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Precise point positioning – Current state

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Abstract

The development of the permanent reference station networks all over the world has led to an increase number of real-time positioning technique users. Improved methods were developed to process the raw GNSS data, calculate the differential correction and transmit the standardized messages to the final users. A new approach, aiming for the individual GNSS error component was instated in terms of Space System Representation (SSR) concept. The expansion of the communication enabled projects such as EUREF-IP or IGS-REAL-TIME SERVICE to provide the necessary data stream over the internet. Precise point positioning (PPP) is the technique that benefits at full of this improved model.

Keywords

GNSS, Space System Representation, Precise Point Positioning.

1. Introduction

Geodesy is one of the first domains that were highly influenced by the development of satellite based navigation systems. Even though they were designed mainly for military purpose, the applicability of the Global Navigation Satellite Systems for the civil and commercial sector was significant.

The broadcasted messages were used by the civilian users from the very beginning, despite the intentional degradation of the navigation signal known as Selective Availability (SA).

The effects of SA feature were overcame by knowing that every GPS receiver from a given area is influenced almost equally, hence having a fix station (base station) with an accurately known position, the SA error value can be measured and transmitted to local GPS receiver from the nearby area in order to correct their position as well.

This approach is known as Differential GPS or DGPS and its availability worldwide has led to ineffectiveness of SA.

DGPS is also effective in mitigating several other GNSS errors, there for it continues to be used even though SA was turned off in May 2000.

A more precise technique used to correct for the important sources of GNSS errors is the Real Time Kinematics (RTK). In this case phase measurement are used instead of pseudo-random noise codes correlation. The major drawback of this method as properly aligning the navigation signals, whereas every cycle of the carrier is similar to every other. This is referred as the Integer ambiguity problem.

The differential methods can be deployed at a local scale, even by a single user, case in which the cost is higher, or in a network of reference stations that has national or even continental coverage.

The next logical step is to use the correction and products provided by a global network of reference stations and enable users to access a globally unique solution for positioning.

This stage is carried out through positioning methods like Precise Point Positioning.

2. The Concept

The different GNSS error components do have different characteristics. Satellite orbit, ionosphere and troposphere are spatially correlated and it is therefore possible to determine the effects in differential GNSS processing. However, the effects decorrelate with distance and introduce a distance dependent error into processing

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results. The clock errors are estimated or eliminated in the modeling approach of the GNSS data processing. Antenna phase variations and multipath are station dependent errors and must either be corrected or be adequately accounted for (Wübbena et al., 2005).

In general the GNSS errors can be determined based on one reference station, but the distance depending error makes the correction accurate only for the location of the reference station. Combining multiple reference stations in a network configuration with a method of interpolation, the correction can be calculated for the position of a user (rover) that is situated in the coverage area of the network. In the figure bellow is represented the principle of error interpolation in a network of reference stations.

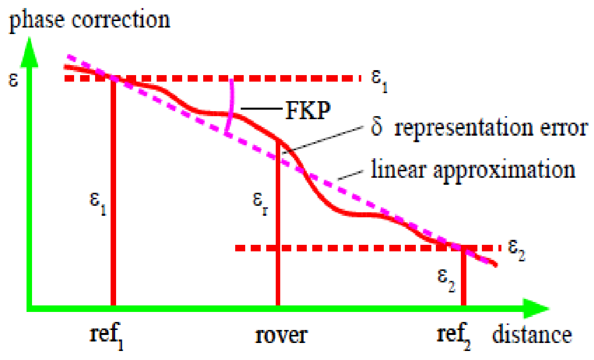


Fig. 1 RTK networking and OSR principle, representation error (FKP, VRS, PRS) for linear approximation.

For the traditional differential methods distance dependent state parameters are derived and combined with reference station observations that are transmitted to GNSS users in the field using the RTCM standards.

This approach is referred as Observation Space Representation (OSR) and is the concept currently used to provide correction to a user in GNSS based positioning.

