 IGS reference stations as shown in Fig. 1 (red diamond) using the estimated satellite clocks and corresponding IGU orbits. The distance between the PPP station and nearest reference station used in the clock estimation ranged from 200 km to more than 4300 km. Data from February 8, 2009 was used to estimate 24 hourly PPP solutions for each station. Two different networks were used in the real-time satellite clocks estimation, namely the NET1 the network with 85 stations and NET2 with 30 stations. To assess the hourly PPP precision and remove system biases in the comparison (Geng et al. 2009), daily PPP was also performed for these stations using the IGS final orbits and clocks to derive reference coordinates with precision of a few millimeters.

Figure 2 shows the precision of the hourly PPP results using satellite clocks estimated from a network of 30 stations. We notice that PPP precision is similar for all stations at about 2 cm in the north-south direction and 3-4 cm in the other directions. Similar precision is achieved when using the NET2. In the data analysis, outliers are identified using a 10-cm threshold which is the normal 3D position accuracy. These outlier solutions amount to around 5% of all hourly solutions. Some stations inside the so-called equatorial scintillation region (covering ±30° both sides of the earth's magnetic equator, Wanninger 1993) have more outlier solutions. These stations include REUN (in ocean), GUAM, ISPA, ASPA and THTI, GLPS (in ocean), KUNM, NKLG and KARR. The mean RMS of all PPP solutions is 2.3, 4.1, 3.7 cm in the North, East and Up directions and the mean 3D RMS is 6.1 cm.

Figure 3 compares the PPP results from the two tests with satellite clocks estimated from different networks NET1 and NET2. We notice similar hourly PPP results with mean differences of 0.1,-0.1,-0.1 cm in the North, East and Up directions, which confirms the limited impact of the number of network stations on the satellite clock estimation.

Figure. 2 Coordinate precision of static PPP using the satellite clocks estimated using a network with 30 stations and the corresponding IGU orbits. Reference coordinates are from daily static PPP estimations.

Figure. 3 Mean coordinates differences of static PPP using different satellite clocks. Satellite clocks are estimated using a network with 30 stations and 85 stations, respectively.

4. Kinematic PPP using real-time GNSS products

PPP positioning has valuable application in precise positioning in remote areas or over the oceans, where ground based RTK cannot reach. To demonstrate the application of real-time products in kinematic PPP positioning, the same data of the 41 IGS stations was analyzed in simulated real-time kinematic PPP mode using the estimated satellite clocks and corresponding orbits IGU_00_03-09h. As the stations are fixed station, we could compare the kinematic PPP results to the daily PPP results to assess the coordinate precision. Figure 4 shows the kinematic coordinate residuals compared to the daily PPP results for station BRAZ (Brasilia). Results show kinematic PPP has a convergence-period of about 20 minutes with the precision after convergence reaching 1.4, 3.2, 4.0 cm in the North, East and Up directions, respectively. We notice similar results for the other stations in the test.

Figure. 4 Kinematic coordinate differences for IGS station BRAZ in the North, East and Up directions, where the reference coordinates are from daily static PPP estimations. Gray bar indicate the first few epochs where kinematic PPP achieves convergence. The solution convergence takes 20 minutes, and the precision after convergence is of 1.4,3.2,4.0 cm in each component.

To investigate the application in truly kinematic positioning, real kinematic data from a GPS receiver onboard a buoy was analyzed. The experiment was carried out on December 8, 2004 using two dual-frequency Leica GPS receivers. One receiver was mounted on a fixed monument on the ground with known coordinates, the other GPS receiver was installed on a buoy flowing in a lake. The initial baseline length between the reference and buoy station was around 150 meters. In order to reduce the multi-path effects, cut-off elevation was set to 10 degrees during the observation and data sampling was set to 1 minutes. The observation session started around 8:00 UTC with common observation period of about 5.2 hours in duration.

