

Accepted Manuscript

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J. Mohammed, T. Moore, C. Hill, R.M. Bingley, D.N. Hansen

PII: S0263-2241(16)30016-1

DOI: <http://dx.doi.org/10.1016/j.measurement.2016.03.048>

Reference: MEASUR 3906

To appear in: *Measurement*

Received Date: 16 January 2016

Revised Date: 8 March 2016

Accepted Date: 23 March 2016

Please cite this article as: J. Mohammed, T. Moore, C. Hill, R.M. Bingley, D.N. Hansen, An Assessment of Static Precise Point Positioning using GPS only, GLONASS only, and GPS plus GLONASS, *Measurement* (2016), doi: <http://dx.doi.org/10.1016/j.measurement.2016.03.048>

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An Assessment of Static Precise Point Positioning using GPS only, GLONASS only, and GPS plus GLONASS

J. Mohammed PhD student in NGI, The University of Nottingham, UK and assistant lecturer in Civil Engineering Department, College of Engineering, University of Wasit, Iraq, (corresponding author). E-mail: jareeral@gmail.com

T. Moore Director of The Nottingham Geospatial Institute (NGI) at The University of Nottingham and Professor of Satellite Navigation, NGI, University of Nottingham, UK, Terry.Moore@nottingham.ac.uk

C. Hill Associate Professor, Nottingham Geospatial Institute, University of Nottingham, UK, chris.hill@nottingham.ac.uk

R. M. Bingley, BIGF Head of Facility and Associate Professor and Reader in Geodetic Surveying, NERC British Isles continuous GNSS Facility (BIGF), University of Nottingham, UK, Richard.Bingley@nottingham.ac.uk

D. N. Hansen Product Developer, NERC British Isles continuous GNSS Facility (BIGF), Nottingham Geospatial Institute, University of Nottingham, Dionne.Hansen@nottingham.ac.uk

Abstract: The aim of this paper is to look into the achievable repeatability and accuracy from Precise Point Positioning (PPP) daily solutions when using GPS only (PPP GPS), GLONASS only (PPP GLO), and GPS plus GLONASS (PPP GPS+GLO) for static positioning. As part of the assessment, a comparison with global double difference (DD) GPS daily solutions is presented. It is shown, therefore, that all of the PPP daily solutions can achieve millimetric level repeatability, similar to the global DD GPS solutions. Furthermore, the mean of the biases between the PPP daily solutions and the global DD GPS daily solutions are constellation type dependent, while an improvement is found in the vertical component for PPP GPS+GLO over PPP GLO, as the latter may be more affected by any imperfections in the models for GLONASS antenna phase centre variations. It is concluded that PPP GLO daily solutions have the ability to be used as independent solutions to PPP GPS daily solutions for static positioning, and as an alternative to PPP GPS+GLO or global DD GPS daily solutions.

Keywords: GNSS, GPS, GLONASS, Precise Point Positioning.

Introduction

Different GNSS constellations are available these days. This has led to an increase in the number of satellites available for the user, and the potential for improvements in the repeatability and accuracy of daily solutions for static positioning, which are significant factors when evaluating the use of multi-constellations as one constellation or a combination. At the same time, the Precise Point Positioning (PPP) technique (Zumberge et al., 1997) has also developed to potentially provide daily solution estimates with millimetric level repeatability and accuracy for static positioning (Larson et al., 2004), as an alternative to the double-difference (DD) technique. Following the restoration of the GLONASS constellation to a similar level as the GPS constellation, much research has been carried out on PPP when using GPS only (PPP GPS) and PPP when using GPS plus GLONASS (PPP GPS+GLO), i.e. using GLONASS as an aid to GPS. For instance Cai (2009) concluded that when using PPP GPS+GLO as opposed to PPP GPS, improvements in accuracy were 40% and 28% in the east and north components respectively and 24 % in the vertical coordinate component. However, according to Cai and Gao (2013) the accuracy will not be significantly improved if there are sufficient numbers of GPS satellites with good geometry. Separately, Reussner and Wanninger (2011) showed that GPS+GLO had a reduced average horizontal coordinate error when compared to PPP GPS, Jokinen et al. (2013a) found that when changing from PPP GPS to PPP GPS+GLO the average vertical and horizontal coordinate errors were reduced by 17% and 4% respectively, and Jokinen et al. (2013b) showed that horizontal, vertical and 3D coordinate errors were reduced by 40%, 24% and 32% respectively when considering PPP GPS+GLO instead of PPP GPS. Alcaay et al. (2012) concluded that there is no significant difference between GPS and GPS+GLO for two networks, however they concluded that GLO is not accurate as GPS or GPS+GLO. While Anquela et al. (2013) concluded that PPP GLO is not accurate as PPP GPS or PPP GPS+GLO in either static or kinematic. Clearly, all of this previous research has tended to focus on comparisons of PPP GPS and PPP GPS+GLO, without any evaluation of PPP GLO itself. Hence, in this paper, as an investigation of the potential benefits to static positioning from using PPP with a single or multi-constellation, the achievable repeatability and accuracy from PPP GLO daily solutions, as independent solutions to PPP GPS daily solutions, and as an alternative to PPP GPS+GLO or global DD GPS daily solutions, will be assessed.

PPP Daily Solutions Methodology

All of the PPP daily solutions presented in this paper were processed using the POINT software, which was developed as part of the iNsight project (www.insight-gnss.org). The POINT software is programmed in C++, and its core is the extended Kalman filter (EKF), as presented in Feng et al. (2008).

