Accuracy improvement techniques in Precise Point Positioning method using multiple GNSS constellations

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INTRODUCTION

The future Global Navigation Satellite Systems (GNSS), including modernized GPS, GLONASS, Galileo and BeiDou, offer three or more signal carriers for civilian use and much more redundant observables. The additional frequencies can significantly improve the capabilities of the traditional geodetic techniques based on GPS signals at two frequencies, especially with regard to the availability, accuracy, interoperability and integrity of high-precision GNSS applications. Furthermore, highly redundant measurements can allow for robust simultaneous estimation of static or mobile user states including more parameters such as real-time tropospheric biases and more reliable ambiguity resolution estimates.

This work outlines an investigation and analysis of accuracy improvement techniques in the Precise Point Positioning (PPP) method using signals from the fully operational (GPS and GLONASS), as well as the currently available Galileo and BeiDou systems. The main aim was to determine the level of improvement in both the positioning accuracy achieved and the time convergence it takes to achieve geodetic-level (10 cm or less) accuracy. To this end, we used freely available observation data from the recent Multi-GNSS Experiment (MGEX) of the International GNSS Service, as well as the open source program RTKLIB which allows the computation of the observer positions with the Precise Point Positioning (PPP) technique using multiple GNSS constellations (Takasu, 2013).

PPP Mathematical Model

The GNSS observation equations for pseudorange P and carrier phase L in i frequencies can be described by the following general expressions:

$$P_i^s = \rho^s + cdt^s - cdT^s + d_{orb}^s + d_{trop}^s + d_{ion,P_i}^s + d_{mult,P_i}^s + \varepsilon_{P_i}^s, \tag{1a}$$

$$\Phi_i^s = \rho^s + cdt^s - cdT^s + d_{orb}^s + d_{trop}^s - d_{ion,\Phi_i}^s + d_{mult,\Phi_i}^s + \lambda_i^s N_i^s + \varepsilon_{\Phi_i}^s \tag{1b}$$

where the indices s and i refer to the GNSS satellites and the signal frequency being used; P_i and Φ_i are the measured pseudorange and carrier phase range; ρ is the true geometric distance between the satellite and receiver phase centers; c is the speed of light; dt and dT are the receiver and satellite clock biases; d_{orb} is the satellite orbit error; d_{trop} is the tropospheric error; d_{ion,P_i} and d_{ion,Φ_i} are the ionospheric errors for the pseudorange and phase observations respectively; λ is the wavelength; N is the integer ambiguity term; d_{mult,P_i} and d_{mult,Φ_i} are the pseudorange and phase multipath effects respectively; ε_{P_i} and ε_{Φ_i} are the measurement errors for the pseudorange and carrier phase observations.

Data Acquisition, Processing and Analysis

For the present study we used GNSS observational data, from 10 days in 2014, collected at the MGEX network stations UNB3 and CUT0, whereas the required precise orbit and clock products were retrieved from CODE Analysis Centre based on the new multi-GNSS monitoring network of (currently over 140) collocated MGEX stations around the globe running in parallel to the legacy IGS network.

In order to assess both the positioning accuracy and the time convergence it takes to achieve geodetic-level accuracy using multiple GNSS systems, the analyses of the available data from the two MGEX stations were carried out in both single- and multi-GNSS modes. Linear combinations of the available pseudorange and carrier phase observations in two frequencies per GNSS system were used so as to eliminate the first order ionospheric error and get estimates for the integer ambiguities and the tropospheric delays.

The computed station coordinates were compared with those obtained from a 10-day combination solution using GPS, GLONASS, Galileo and BeiDou data, whereby the spatial geometry and the position accuracy that is achieved can be considered that is theoretically optimized due to the significant increase in the number of observed satellites.

A measure of position accuracy of PPP solutions for various scenarios (with regard to session duration, the elevation cut-off angle and the integer ambiguity resolution capability) was obtained with respect to the 10-day solution using the Root Mean Square Deviation (RMSD) indicator:

$$RMSD = \sqrt{\frac{\sum_t^n (x_{1,t} - x_{2,t})^2}{n}} \tag{2}$$

where the $x_{1,t}$ and $x_{2,t}$ refer to the 10-day solution time series and specific scenario solution respectively, and n is the total number of observations.