Data processing was performed in a simulated real-time mode with data epoch-by-epoch streamed from the Rinex files. In the first step, satellite clocks were estimated using the data from the above mentioned IGS network with 50 stations. Kinematic PPP was then performed at the buoy station applying the estimated satellite clocks and corresponding IGU orbits. For comparison, commercial software was used to derive kinematic coordinates for the buoy using RTK method, where data of the above-mentioned reference station was used and coordinates held fixed to known values. Fig. 5 shows the buoy horizontal displacement and a time series of the height component. We observe that the biggest motion of the buoy is in the north-south direction. Short- and long-term patterns are presented in the buoy's height time-series, reflecting the pattern of the wave in the lake. Figure 6 presents the kinematic PPP coordinates residuals compared to the RTK results. We observe that kinematic PPP requires a convergence-period of around 20 minutes and its precision after convergence reaches 2.2, 4.2, 6.1 cm in the North, East and Up directions, respectively. Compared to the RTK method, the precision of the PPP approach is about two times worse but still at cm level. Furthermore, applying the PPP approach, the precision of kinematic PPP coordinates is similar at any point in the globe, thus overcomes the limits of the RTK method.

Figure. 5 Horizontal displacement and time series of height component of the buoy flowing on the river. Comparing to the given initial a priori coordinates, we observe the buoy moved at the range of [-1.9,2.3] meter in the east-west direction and of [-2.6,6.5] meter in the north-south direction and the range of the height changes is of [-3.9,-3.0] meter.

Figure. 6 Coordinate differences for the buoy in the North, East and Up directions, where the reference coordinates are from RTK estimations. Gray bar indicate the first few epochs where kinematic PPP achieves convergence. The solution convergence takes 20 minutes, and the precision after convergence is of 2.2,4.2,6.1 cm in each component.

5 Conclusion and discussion

Latency, efficiency and precision are the main concerns in real-time PPP applications. We have studied the main factors influencing the real-time products of the IGS-RTPP, including orbits precision, network configuration and analysis strategies. Results show that the precision of real-time satellite clocks is at 0.1 ns level using the IGU orbits, which in general meet requirements for real-time PPP positioning. Considering the processing efficiency and product precision, we consider a network with ~50 stations suitable for the generation of real-time products.

Hourly static PPP using real-time products gives coordinates with precision of 2-3 centimeters in the North and 3-4 centimeters in the East and Up components, for any location around the globe. Kinematic experiment using GPS data from a buoy shows that kinematic PPP convergence can be achieved in 20 minutes. After the solution convergences, the precision of 2.2, 4.2, 6.1 cm is obtained in the North, East and Up directions, respectively.

With the development of the IGS-RTPP, the availability, reliability and precision of real-time products will be improved and the application of real-time PPP will be increased. As further developments, regional troposphere and ionosphere models (Zhang and Li, 2012) could be developed and related corrections can be sent to end-users along with satellite clocks, reducing PPP convergence time while improving position accuracy.

Acknowledgments. This research is supported by 100 Talents Programme of The Chinese Academy of Sciences and the National Natural Science Foundation of China (NSFC) (No. 40974018). Acknowledgment goes to BKG for providing the open-source BNC software. Two anonymous reviewers and Associate Editor are thanked for their constructive review of this manuscript. The members of the IGS group at the GFZ are acknowledged as part of this work was carried out when the first author worked there. The figures were produced using the Generic Mapping Tools (Wessel and Smith 1998).

References

Bock, Y., R. M. Nikolaidis, P. J. de Jonge, and M. Bevis. 2000. Instantaneous geodetic positioning at medium distances with the Global Positioning System, J. Geophys. Res., 105: 28,233-28,253.

Caissy, M. 2006. The IGS Real-time Pilot Project –Perspective on Data and Product Generation. In: Streaming GNSS Data via Internet Symposium, 6-7 Feb., 2006 Frankfurt.

Chen, J., M. Ge, M. Vennebusch, et al. 2008. Progress of the real-time GNSS software development at GFZ, Oral presentation at International GNSS Service Analysis Center Workshop, Miami Beach, Florida, USA. 2-6 June, 2008.

Chen, J., M. Ge, J. Dousa, G. Gendt. 2009. Evaluation of EPOS-RT for Real-time Deformation Monitoring. Journal of Global Positioning Systems 8(1): 1-5.