Undifferenced observations are used for each PPP daily solution, with the general observation equations for code and phase being as follows:

For pseudo-range using C/A-Code on L_1 :

$$C_1^i = e^i + c\delta_r - c\delta^i + \frac{I^i}{f_1^2} + \frac{S^i}{f_1^3} + T^i + M_{C1}^i + Q_{C1}^i + bias_{C1} - bias_{C1}^i \quad (1)$$

For Pseudo-range using on L_1, L_2 :

$$P_F^i = e^i + c\delta_r - c\delta^i + \frac{I^i}{f_F^2} + \frac{S^i}{f_F^3} + T^i + M_{PF}^i + Q_{PF}^i + bias_{P,F} - bias_{P,F}^i \quad (2)$$

For carrier phase

$$L_F^i = e^i + c\delta_r - c\delta^i - \frac{I^i}{f_F^2} - \frac{S^i}{f_F^3} + T^i + m_F^i + q_F^i + \lambda_F(N_F^i + B_F - B_F^i) \quad (3)$$

Where:

i is the satellite index;

F represents the index of the GNSS frequency - for GPS satellites $F = 1$ (GPS L1) and $F = 2$ (GPS L2), while for GLO satellites $F = 1$ (GLO L1) and $F = 2$ (GLO L2) with

$$f_{k L1} = f_{0L1} + k\Delta f_{L1} \quad (4)$$

$$f_{k L2} = f_{0L2} + k\Delta f_{L2} \quad (5)$$

and

k represents the frequency channel; $f_{0L1} = 1602$ MHz for GLONASS L1 band; $\Delta f_{L1} = 562.5$ kHz frequency separation between GLONASS carriers in the L1 band; $f_{0L2} = 1246$ MHz for GLONASS L2 band; $\Delta f_{L2} = 437.5$ kHz frequency separation between GLONASS carriers in the L2 band.

e^i represents the geometric distance from the receiver to the satellite; $c\delta_r$ is the receiver clock offset; $c\delta^i$ is the satellite clock offset; I^i is the first-order ionospheric bias term; S^i is the second-order ionospheric bias term; f_f is the GNSS frequency in Hz; T^i is the tropospheric bias; M_{PF}^i is the multipath error for pseudo-range measurements on the frequency F ; M_{C1}^i is the multipath error for C/A code measurements on L1; m_F^i is the multipath error for carrier-phase measurements on the frequency F ; Q_{PF}^i is the noise for the pseudo-range measurements on the frequency F ; Q_{C1}^i is the

noise for the C/A code measurements on L1; q_F^i is the noise for the carrier-phase measurements on the frequency F ; $bias_{p,F}$ is the receiver code bias for pseudo-range measurements on the frequency F ; $bias_{c_1}$ is the receiver code bias for C/A code measurements on L1; $bias_{p,F}^i$ is the satellite code bias for pseudo-range measurements on the frequency F ; $bias_{c_1}^i$ is the satellite code bias for C/A code measurements on L1; λ_F is the wavelength on the frequency F ; N_F^i is the carrier phase ambiguity term on the frequency F ; B_F is the receiver fractional cycle bias (FCB) on the frequency F ; B_F^i is a satellite fractional cycle bias (FCB) on the frequency F .

For all of the PPP daily solutions, a decoupled receiver clock is applied for both GPS and GLO (Collins et al., 2010), and the ionospheric-free observable is used, with no second order ionospheric bias corrections applied. The ionospheric-free combinations for the code and phase observables follow (Dach et al., 2007a):

$$P_3 = \frac{1}{f_i^2 - f_j^2} (f_i^2 P_{L1} - f_j^2 P_{L2}) \quad (6)$$

$$L_3 = \frac{1}{f_i^2 - f_j^2} (f_i^2 L_1 - f_j^2 L_2) \quad (7)$$

Where:

P_3 and L_3 refer to the ionospheric-free code and ionospheric-free carrier combinations respectively; P_{L1} and P_{L2} refer to the pseudo-range measurements on L_1 and L_2 respectively; L_1 and L_2 refer to carrier phase measurements on L_1 and L_2 frequency; f_i is the frequency on the L_1 carrier; f_j is the frequency on the L_2 carrier; and $i = 1, j = 2$ for GPS and GLO, except that for GLO f_1 and f_2 come from equations (4) and (5).

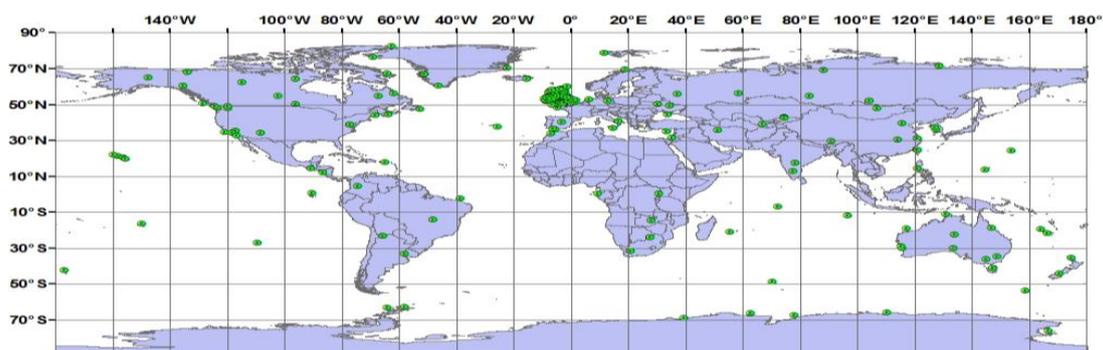
In terms of the troposphere, the hydrostatic component of the zenith total delay is modelled using Saastamoinen (Saastamoinen, 1973) and the wet component of the zenith total delay is estimated as a state in the Kalman filter for every epoch, i.e. at 30 second intervals. For describing how the slant tropospheric delay varies with respect to the receiver-to-satellite elevation angle, the Niell Mapping function (Niell, 1996) or NMF is used. The azimuthal inhomogeneity of the troposphere is also taken into account by estimating two states for tropospheric gradient (E, N) using the Chen model (Meindl et al., 2004) and the Chen mapping function (Chen and Herring, 1997) to map the tropospheric gradient into the range domain. The Differential Code Bias (DCB) between C_1 and P_1 , and between C_2 and P_2 are corrected using the products from the Centre for Orbit Determination in Europe (CODE) (Dach et al., 2007a). To look at the actual performance of the individual constellation, no weighting functions are applied to the observations, except for the measurement noise standard deviations that is needed for the EKF and is set to 2.0 m for pseudo-range measurements, and 0.01 m for carrier phase measurements, for both GPS and GLO.

