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Precise orbit determination and point positioning using GPS, Glonass, Galileo and BeiDou

Abstract: State of the art Precise Point Positioning (PPP) is currently based on dual-frequency processing of GPS and Glonass navigation systems. The International GNSS Service (IGS) is routinely providing the most accurate orbit and clock products for these constellations, allowing point positioning at centimeter-level accuracy. At the same time, the GNSS landscape is evolving rapidly, with the deployment of new constellations, such as Galileo and BeiDou. The BeiDou constellation currently consists of 14 operational satellites, and the 4 Galileo In-Orbit Validation (IOV) satellites are transmitting initial Galileo signals. This paper focuses on the integration of Galileo and BeiDou in PPP, together with GPS and Glonass. Satellite orbits and clocks for all constellations are generated using a network adjustment with observation data collected by the IGS Multi-GNSS Experiment (MGEX), as well as from Fugro proprietary reference station network. The orbit processing strategy is described, and orbit accuracy for Galileo and BeiDou is assessed via orbit overlaps, for different arc lengths. Kinematic post-processed multi-GNSS positioning results are presented. The benefits of multi-constellation PPP are discussed in terms of enhanced availability and positioning accuracy.

Keywords: BeiDou, Galileo, Intersystem-biases, Multi-constellation Precise Point Positioning

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1 Introduction

The Precise Point Positioning (PPP) technique (Zumberge et al. (1997)) has become increasingly significant in high-precision positioning applications during recent years (Kanzaki et al. (2011); Geng et al. (2010)), as it allows the estimation of accurate receiver coordinates, without the need of a nearby reference station. PPP has other interesting applications, such as time-transfer (Defraigne et al. (2008)), ionospheric (Leandro et al. (2007)) and tropospheric characterization (Kjørsvik et al. (2006)), or biases calibration (Leandro et al. (2010)).

The International GNSS Service (IGS) is routinely generating the most accurate orbit and clock estimates, for GPS and Glonass satellites, by means of a dense global network and several contributing analysis centers (Dow et al. (2009)). Making use of these products and precise observation modeling (Kouba and Héroux (2010)), static absolute positioning can be achieved at centimeter level accuracy in post-processing. Sub-decimeter level accuracy can be achieved in kinematic applications (Hesselbarth (2011)). Real-time users can also access orbit and clock corrections via RTCM streams, enabling decimeter-level accuracy in real-time (Caissy et al. (2012)). In addition, there are several commercial PPP services making use of GPS and Glonass, such as Fugro's G2 (Melgard et al. (2009)) or Trimble's RTX (Leandro et al. (2011)), which also supports the Japanese QZSS (Quasi-Zenith Satellite System).

The current development of BeiDou and Galileo constellations offers new prospects for precise navigation, when combined with traditional GPS and Glonass PPP, thanks to the increased number of satellites available. At the time of writing, the BeiDou constellation consists of 5 Geostationary Orbit (GEO), 5 Inclined Geosynchronous Orbit (IGSO) and 4 Medium-Earth Orbit (MEO) satellites, providing regional coverage around China for continuous positioning. The constellation deployment is expected to resume in 2014, with the further development of the MEO constellation, in order to achieve global coverage before the end of this decade. The Galileo constellation is currently composed of 4 initial In-Orbit-Validation (IOV) satellites. The Full Operational Capability (FOC) phase is expected to start also in 2014 with the launch of the first operational satellites.

This article focuses on the contribution of Galileo and BeiDou to PPP. A prerequisite is the generation of precise

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satellite orbits and clocks for the new constellations. This is done using a network least-squares adjustment, making use of observation data from the IGS Multi-GNSS Experiment (MGEX), as well as from Fugro's proprietary network, which has been made available for this study. The network and the observables available are described in section 2.

Ionosphere-free observation equations for multi-GNSS PPP are presented in section 3, where constellation-dependent intersystem biases are introduced, for Galileo and BeiDou. The processing strategy for orbit and clock estimation is presented in section 4, together with an assessment of the orbit accuracy. The estimated intersystem biases are presented in section 5. Kinematic multi-GNSS positioning results are presented in section 6, where the benefits of adding Galileo and BeiDou to PPP are discussed. Conclusions are summarized in section 7.

2 Tracking data

For GPS and Glonass, the International GNSS Service (IGS) has been providing observation data for scientific purposes during the last twenty years. With the development of new navigation systems, IGS started in 2011 the Multi-GNSS Experiment (MGEX) (Rizos et al. (2013)), aiming at upgrading the current station network to support new constellations. Most of the stations in the MGEX campaign are Galileo-capable, and a subset of them are also tracking BeiDou. The network also observes the Japanese QZSS system, but this system has not been included in this study, as the contribution to PPP is still relatively small, with only one satellite (QZSS-1) available at the moment. At the same time, Fugro is operating a worldwide reference station network for supporting its commercial positioning services, mainly for maritime applications. A subset of the stations in the network has been upgraded to Galileo and BeiDou capability.