Crétaux, J.-F., S. Calmant, V. Romanovski, F. Perosanz, S. Tashbaeva, P. Bonnefond, D. Moreira, C. K. Shum, F. Nino, M. Bergé-Nguyen, S. Fleury, P. Gegout, R. Abarca Del Rio, P. Maisongrande. 2011. Absolute Calibration of Jason Radar Altimeters from GPS Kinematic Campaigns Over Lake Issykkul, Marine Geodesy, 34(3-4): 291-318.

Watson, C., N. White, J. Church, R. Burgette, P. Tregoning, R. Coleman. 2011. Absolute Calibration in Bass Strait, Australia: TOPEX, Jason-1 and OSTM/Jason-2, Marine Geodesy, 34(3-4): 242-260.

Dousa, J. 2010. The impact of errors in predicted GPS orbits on zenith troposphere delay estimation, GPS Solut., 14(3): 229-239, DOI: 10.1007/s10291-009-0138-z.

Dow, J., R. Neilan, G. Gendt. 2005. The International GPS Service: celebrating the 10th anniversary and looking to the next decade. Adv Space Res 36(3): 320–326. doi:10.1016/j.asr.2005.05.125.

Gao, Y. and K. Chen. 2000. Performance Analysis of Precise Point Positioning Using Rea-Time Orbit and Clock Products, Journal of Global Positioning Systems, 3(1-2): 95-100.

Ge, M., J. Chen, J. Dousa, G. Gendt, J. Wickert. 2011. A computationally efficient approach for estimating high-rate satellite clock corrections in realtime. GPS Solut. doi: 10.1007/s10291-011-0206-z.

Geng, J., F.N. Teferle, C. Shi, X. Meng, A.H. Dodson, J. Li. 2009. Ambiguity resolution in precise point positioning with hourly data. GPS Solut 13(4): 263–270.

Gurtner, W. 1994. RINEX: The receiver-independent exchange format. GPS World, **5** 7.

Kouba, J. 2005. A possible detection of the 26 December 2004 Great Sumatra Andaman Islands earthquake with solution products of the international GNSS service. Studia Geophysica et Geodaetica 49(4): 463–483, doi:10.1007/s11200-005-0022-4.

Li, H., J. Chen, J. Wang, C. Hu, Z. Liu. 2010. Network based Real-time Precise Point Positioning. Adv Space Res 46(9): 1218-1224 .doi:10.1016/j.asr.2010.06.015.

Rizos, C. 2003. Network RTK Research and Implementation: A Geodetic Perspective, Journal of GPS, 1(2): 144 –151.

Rocken, C., L. Mervart, Z. Lukes, J. Johnson, M. Kanzaki. 2004. Testing a New Network RTK Software System, In: Proceedings of GNSS 2004. Institute of Navigation, Fairfax, 2004, 2831-2839.

Wang, J., J. Chen. 2011. Development and Application of GPS Precise Positioning Software, JOURNAL OF TONGJI UNIVERSITY (NATURAL SCIENCE),PP 764-767, 39(5),2011. (in Chinese).

Wanninger, L. 1993. Ionospheric Monitoring using IGS data, in Proceedings of the 1993 IGS Workshop, 25-26Mar., Bern, Switzerland, pp. 351-360.

Weber, G., L. Mervart. 2008. The BKG Ntrip Client (BNC). In International GNSS Service, Analysis Center Workshop 2008. Miami, Florida, 4-6 June. Available at: http://www.ngs.noaa.gov/IGSWorkshop2008/docs/RT-ops-weber1.pdf

Wessel, P., W.H.F. Smith. 1998. New, improved version of generic mapping tools released. EOS

Trans Am Geophys U 79(47): 579. doi:10.1029/98EO00426.

Zhang, X., X. Li. 2012. Instantaneous re-initialization in real-time kinematic PPP with cycle slip fixing, GPS Solutions (Online First), doi:10.1007/s10291-011-0233-9.

Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, F.H. Webb. 1997. Precise point positioning for the efficient and robust analysis of GPS data from large networks, Journal of Geophysical Research, 102(B3): 5005-5017.

2011-0041.R2 captions

Figure. 1 Station distribution. The green circles denote the real-time network used in this paper for real-time clock determination. The mean observation latency of each station is plotted according to the scale. The red diamonds denote the selected IGS05 reference stations for the hourly PPP tests.