OSR describes the cumulative influence of the errors that are affecting the navigation signal. This influence is close related to the reference station, and the satellite system signal characteristics.

OSR is the currently used method to provide correction as well in RTK network applications. Several particular methods were implemented based in this concept along the time:

- observation data + network correction: RS (Reference Station) + FKP
- network-corrected (individualized) observation data: PRS (Pseudo Reference Station) or VRS (Virtual Reference Station)
- observation data of multiple reference stations: MAC (Master-Auxiliary-Concept)

In contrast to OSR is the State Space Representation that is used for the representation of the complete GNSS state. Meaning that the state space modeling (SSSM) follows the idea to model the actual error sources instead of handling the effects of the errors as OSR currently does.

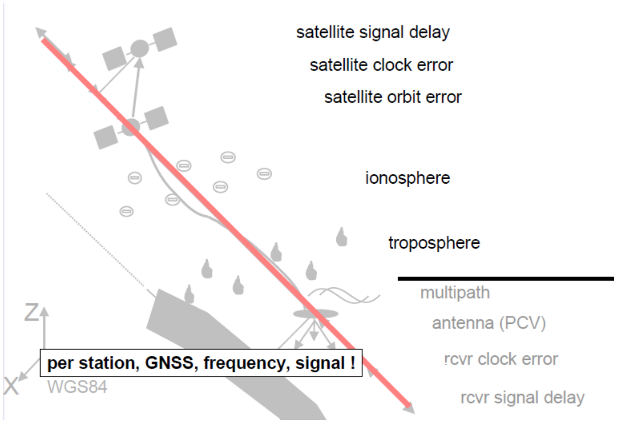


Fig. 2 Observation System Representation Schmitz, M (2010) - State Space Technology – Principle, RTCM Standardization and Examples on "GNSS-reference networks", June 2010, Hannover, page 6

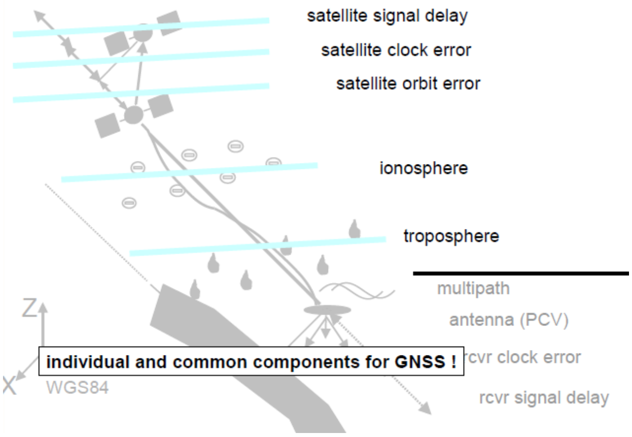


Fig. 3 State Space Representation- Schmitz, M (2010) - State Space Technology – Principle, RTCM Standardization and Examples on "GNSS-reference networks", June 2010, Hannover, page. 7.

The state space representation is a description of the actual state of the environment in which the positioning is accomplished. The state of the system is transmitted to the rover as correction parameters for individual errors. At the rover side the observation are corrected based on this parameters. Using observation from a global network of reference stations to compute the parameters gives the SSR concept a global acceptance in terms of positioning. As in the case of differential methods based on OSR, single and dual frequency application could be implemented with SSR as well.

Table 1 Comparison of different state representation techniques (++ very good, + good, - fair to bad) Wübbena,G; Schmitz,M; Bagge,A (2005) – ION GNSS-05 - PPP-RTK: Precise Point Positioning Using State-Space Representation in RTK Networks – september 2005, California, page 5.