In addition, for all of the PPP daily solutions:

Natural Resources Canada (NRCan) final precise ephemeris products are used as input, for satellite coordinates and satellite clock corrections; satellite and receiver antenna phase centre offsets and variations are corrected using an Antenna Exchange Format (ANTEX) (Kouba, 2009) file from the IGS, i.e. the I08.ATX file which is consistent with what was used in the creation of the precise ephemerides; periodic deformations of the Earth's crust as solid Earth tides and ocean tidal loading are taken into account following Kouba (2009); phase wind up correction is also applied in accordance with Wu et al. (1993). Sub-daily pole and nutation motions are corrected according to the IERS conventions (McCarthy and Petit, 2004). Lastly, for all of the PPP daily solutions the carrier phase ambiguities were not fixed to integers, but kept as float, and the cycle slip detection method implemented follows Liu (2011).

Global DD GPS Daily Solutions Methodology

All of the global DD GPS daily solutions presented in this paper were processed using the Bernese software version 5.2 (Dach et al., 2007b). These daily solutions were created by the NERC British Isles continuous GNSS Facility (BIGF) from a re-processing and re-analysis of daily data from 1997 to 2014. The daily solution coordinate estimates were created using: C13 (CODE repro2/repro_2013) re-analysed satellite orbit and earth orientation parameter products; a global network, the IGB08 reference frame; mitigation of 1st and higher order (2nd and 3rd order and ray bending) ionospheric effects; a-priori modelling of troposphere effects using VMF1G and mitigation using zenith path delay and gradient parameters; I08.ATX models for antenna phase centre variations; ambiguities were fixed to integer; and models for Solid Earth tides, ocean tidal loading and atmospheric tidal loading. A total of approximately 150 continuous GNSS stations (CGNSS) in the British Isles, including 100+ that are part of the Ordnance Survey of Great Britain (OSGB) national network, were included in the processing along with some 200+ IGS stations, as illustrated in Figure 1. The epoch of the DD solutions is the observed day, with the daily coordinates of the 200+ IGS stations motioned forward from the IGB08 reference epoch of 2005-01-01 to the observed day using the IGB08 velocities. No stations are fixed for the network solution, but rather an adjustment of the global network on to the IGB08 reference frame is effected using a no-net translation and no-net scale minimum constraints approach.



the mean to create daily coordinate differences in terms of Easting, Northing and Up components, as shown in Figure 3 and Figure 4 for ALDB and AMER stations respectively after removing the trend caused by the tectonic plate motion. Figure 3 and 4 clearly illustrate the stability of the daily solutions as well as the products used for all scenarios, i.e. PPP (GPS, GLO and GPS+GLO) and global DD GPS. Following this, it was possible to use the daily coordinate differences in order to calculate the repeatability of the daily solution coordinate estimates in each case in terms of Easting, Northing and Up components, following (Blewitt, 1989):

$$REP = \sqrt{\left(\frac{n}{n-1} * \frac{\sum_{i=1}^n \frac{(R_i - R_m)^2}{\sigma_i^2}}{\sum_{i=1}^n \frac{1}{\sigma_i^2}} \right)} \quad (1)$$

Where n is the number of days processed; R_i is the daily solution estimated coordinate component for day “ i ”; σ_i is the standard error of the daily solution estimated coordinate component for day “ i ”; and R_m is the mean of the daily solution estimated coordinate component.

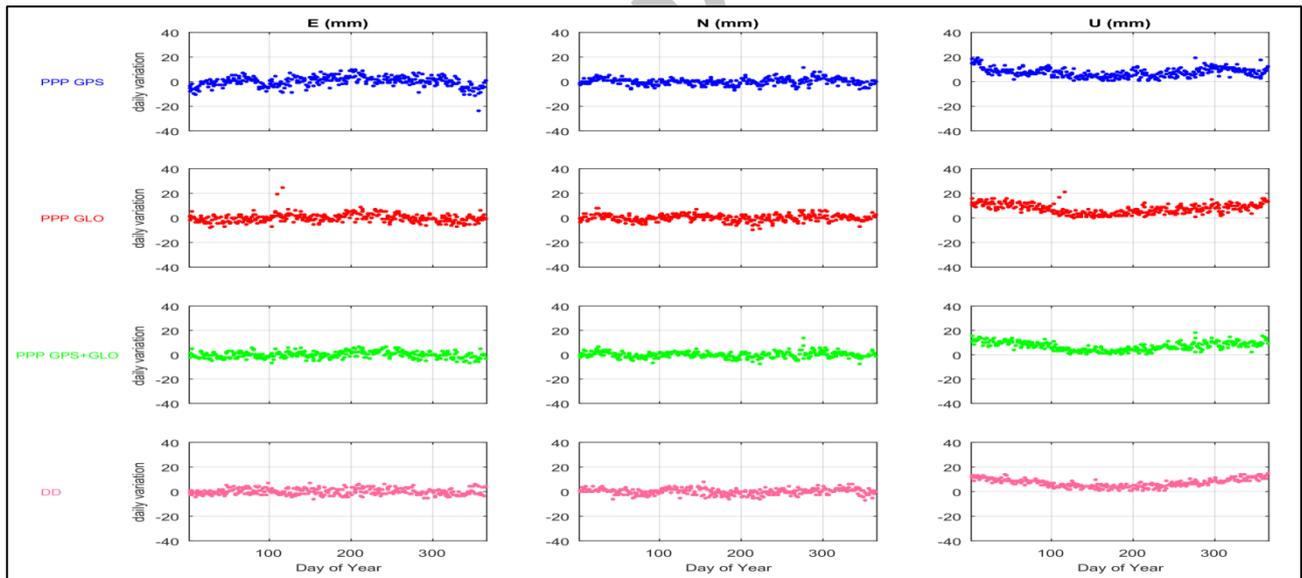


Fig 3 daily coordinates differences from the mean for one year for the AMER of 350 days