As shown in Fig. 1, typically the positioning accuracy for GPS- and GLONASS-only solutions can be better than 10 cm after a convergence time of about 30 and 40 minutes respectively. A significant improvement is noted in the combined GPS/GLONASS solutions, whereas the improvement is less noticeable in the case of GPS/Galileo and GPS/BeiDou solutions, mainly due to the small number of currently available Galileo satellites and the low visibility of the BeiDou satellites at station UNB3. The corresponding four GNSS systems combined solution shows a much faster convergence to the level of 10 cm and the highest accuracy for all three coordinate components, as illustrated by the fact that it takes only 2, 1 and 5 minutes for the multi-GNSS solution to achieve this accuracy compared to the GPS-only solution which converges at 5, 4 and 30 minutes in North, East and Up directions. In all other tests performed the improvement was about 15-25%, 10-30%, 20-25% in the positioning accuracy achieved by multi-GNSS solutions compared to GPS-only solutions in North, East and Up directions respectively.

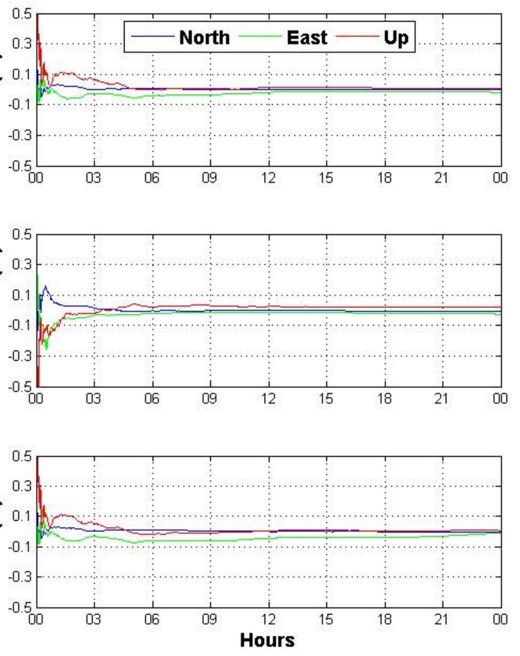

Figure 1: PPP performance vs. session duration, at station UNB3. The combination solutions are designated using the notation G (GPS), R (GLONASS), E (Galileo) and C (BeiDou).

It is well known from practical experience that in GPS- or GLONASS-only PPP solutions when the imposed elevation cut-off angle increases, the obtainable accuracy decreases, largely due to the smaller number of satellites observed at each station, and this influence is mostly observed in the Up direction.

Fig. 2 exhibits the variation of the Root Mean Square (RMS) values of the static PPP solutions as calculated at station CUT0 for all the selected days and for an observation session duration of 24 hours using elevation cut-off angles 10° to 40°. The RMSD values shown indicate that, although the GPS-only PPP solutions generally provide accuracy better than 20 cm in all three components for cut-off angles up to 30°, an improvement of the order of 45% in the PPP positioning accuracy is still possible with the combined use of the four GNSS systems, especially along the North direction.

Clearly, the combination of multiple GNSS systems data creates a more robust model due to the significant increase of the number of observed multi-GNSS satellites, which even in 40° cut-off angles can reach up to some 15 or more satellites, as compared to only 4-5 GPS satellites being typically observed at such high elevation angles. Generally, it is worth mentioning that, from several such daily session tests performed, while in the case of GPS-only solutions the noted maximum RMSD values in the North and East directions were up to the level of 45 cm, the corresponding maximum RMSD values from the combined GPS/GLONASS and GPS/GLONASS/Galileo/BeiDou solutions were reduced to the level of 15 cm or better.