	Representation Technique	*Broadcast*	*Covered Area*	*Bandwidth*	*Representation Error*	*Kinematic Applications*	*International Standards*
SSR	SSR	++	unlimited	++	++	++	+ / -
OSR	RS+FKP	+	100 km	+	+	++	+ (SAPOS)
	PRS+FKP	+	100 km	+	+	++	-
	PRS	-	100 km	+	+	++	-
	VRS	-	local	+	-	-	-
	MAC	+	MA stations	-	+ / -	++	++

3. The Method

At the very base of the Space State Representation is the Precise Point Positioning method.

Relevant works concerning Precise Point Positioning has been carried out along the years by:

- Zumberge et al. (1997)
- Witchayangkoon (2000)
- Kouba and Héroux (2001)
- Gao and Shen (2001),
- Bisnath et al.(2002)
- Deo et al. (2003)
- Columbo et al.(2004)
- Chen et al.(2009)
- Geng et al(2010)
- Soycan and Ata (2011)
- Martin et al. (2012)

Precise point positioning can be seen as an improved single point positioning technique that uses precise orbit and clock information instead of the broadcast data. To get this enhanced data the user must have access to the Internet. More than this only one receiver is used for positioning and no reference stations are involved in the processing. Thanks to this precise point positioning (PPP) has gained more and more popularity in the GNSS scientific community.

The performance of PPP for positioning determination has been demonstrated in various studies of the above mentioned researchers, mainly using post-mission precise orbit and clock from IGS or other organisations. PPP was originally developed for static applications, but with the improved near real-time or real-time clocks and satellites orbits, real time precision positioning was also proved to be possible.

Unlike relative positioning, common mode errors do not cancel in PPP, since is a zero-difference approach. Station movements that result from geophysical phenomena such as tectonic plate motion, Earth tides and ocean loading enter the PPP solution in full, as do observation errors resulting from the troposphere and ionosphere. Relevant satellite specific errors are satellite clocks, satellite antenna phase center offset, group delay differential, relativity and satellite antenna phase wind-up error. Receiver specific errors are receiver antenna phase center offset and receiver antenna phase wind-up (Witchayangkoon, 2000)

Dual frequency receivers are used to compensate for the ionosphere effect by modeling an ionosphere free combination of:

code pseudoranges

$$P_{IF} = \frac{f_1^2 * P_1 - f_2^2 * P_2}{f_1^2 - f_2^2} =$$

$$= \rho + cdt + d_{trop} + dm_{IF} + \varepsilon(P_{IF})$$

and carrier phases.

$$P_{IF} = \frac{f_1^2 * P_1 - f_2^2 * P_2}{f_1^2 - f_2^2} =$$

$$= \rho + cdt + d_{trop} + dm_{IF} + \varepsilon(P_{IF})$$

where,

P_{IF} is the measured pseudorange on $L_I(m)$,

Φ_{IF} is the measured carrier phase on $L_I(m)$,

ρ is the geometric range,

c is the speed of light

dt is the receiver clock error,

d_{trop} is the tropospheric delay,

f_I is the frequency of L_I,

N_1 is the integer ambiguity on L_I,

δm_{IF} is the multipath efect,

ε is the measurement noise

The clock and satellite orbit errors were removed from the equations since the use of precise ephemerides makes these parameters known quantities. Yet we must bear in mind that precise clock files are only available with rapid and final ephemeris and therefore you can expect worse accuracy with ultra-rapid ephemeris.

The unknown parameters in a PPP vector processing are the three coordinates, the tropospheric delay, receiver clock error and ambiguity term (Gao and Chen, 2004)

In the case of single frequency receivers the ionosphere effect is counteracted by applying a model for its influence.

Although accurate ionosphere models are not general available, single frequency receivers can be used for positioning in non-critical applications.