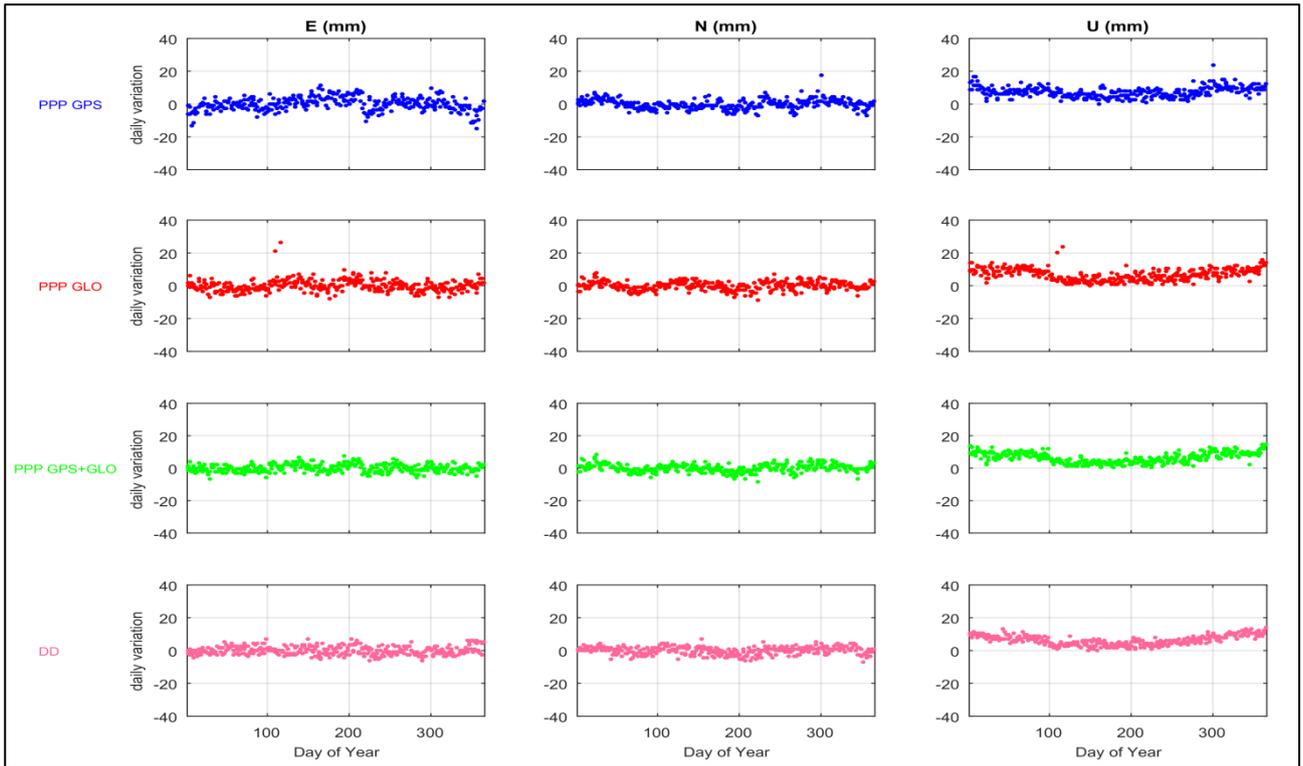


Fig 4 Daily coordinate differences from the mean for one year for the ALDB of 354 days.

Bar charts representing the repeatability of the daily solution coordinate estimates as individual coordinate components (Easting, Northing, and Up) for the ALDB and AMER CGNSS stations are presented in Figures 5 and 6 respectively.

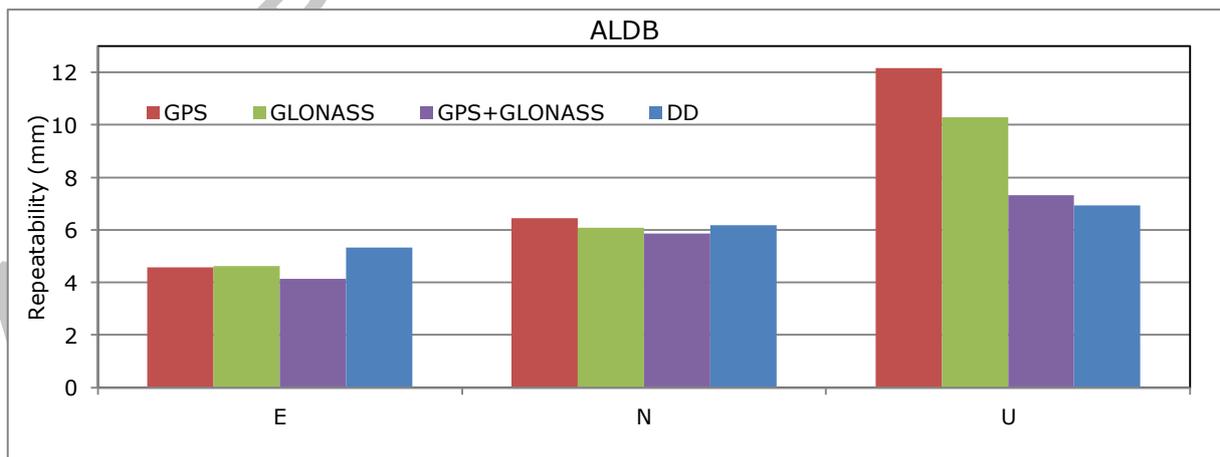


Fig. 5 Repeatability of the daily solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and global DD GPS for ALDB CGNSS station.