Figure. 2 Coordinate precision of static PPP using the satellite clocks estimated using a network with 30 stations and the corresponding IGU orbits. Reference coordinates are from daily static PPP estimations.

Figure. 3 Mean coordinates differences of static PPP using different satellite clocks. Satellite clocks are estimated using a network with 30 stations and 85 stations, respectively.

Figure. 4 Kinematic coordinate differences for IGS station BRAZ in the North, East and Up directions, where the reference coordinates are from daily static PPP estimations. Gray bar indicate the first few epochs where kinematic PPP achieves convergence. The solution convergence takes 20 minutes, and the precision after convergence is of 1.4,3.2,4.0 cm in each component.

Figure. 5 Horizontal displacement and time series of height component of the buoy flowing on the river. Comparing to the given initial a priori coordinates, we observe the buoy moved at the range of [-1.9,2.3] meter in the east-west direction and of [-2.6,6.5] meter in the north-south direction and the range of the height changes is of [-3.9,-3.0] meter.

Figure. 6 Coordinate differences for the buoy in the North, East and Up directions, where the reference coordinates are from RTK estimations. Gray bar indicate the first few epochs where kinematic PPP achieves convergence. The solution convergence takes 20 minutes, and the precision after convergence is of 2.2,4.2,6.1 cm in each component.

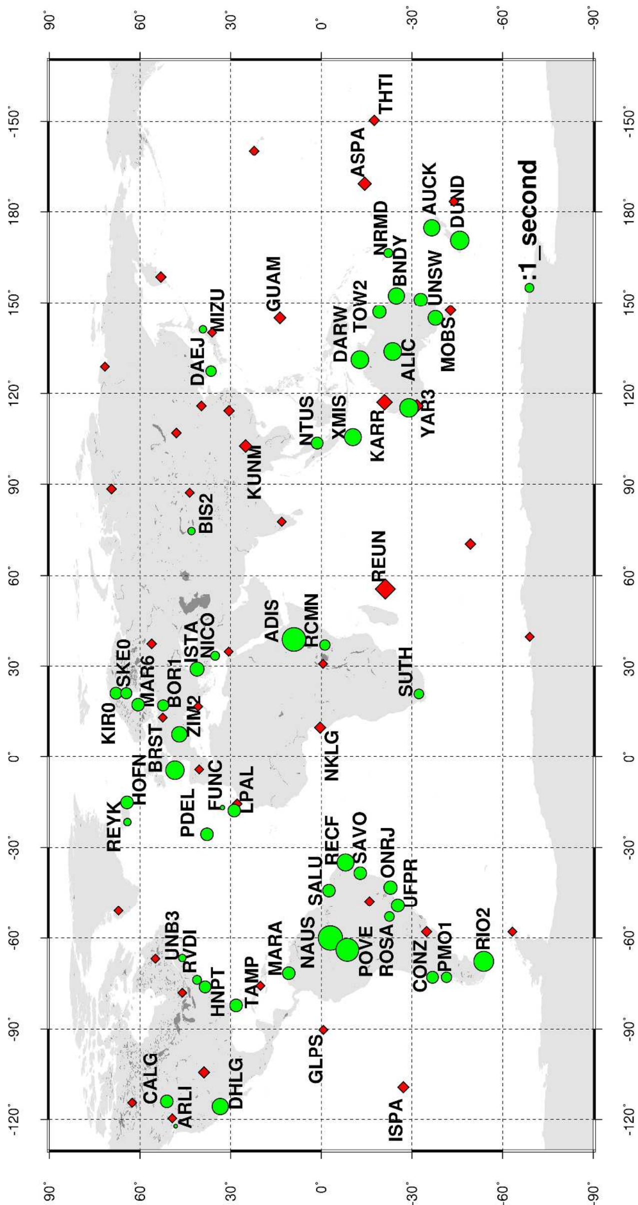
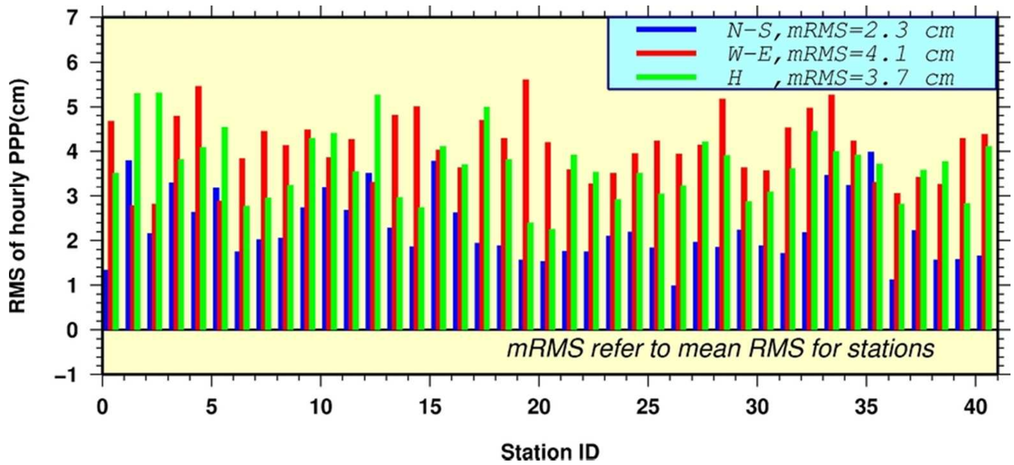
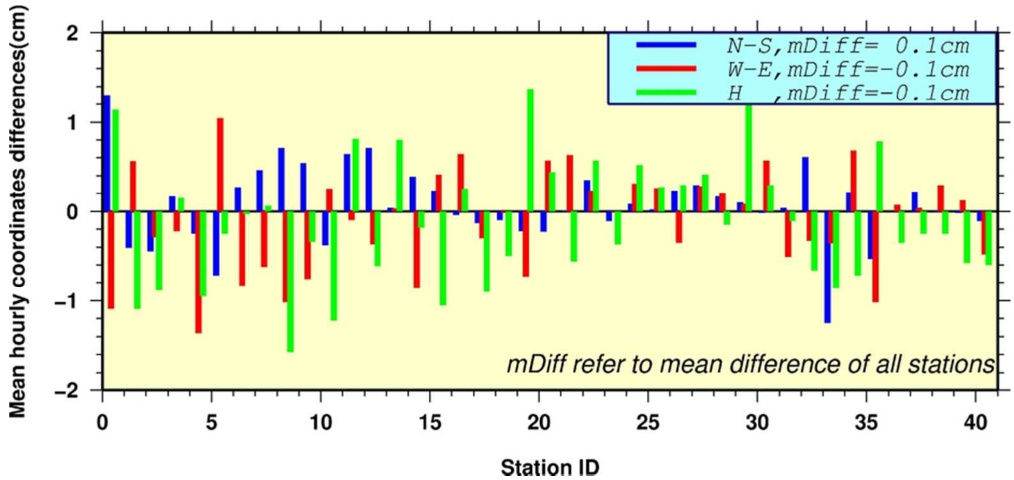