As for the tools used to accommodate PPP, several software products implementing a PPP processing strategy have been developed by government agencies, universities, industries and individuals, even some online PPP services are also available at the PPP Software Centre that is a website that was created under the auspices of the Geomatics for Informed Decisions (GEOIDE) Network of Centres of Excellence Project 31 in Canada. The website has been functioning since May 2009. The main purpose of this website is to allow access to four different PPP applications via RINEX observation files sent by e-mail. These four different services are as follows:

- The CSRS-PPP, operated by the Geodetic Survey Division of Natural Resources, Canada, uses the in-house NRCan-PPP software, employing a least-squares batch process (Héroux et al., 1993).

http://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/tools-applications/10925#ppp

- The APPS, operated by the Jet Propulsion Laboratory, United States, uses version 6.3 of the GIPSY-OASIS software (Zumberge et al., 1997).

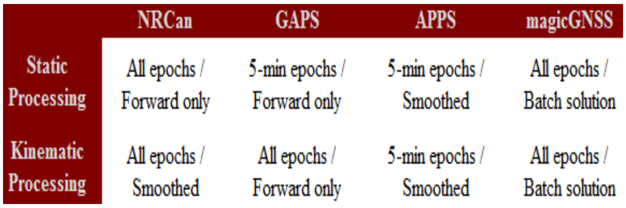
http://apps.gdgps.net/

- The GAPS, v5.5 operated by the University of New Brunswick, Canada, uses software that was originally written in MatLab but has been re-designed and re-written in C++ (Leandro et al., 2008).

http://gaps.gge.unb.ca/

- The MagicGNSS, v2.5 operated by GMV Aerospace and Defense, Spain, is based on software developed for GALILEO orbit determination and time synchronization. A batch least-squares algorithm is used to minimize measurement residuals, and to determine orbits, satellite and station clock offsets, phase ambiguities, tropospheric zenith delays and station coordinates (Píriz et al., 2008).

http://magicgnss.gmv.com/ppp/



	NRCan	GAPS	APPS	magicGNSS
Static Processing	All epochs / Forward only	5-min epochs / Forward only	5-min epochs / Smoothed	All epochs / Batch solution
Kinematic Processing	All epochs / Smoothed	All epochs / Forward only	5-min epochs / Smoothed	All epochs / Batch solution

Fig. 4 Software Characteristics and solution type offered by The PPP Software Centre

In Martín et al. (2011), a comparison of these four software tools can be found for a static PPP configuration. Also numerous tests had estimated the accuracy of PPP in kinematic applications. The software packages had evolved so that the processing can be done in post mission or in real-time, and the programs can be run in either static or kinematic mode.

Precise point positioning based on RTK networks (PPP-RTK) overcomes the limitations of ambiguity resolution, convergence time and accuracy offering centimeter-accuracy in a few seconds (Wübbena et al., 2005).

4. The Infrastructure

For more than 20 years, International GNSS Service (IGS) is the main provider for GNSS the data product. Based on a network of over 350 reference stations from more than 200 organizations IGS is the largest free-access provider of GNSS product.

Real-time Service (RTS) deliver the users GPS orbit and clock corrections that are crucial for PPP. RTS is intended to reach its full capability by the end of this year and offer data products for GLONASS observations as well. This stage is already implemented since final orbit correction for GLONASS satellites are already available with 3m accuracy and a latency of 12 – 18 days. The main characteristics of the offered products that present interest for PPP are:

- The IGS Final products have the highest quality and internal consistency of all IGS products. They are made available on a weekly basis, by each Friday, with a delay up to 13 (for the last day of the week) to 20 (for the first day of the week) days. The IGS Final products are the basis for the IGS reference frame and are intended for those applications demanding high consistency and quality.
- IGS Rapid products (IGR) The IGS Rapid products have a quality nearly comparable to that of the Final products. They are made available on a daily basis with a delay of about 17 hours after the end of the previous observation day; i.e., the IGS Rapid products are released daily at about 17:00 UTC. For most applications the user of IGS products will not notice any significant differences between results obtained using the IGS Final and the IGS Rapid products.