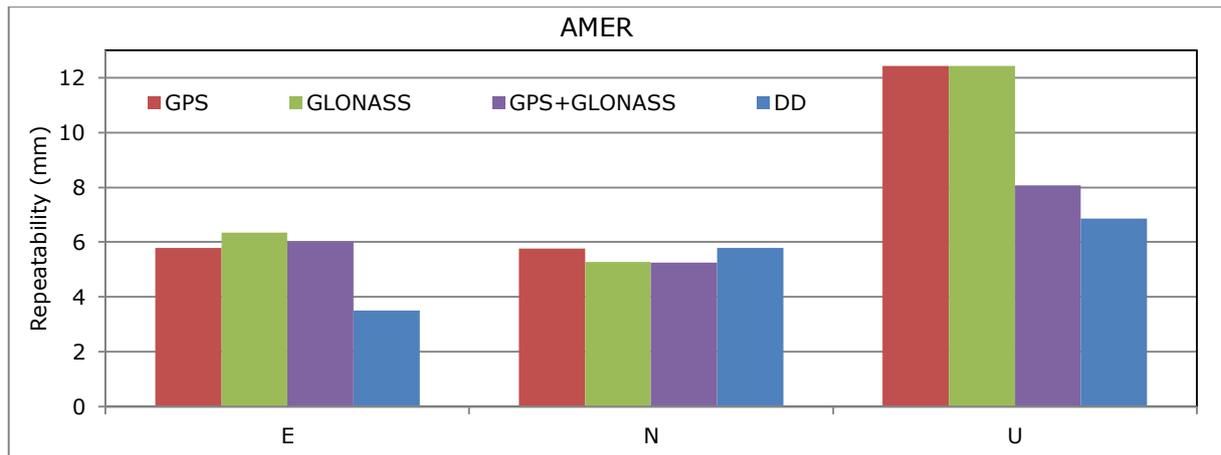


Fig. 6 Repeatability of the daily solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and global DD GPS for AMER CGNSS station.

It can be seen from Figures 5 and 6 that PPP GPS, PPP GLO and PPP GPS+GLO have similar repeatabilities in the Easting and Northing coordinate components as global DD GPS, and that PPP GPS+GLO has similar repeatability in the Up coordinate component as global DD GPS. Furthermore, it is clear that PPP GLO has similar repeatabilities to PPP GPS in all coordinate components.

Experimental Results: Extended Investigation

Following the promising results from the initial investigation, an extended investigation was carried out based on all 100+ OSGB CGNSS stations (see Figure 2) over a 7 week period, as detailed in Table 1. In this extended investigation, only OSGB CGNSS stations that were continuous for a specific GPS week, had optimal 24 hour observations recorded each day, and were also present in the global DD daily solutions were included, which led between 56 and 85 OSGB CGNSS stations per week being available for analysis, as also detailed in Table 1. Bear in mind that the GPS week 1775 stations (56) are the common stations for the 7 weeks.

Table 1 GPS week and the number of OSGB CGNSS stations considered in the analysis for each week

GPS Week	No. of CGNSS Stations
1775	56
1776	85
1777	79
1778	74
1783	74
1784	76
1785	79

Apart from that, the analysis in terms of repeatability followed a similar approach to the analysis used in the initial investigation but, in some instances, also considered weekly solution coordinate estimates as opposed to daily solution coordinate estimates for the stations mentioned in Table 1 with their relevant GPS week. In these instances, for each of the three PPP daily solutions (GPS, GLO and GPS+GLO) and the global DD GPS daily solution, the mean of the daily solution coordinate estimates for seven weeks were calculated. The weekly solution coordinate estimates for each week were then subtracted from the mean to create weekly coordinate differences in terms of Easting, Northing and Up components. Following this, it was possible to use the weekly coordinate differences in order to calculate the repeatability of the weekly solution coordinate estimates in each case in terms of Easting, Northing and Up components.

A bar chart representing the RMS of the repeatabilities of the weekly solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and global DD GPS as individual coordinate components (Easting, Northing, and Up) for all of the CGNSS stations considered is presented in Figure 7.

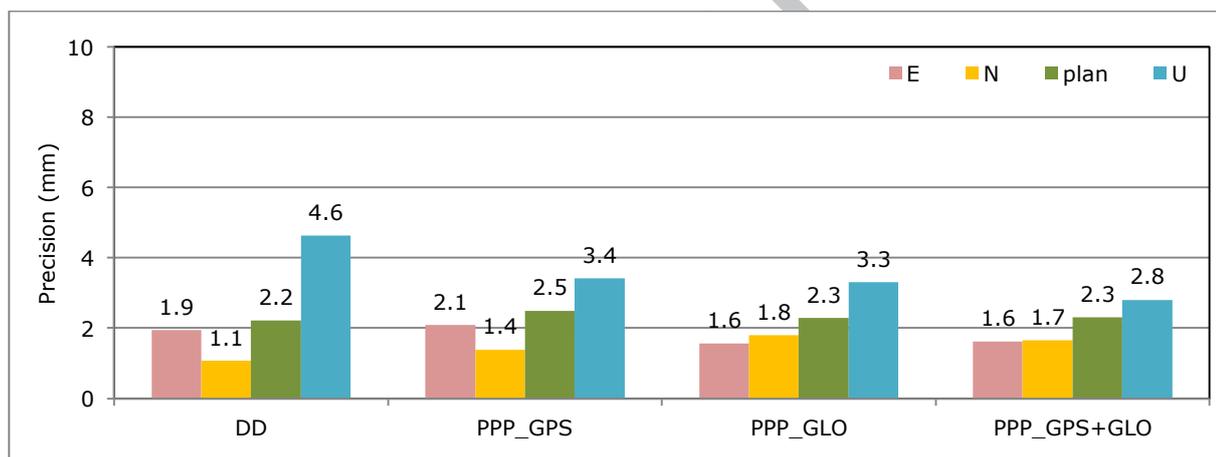


Fig. 7 RMS of the repeatabilities of the weekly solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and global DD GPS for all CGNSS stations considered.

As can be seen from Figure 7, the RMS of the repeatabilities of the weekly solution coordinate estimates in terms of Easting, Northing and Up components respectively is found to be: 2.1, 1.4 and 3.4 mm for PPP GPS; 1.6, 1.8 and 3.3 mm for PPP GLO; 1.6, 1.7 and 2.8 mm, and 1.6, 1.7 and 2.8 mm for PPP GPS+GLO; and 1.9, 1.1 and 4.6 mm for global DD GPS. Considering PPP GPS and PPP GLO, it can be seen from that the repeatabilities are the same to within sub-millimetres, which provides an indication of the potential for using PPP GLO as an independent solution to PPP GPS, rather than simply using GLONASS to aid GPS (PPP GPS+GLO).

In addition to repeatability, it is also possible to estimate any differences between the weekly solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the weekly solution coordinate estimates from global DD GPS. In

this regard, measures of accuracy are obtained if the weekly solution coordinate estimates from global DD GPS, which are independent of the weekly solution coordinate estimates from PPP, are assumed to represent the most probable values.