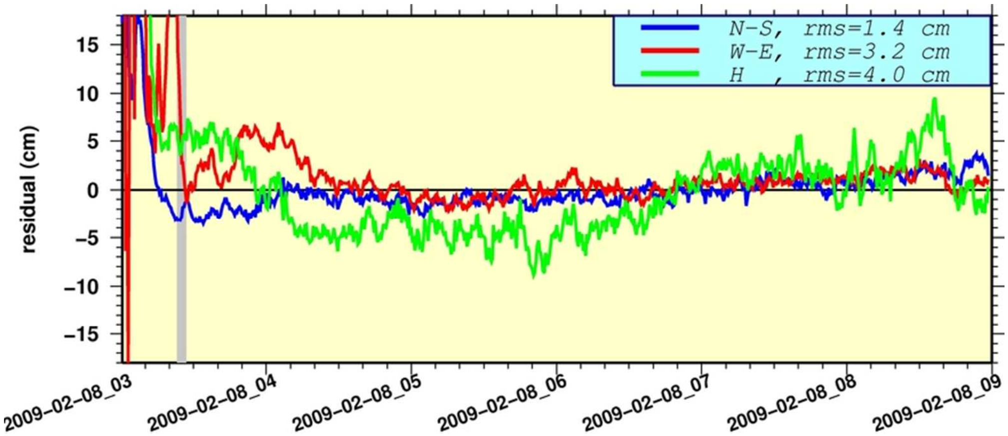
Figure 1
275x527mm (300 x 300 DPI)