Nowadays over 70 satellites are already on the sky, and with the completion of the present GNSS emerging systems their number will rise up to 120 in couple of years. The development of new constellations of satellites had led to the need of expanding and updating the IGS network. From this aspect the Multi GNSS Experiment (MGEX) was born. Numbering 90 stations at the present time, MGEX will collect and analyze observation from GPS, GLONASS, and at least from one new emerging system: Gallileo or BeiDou. MGEX network is deployed around the globe in parallel with the legacy IGS network that tracks GPS and GLONASS satellites.

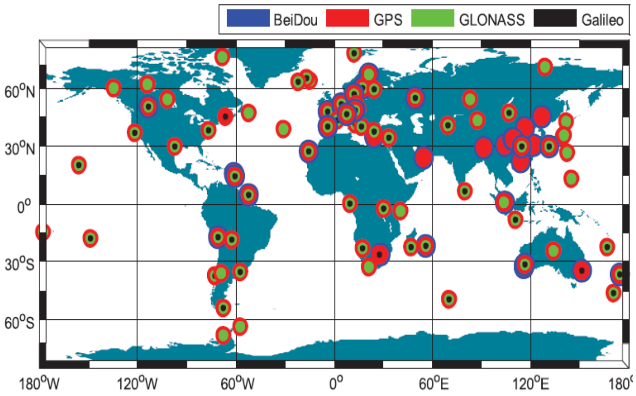


Fig. 5 The distribution of multi-GNSS stations from MGEX
Li et al. 2015

1. The Accuracy

In a Master's of Science Thesis in Geodesy from KTH Institute of Sweden, testing of PPP static method was undertaken using observation files from three different sources: three SWEPOS-stations at two different days, four IGS-stations and four self-measured points situated in different types of environment. Five different sets of ephemerides (final, rapid, ultra-rapid measured, ultra-rapid predicted 12h and 24h (predicted 8h and 13h for self-measured)) were used to process the observation files (24h, 6h, 2h and 1h) under the Bernese and Auto-Gipsy software.

As expected best results were achieved with final and rapid solutions for ephemerides, under 10 cm of accuracy after one hour of observation.

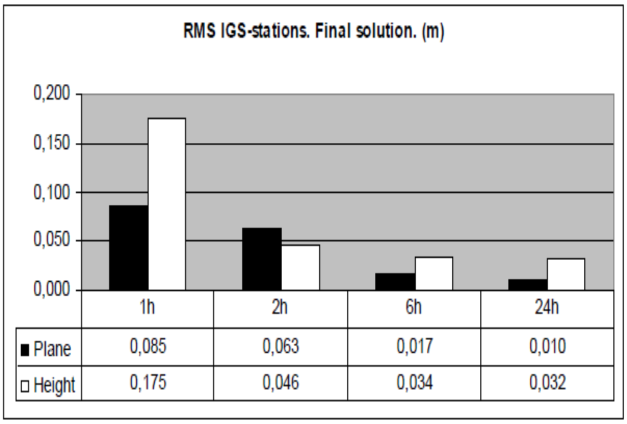


Fig. 6 RMS (m) for IGS stations (Bernese software)
Trehn, E. (2006) - „GPS Precise Point Positioning
An Investigation in Reachable Accuracy"

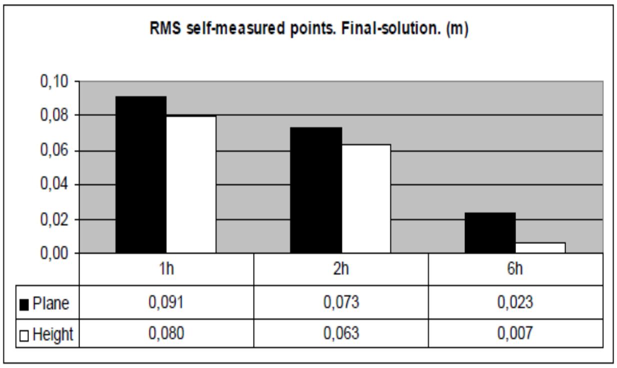


Fig. 7 RMS (m) for self-measured points (Bernese software)
Trehn, E. (2006) - „GPS Precise Point Positioning
An Investigation in Reachable Accuracy"

In Gao and Shen (2004), tests of kinematic PPP for a vehicle and a helicopter were conducted. The results indicate that positioning information with an accuracy level of 10 cm could be obtained.