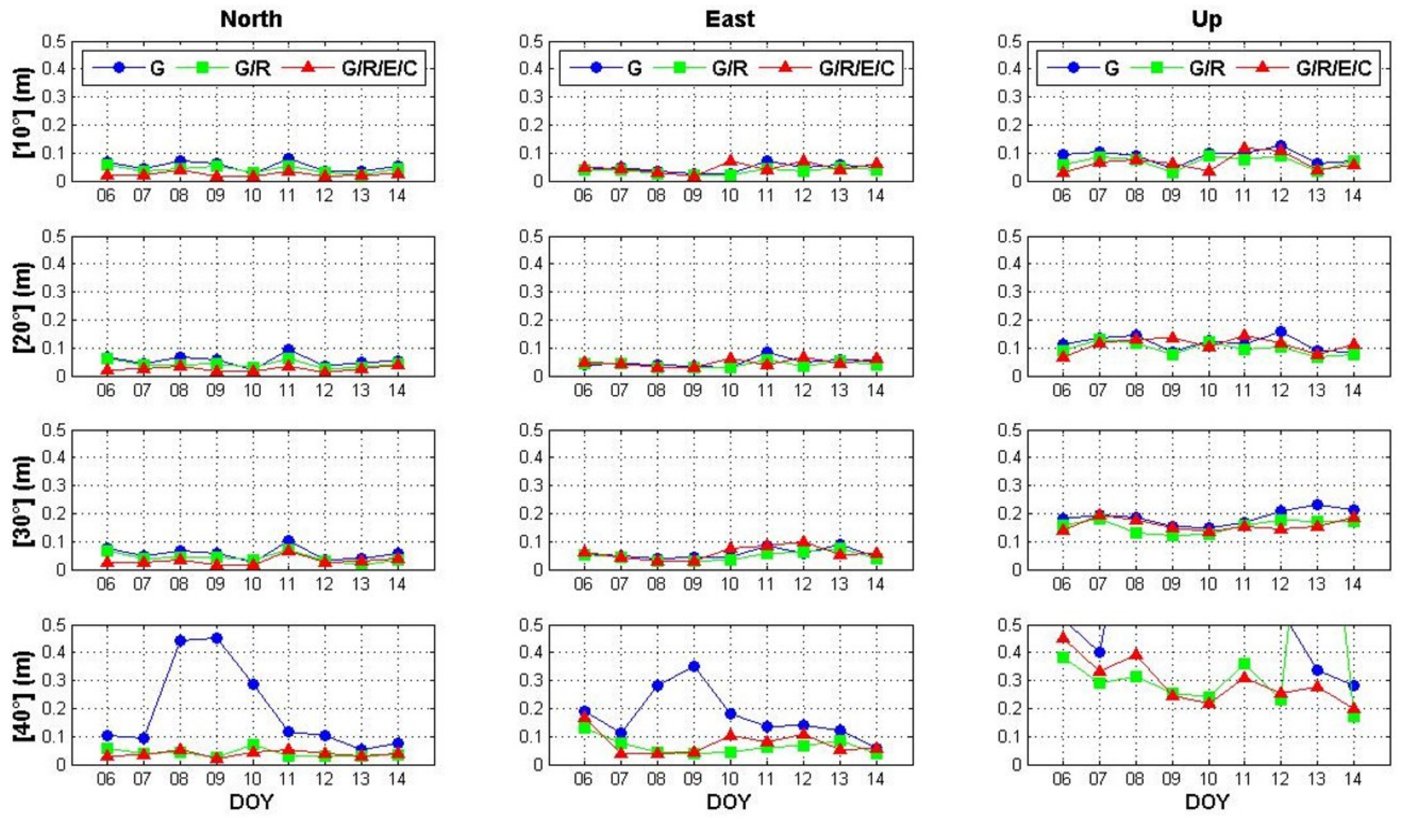

Figure 2: RMSD values (in meters) of static PPP solutions at station CUT0 in a 24-hour long session in single-, dual, and four-system modes under various elevation cut-off angles.

The performance of the standard PPP processing model is vastly restricted due to the inability to resolve the carrier phase ambiguities to their (inherently) integer values, a fact caused by the existence of the fractional cycle biases (FCB) in the carrier phase observables that cannot usually be separated from the integer ambiguities (Ge et al., 2008).

Fig. 3, shows that adding in the PPP processing the wide-lane FCBs, which are provided in the clock products by CNES since November 2009 (Laurichesse, 2011), shortens significantly the convergence time of GPS-only solutions, since it takes only 5, 5 and 10 minutes for GPS-integer fixed ambiguities solutions to converge to the 10 cm desired threshold while the GPS-floating ambiguities solutions require 7, 20 and 30 minutes in the North, East and Up directions respectively. Overall, in all similar tests performed in our study, it was generally observed that there was a shortening of the convergence time about 65%, 50% and 72% in the directions North, East and Up respectively when externally available GPS FCBs were included in the PPP processing.