A bar chart representing the RMS of the differences between the weekly solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the weekly solution coordinate estimates from global DD GPS as individual coordinate components (Easting, Northing, and Up) for all of the CGNSS stations considered is presented in Figure 8.

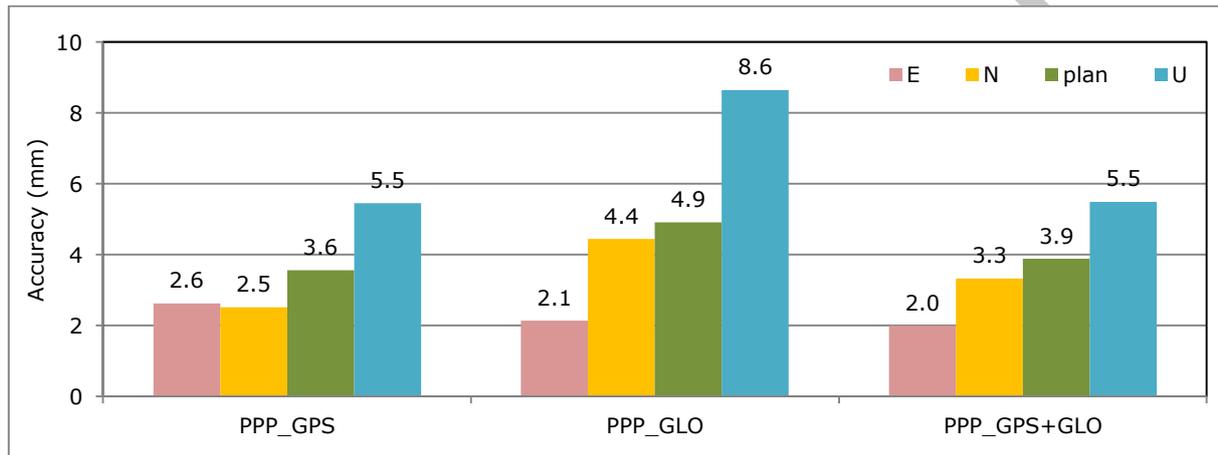


Fig. 8 RMS of the differences between the weekly solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the weekly solution coordinate estimates from global DD GPS for all CGNSS stations considered.

As can be seen from Figure 8, the RMS of the differences between the weekly solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the weekly solution coordinate estimates from global DD GPS in terms of the Easting, Northing and Up components respectively are found to be: 2.6, 2.5 and 5.5 mm for PPP GPS; 2.1, 4.4 and 8.6 mm for PPP GLO; and 2.0, 3.3 and 5.5 mm for PPP GPS+GLO, which provides a further indication of the potential for using PPP GLO as an independent solution to PPP GPS, rather than simply using GLONASS to aid GPS (PPP GPS+GLO).

As a further check, a bar chart representing the RMS of the differences between the daily solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the daily solution coordinate estimates from global DD GPS as individual coordinate components (Easting, Northing, and Up) for all of the CGNSS stations considered is presented in Figure 9.

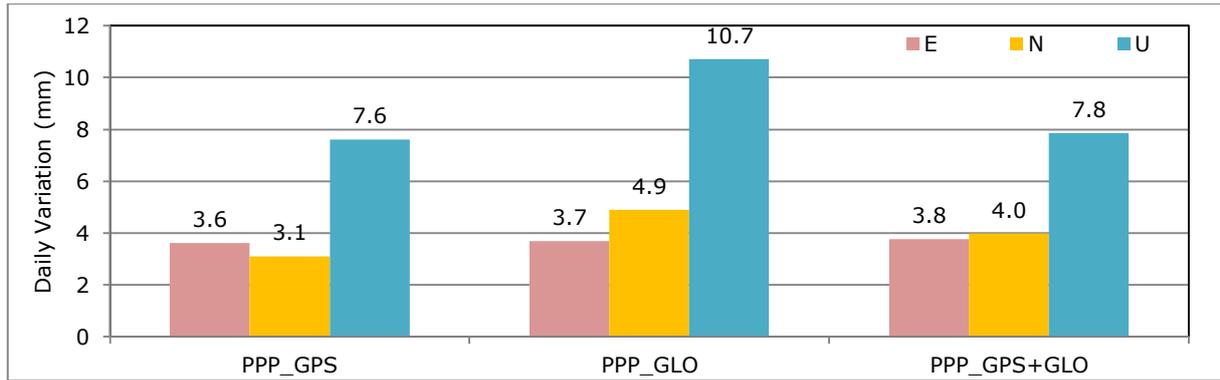


Fig. 9 RMS of the differences between the daily solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the daily solution coordinate estimates from global DD GPS for all CGNSS stations considered.

As can be seen from Figure 9, the RMS of the differences between the daily solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the daily solution coordinate estimates from global DD GPS in terms of the Easting, Northing and Up components respectively is found to be: 3.6, 3.1 and 7.6 mm for PPP GPS; 3.7, 4.9 and 10.7 mm for PPP GLO; and 3.8, 4.0 and 7.8 mm for PPP GPS+GLO, which confirms the previous statements made with regards to the potential for using PPP GLO as an independent solution to PPP GPS, rather than simply using GLONASS to aid GPS (PPP GPS+GLO).

However, it is clear that the RMS of the differences statistic does not give a complete picture of any biases present, as it does not consider the fact that these differences can be positive or negative. To overcome this, a bar chart representing the mean of the differences, or the biases, between the daily solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the daily solution coordinate estimates from global DD GPS as individual coordinate components (Easting, Northing, and Up) for all of the CGNSS stations considered is presented in Figure 10.