In Héroux et al. (2004), the precise GPS positions of two aircraft GPS antennas were computed using kinematic PPP processing. For the distance between the two antennas (3.804 m), the Root Mean Square (RMS) was below 5 cm and the range was below 25 cm.

In Leandro and Santos (2006), GAPS software was used to determine the trajectory of a boat via kinematic PPP. The results include RMS values of 6.5, 5.5 and 13.9 cm for the North, East and up components, respectively.

In Hu et al. (2008), the IGS station SHAO was evaluated in kinematic mode on days 295, 296 and 297 of the year 2007. The maximum mean differences were 0.6, 3.2 and 4.3 cm for the North, East and up components, respectively.

In Tsakiri (2008), seven continuous days (24 h, 30 s observation files) of data for 2 IGS stations were processed using kinematic PPP with the CSRS-PPP software. Centimetric standard deviations in both the horizontal and vertical components were obtained. A kinematic vehicle test was also performed that yielded results of 5 to 6 cm for the horizontal component and 13 to 14 cm for the vertical component.

In Kjorsvik et al. (2009), the researchers analyzed 14 days of continuous observations of a ferry route between Lauvvik and Oanes (Norway) at a 1 Hz observation rate. The comparison of the PPP results with the reference trajectory computed via differential positioning yielded mean error rates of 6.7 and 10.0 cm for the horizontal and vertical components, respectively.

In Martin et al. (2012) a comprehensive test of kinematic PPP was taken. GPS observations from 8 permanent IGS stations (BRST, CONZ, KOUR, MDVJ, MTKA, NANO, REUN and TOW2) were used. The data sets used cover the first four hours of days 33, 211 and 347 of the year 2010, with data recorded at 30 s intervals. The coordinate bias (accuracy) was obtained by comparing the solution for every epoch obtained using the kinematic PPP method with the static PPP solution for the day under consideration.

Table 2 Mean kinematic PPP bias (m) for the IGS permanent sites

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Software	N		E		Up	
	σ	range	σ	range	σ	range
APPS	0.014	0.133	0.013	0.120	0.043	0.515
GAPS	0.244	1.789	0.225	1.448	1.107	6.655
NRCan	0.052	0.506	0.036	0.301	0.095	0.735
MagicGNSS	0.020	0.173	0.019	0.180	0.062	0.558

In order to simulate real conditions and introduce multipath biases the trajectory of two airplanes were recorded using GAPS, NRCan and MagicGNSS software, and also the trajectory of a car, and a moving pedestrian.

Table 3 Mean kinematic PPP bias (m) for one airplane

Software	N		E		Up	
	σ	range	σ	range	σ	range
GAPS	0.337	2.368	0.477	2.827	0.989	8.389
NRCan	0.015	0.087	0.013	0.069	0.029	0.147
MagicGNSS	0.008	0.065	0.011	0.068	0.021	0.137

Table 4 Mean kinematic PPP bias (m) for the car trajectory

Software	N		E		Up	
	σ	range	σ	range	σ	range
GAPS	0.267	2.182	0.191	1.678	1.002	3.895
NRCan	0.085	1.514	0.095	1.416	0.174	1.299
MagicGNSS	0.082	1.480	0.089	1.366	0.331	2.603

Table 5 Mean kinematic PPP bias (m) for the moving pedestrian

Software	N		E		Up	
	σ	range	σ	range	σ	range
GAPS	0.250	1.195	0.180	0.932	0.365	2.325
NRCan	0.106	0.685	0.079	0.548	0.255	1.705
MagicGNSS	0.105	0.57	0.044	0.487	0.156	1.431

Upon the development of the MGEX project a series of testing involving observations from GPS, GLONASS, Gallileo and BeiDou were undertaken. The results obtained for single-, dual and four-system modes at station CUT0 from Australia were compared.