76x34mm (300 x 300 DPI)



78x37mm (300 x 300 DPI)



74x31mm (300 x 300 DPI)

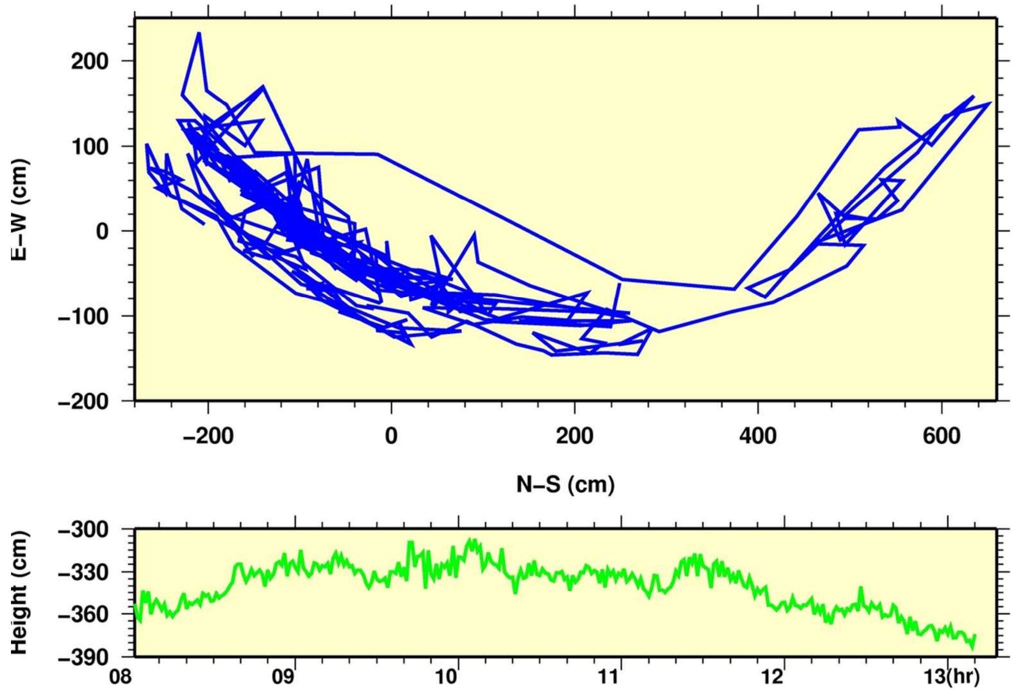
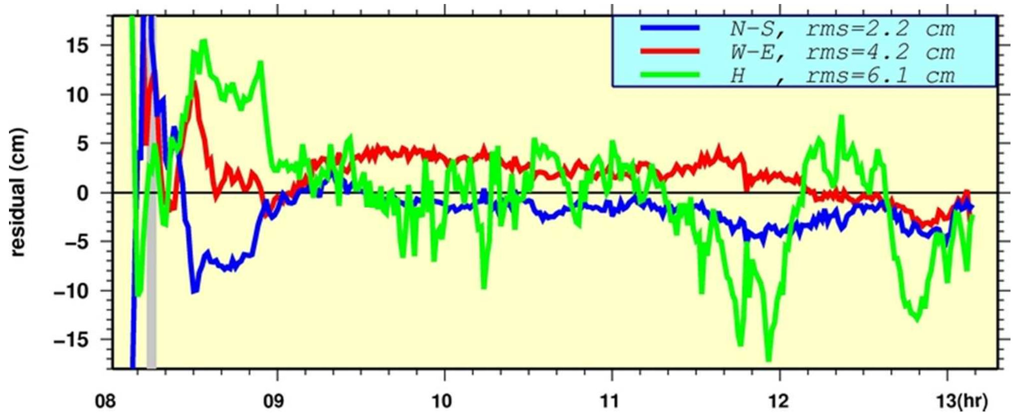


Figure 5
107x73mm (300 x 300 DPI)



69x28mm (300 x 300 DPI)