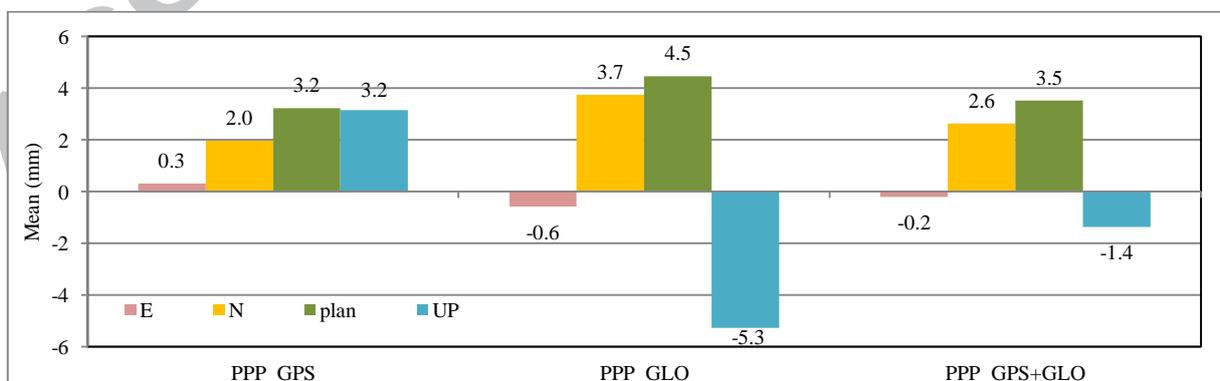


Fig. 10 Mean of the differences, or the biases, between the daily solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the daily solution coordinate estimates from global DD GPS for all CGNSS stations considered.

It is clear from Figure 10, therefore, that the mean of the differences, or the biases, between the daily solution coordinate estimates from PPP (GPS, GLO and GPS+GLO) and the daily solution coordinate estimates from global DD GPS are constellation type dependent. There is also a slight worsening in the Easting and Northing coordinate components and an obvious worsening in the Up coordinate component for PPP GLO when compared to PPP GPS.

At this stage, it is also worth considering the validity of the assumption that the weekly/daily solution coordinate estimates from global DD GPS, which are independent of the weekly solution coordinate estimates from PPP (GPS, GLO and GPS+GLO), are assumed to represent the most probable values. It is clear from Figure 10 that there is a consistently larger bias in the Northing component than in the Easting component, with the Northing component from PPP (GPS, GLO and GPS+GLO) being to the north of the Northing component from global DD GPS. One reason for this could be a reference frame issue, as while the PPP technique relies only on the precise ephemeris products, the DD technique relies on these but is also affected by the network of global CGNSS stations that were used. Re-considering Figure 1, which gives an example of the network that was used for the global DD GPS solution on 2014/01/12 (DOY 012 of 2014), the global network contains 97 CGNSS stations to the south of the lowest latitude OSGB CGNSS station (SCIL, lat = 49.9) but only 19 CGNSS stations to the north of the highest latitude OSGB CGNSS station (KIRW, lat = 58.9).

Furthermore, the subtle differences in the biases for the Northing coordinate component for PPP GLO and PPP GPS could be a constellation issue related to the higher inclination of the GLONASS satellites when compared to GPS, which results in a significantly different pattern for the GLONASS and GPS constellations as shown in Figure 11.

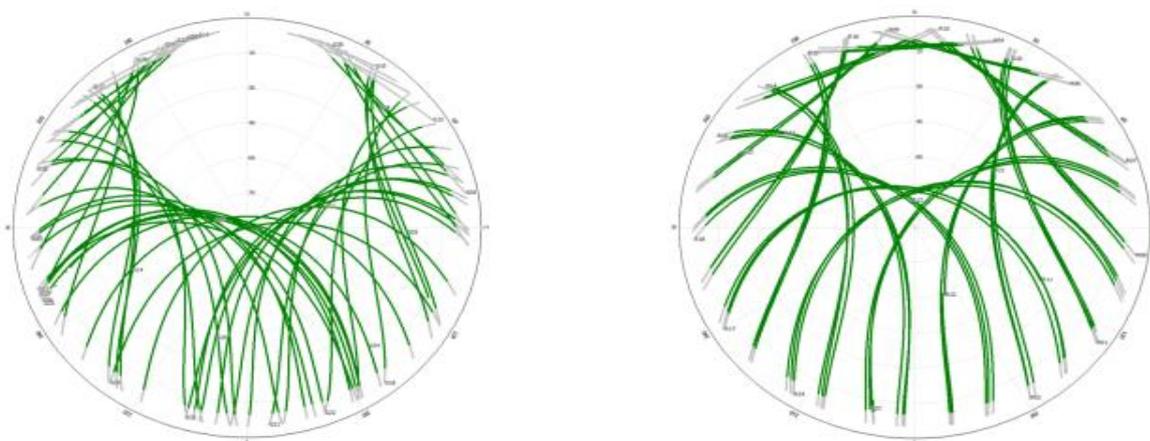


Fig. 11 Representative satellite constellation availability (Left: GPS, Right: GLONASS) for ALDB station on DOY 12, 2014.

To support that idea, the differences between the mean weekly solution of PPP GPS, PPP GLO and PPP GPS+GLO were subtracted from the mean weekly solution from the global DD GPS; see Figure 12 for 85 stations in GPS week 1776.