The left sub-figures show the single-system PPP results of GPS-only, BeiDou-only, GLONASS-only and Galileo-only, respectively. For the GPS-only solution, the positioning accuracy can be better than 1 dm after a convergence time of about 30 minutes. About 2 hours of convergence is required to ensure an accuracy of better than 5 cm in all three components. The mm accuracy can be achieved after the long convergence time of several hours. The convergence of GLONASS-only PPP is longer compared to GPS-only PPP, about 3 hours to achieve an accuracy of a few centimeters. Meanwhile, the GLONASS positioning accuracy after sufficient convergence time is also slightly worse compared to the GPS solution. The BeiDou-only PPP presents good performance in the horizontal components, few cm accuracy can be achieved within one hour. However, the vertical component is much more unstable than GPS and GLONASS. A Galileo-only PPP solution cannot be derived at this station as not enough satellites can be observed.

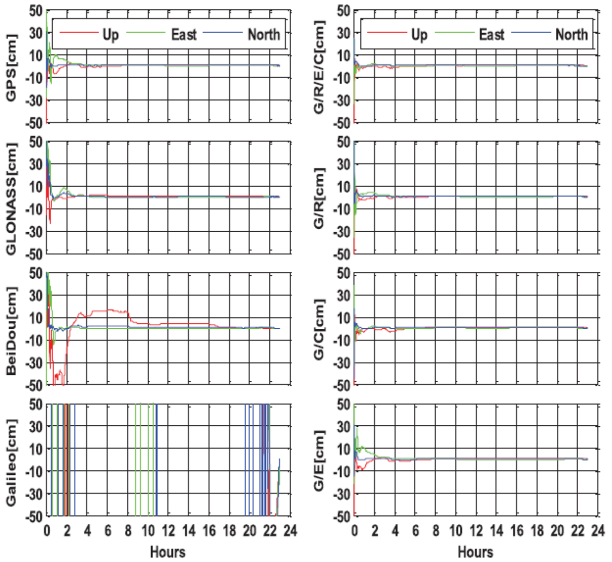

Fig 8 Static PPP solutions of single-system (G, R, E, and C), dual-system (G/R, G/C, and G/E) and four-system (G/R/E/C) modes at station CUT0 (Australia, 32.006S, 115.896E,), on September 3, 2013 (GPS Time). The north, east and up components are shown by the blue, green and red lines, respectively. (Li et al. 2015)

The combined GPS/BeiDou, GPS/GLONASS, GPS/Galileo, GPS/BeiDou/GLONASS/Galileo PPP solutions are shown in the right sub-figures. Obviously, the multi-GNSS combination significantly improves the PPP performance, compared to the left sub-figures of the single-system solutions. It can be clearly seen that the combined GPS/BeiDou and GPS/GLONASS solutions significantly shorten the convergence time and improve the position series compared to single- system PPP. The Galileo satellites also contribute to the combined GPS/Galileo PPP solution to some extent, although they are not sufficient for autonomous positioning. The combined GPS/BeiDou/GLONASS/Galileo PPP present the fastest convergence, the most stable position series and highest accuracy for all three components. It only takes several minutes to achieve an accuracy of better than 10 cm, less than 30 minutes to be better than 5 cm, and a few hours to reach mm level accuracy. (Li, et al, 2015)

5. Conclusion

In the context of the modern advent of GNSS technology new improved positioning methods that take full advantage of the created conditions had been developed. Precise Point Positioning is one of these methods. Increased popularity of PPP among researchers and users reveals with every study the real potential and efficiency of this precise positioning method. PPP offers a global stable, high accuracy solution and eliminates the need of high density reference station.

Seen by some of the authors as a method limited only by the present state of the communication systems, PPP is obviously offering great advantages in terms of obviously precision and cost.

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