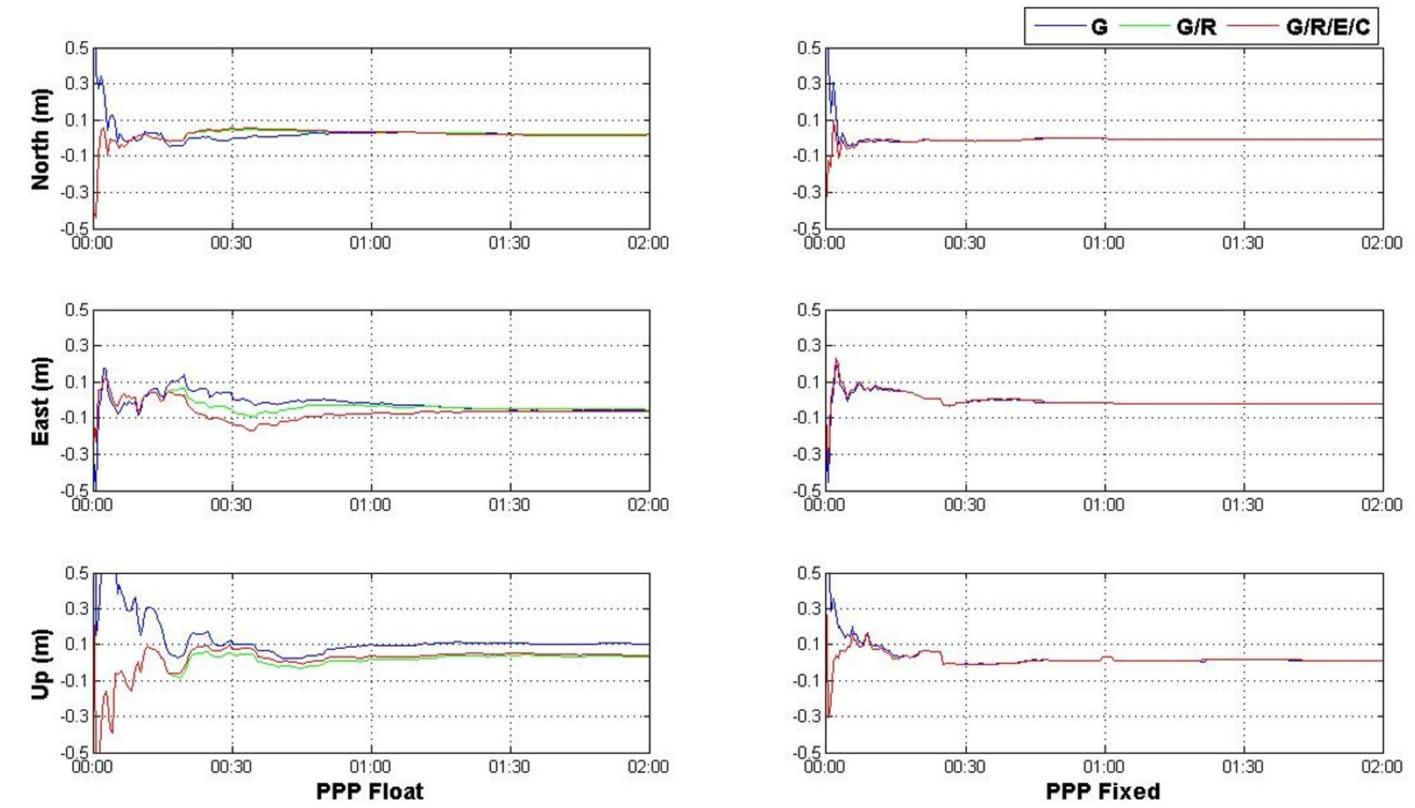

Figure 3: PPP performance, at station UNB3, for integer vs. floating ambiguity resolution solutions with data during the first 2 hours on 07/01/2014.

Conclusions

Combining data from GPS, GLONASS, Galileo and BeiDou systems is becoming increasingly important nowadays, as a means of achieving a geodetically viable position accuracy increase (mostly in the less favorable East direction) and a large reduction of convergence time in PPP solutions compared to GPS-only PPP solutions.

GPS-only solutions with data from high elevation cut-off angles, generally lead to position accuracy and convergence time deviating from satisfactory geodetic thresholds. By contrast, respective multi-GNSS PPP solutions not only show improvement, but also lead to geodetic level accuracies even in extreme 40° elevation cut-off angles.

Analogous improvement is obtained in multi-GNSS solutions whereby handling the GPS ambiguity resolution problem is done by using externally supplied GPS wide-lane FCBs, even though the respective GLONASS, Galileo and BeiDou carrier phase ambiguities retained in their floating values, since no relevant information about them is provided in the clock products available to date from the IGS analysis centres.

References

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