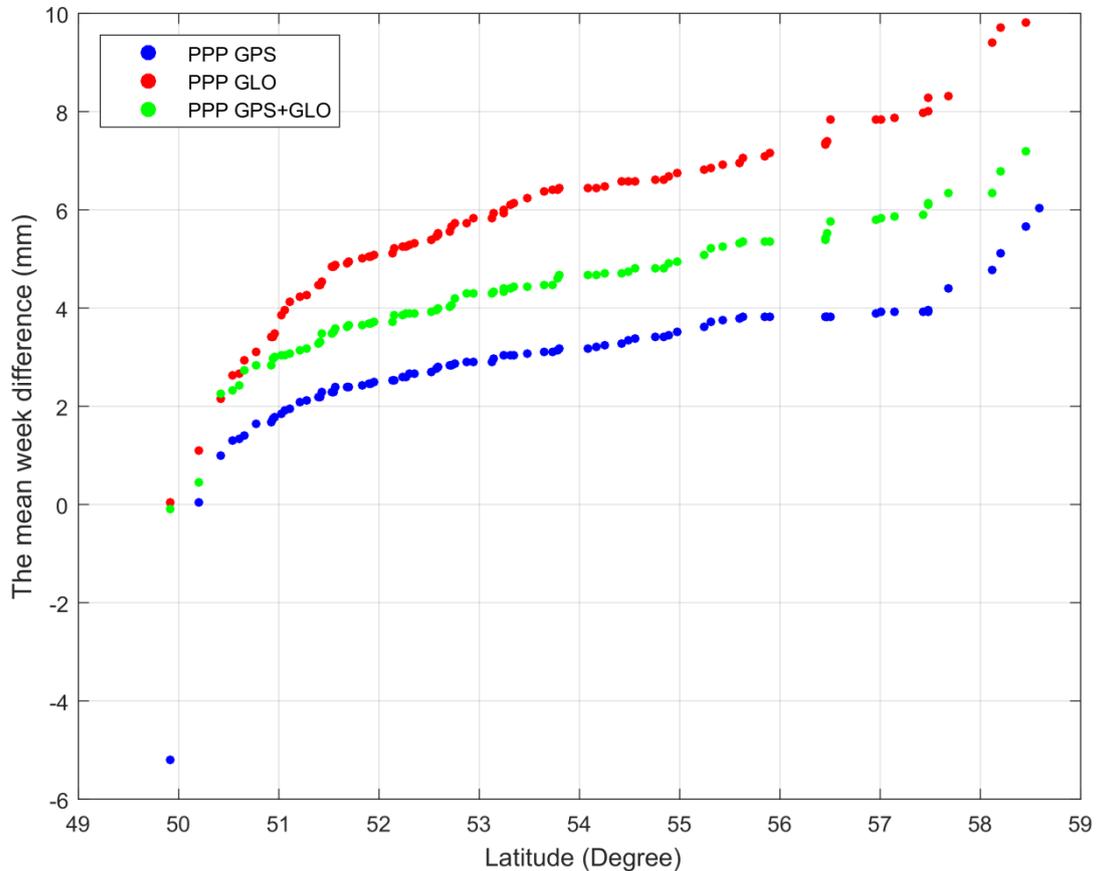


Fig. 12 North biases relative to the DD Solution for 85 stations in GPS week 1775.

It is clear from the Figure 12, that all PPP scenarios' northing differences have almost the same shape and increasing differences with the increasing of the station latitude. These increasing differences indicate the effect of the reduced CGNSS stations to the north for global DD GPS solution. In addition, while PPP GLO has available satellites to the north, it has larger differences than PPP GPS because of the reduced availability of the GPS constellation with the increasing of the station latitude. While PPP GPS+GLO will have the balanced differences between both constellations as shown in Figure 12.

Lastly, considering the biases in the Up coordinate component, it is clear that in the case of PPP GPS+GLO there is effectively a balancing of the errors present in PPP GPS and PPP GLO. This clearly results in an improvement in the Up component for PPP GPS+GLO over PPP GLO, as the latter may be more affected by any imperfections in the models for GLONASS antenna phase centre variations.

Conclusions

In this paper, the achievable repeatability and accuracy from PPP daily solutions when using GPS only (PPP GPS), GLONASS only (PPP GLO), and GPS plus GLONASS (PPP GPS+GLO) for static positioning has been assessed. As part of the assessment, a comparison with global DD GPS daily solutions has been presented. Based on the RMS of the repeatabilities of the weekly solution coordinate estimates, and the RMS of the differences between the PPP daily solution coordinate estimates and the global DD GPS daily solution coordinate estimates, it is shown that all of the PPP daily solutions can achieve millimetric level repeatability, similar to the global DD GPS solutions. Furthermore, the mean of the biases between the PPP daily solutions and the global DD GPS daily solutions are constellation type dependent, while an improvement is found in the Up component for PPP GPS+GLO over PPP GLO, as the latter may be more affected by any imperfections in the models for GLONASS antenna phase centre variations.

It is concluded, therefore, that PPP GLO daily solutions have the ability to be used as independent solutions to PPP GPS daily solutions for static positioning, and as an alternative to PPP GPS+GLO or global DD GPS daily solutions.

Acknowledgments: The services of the Natural Environment Research Council (NERC) British Isles continuous GNSS Facility (BIGF), www.bigf.ac.uk, in providing archived GNSS data and products to this study, are gratefully acknowledged. Also, the first author acknowledges the financial support he received from his government in Iraq during the period of his postgraduate research study at the University of Nottingham.

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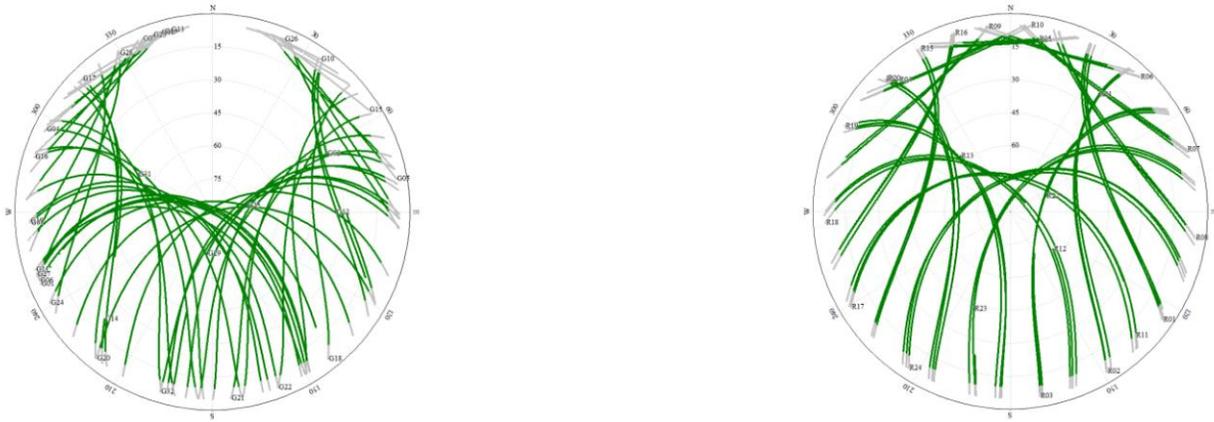


Figure 11

Highlights

- Comparison between Precise Point Positioning (PPP) and Global Double Difference (DD).
- PPP GLO can reach the Accuracy and the Precision of the Global DD.
- PPP has a constellation type biases because of the geometry of the constellation.
- PPP biases are affected by the station's latitude.

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