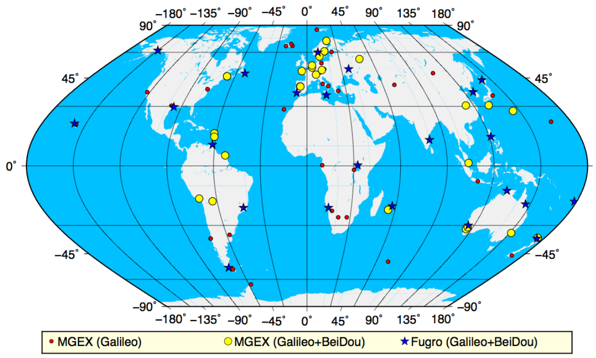

Fig. 1. Geographical distribution of MGEX and Fugro stations, indicating tracking capability for Galileo and Beidou (August 2013).

A map of the stations available in both networks is depicted in Fig. 1. It can be observed that, although there is a concentration of stations in Europe, the network still provides a fairly good global coverage. Particularly relevant are the stations located in Asia-Pacific area, for the tracking of BeiDou IGSO and GEO satellites.

Regarding the frequency plan for the new constellations, BeiDou is broadcasting signals in three carrier frequencies: 1589.74 MHz (B1), 1207.14 MHz (B2) and 1268.52 MHz (B3) (Grelier (2007)), whereas Galileo is transmitting open signals in E1 (1575.42 MHz), E5a (1176.45 MHz), E5b (1207.14 MHz) and E5a+b (1195.795 MHz) (European Commision (2010)), in addition to the future commercial service in the E6 carrier (1278.75 MHz). It is to be noted that BeiDou and Galileo are sharing the B2/E5b carrier, while Galileo and GPS are sharing both L1/E1 and L5/E5a carriers. This opens the door to interoperability applications, which are out of the scope of this study. The reader is referred to Melgard et al. (2013) for a study on interoperability of GPS and Galileo using E1/E5a in PPP.

All the Fugro stations, equipped with Trimble NETR9 receivers, are providing Galileo and BeiDou data in all frequencies. However, it has been found that, for MGEX stations, the signals availability depends on the receiver model, the firmware installed in each receiver and/or the way of generating Rinex3 files from raw data. Table 1 summarizes the number of stations per receiver type in the network, and the availability of Galileo and BeiDou tracking for each receiver type.

For instance, the majority of Javad G3T Delta receivers are tracking Galileo only on E1 and E5a frequencies. Actually only one Javad receiver (WTZZ, Wetzell, Germany), which is equipped with the most modern receiver board and firmware, is also tracking E5b and E5a+b signals, as well as BeiDou B1 and B2 signals.

Septentrio receivers are generally not able to track the BeiDou B3 signals, due to a limitation in the current receiver firmware. Some other stations equipped with Trimble NETR9 receivers are not providing any Galileo or BeiDou measurements, probably due to the way these receivers are configured by the station operators.

In order to maximize data availability with the existing observations, Galileo E1 and E5a, as well as BeiDou B1 and B2 signals have been selected for the subsequent analysis. The observables are processed using the ionosphere-free linear combination, whose observation equations are detailed in the next section.

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Table 1. Receiver type distribution in the MGEX network as per August 15th, 2013. Number of stations tracking each Galileo and BeiDou frequency are shown.

Receiver Brand	Model	Number of stations	Galileo				BeiDou		
			E1	E5a	E5b	E5a+b	B1	B2	B3
Javad	Delta G2T	3	3	3	0	0	0	0	0
	Delta G3T	23	23	23	1	1	1	1	0
Leica	GR10	4	4	4	4	4	0	0	0
	GR25	4	4	4	1	1	0	0	0
	GRX1200	5	5	5	5	5	0	0	0
Novatel	OEM6	1	1	1	0	0	0	0	0
Septentrio	AsteRx3	1	1	1	1	1	1	1	0
	PolaRx4	6	6	6	6	6	6	6	0
	PolaRx4TR	2	2	2	2	2	1	1	0
	PolaRxS	1	1	1	1	1	1	1	0
Trimble	NETR9	26	22	22	22	22	17	17	17
TOTAL		76	72	72	43	43	27	27	17

3 Observations equations

For this study, the GPS observation equations proposed in Collins et al. (2008) have been extended for accommodating multi-GNSS observations, adding inter-systembias parameters between different constellations. The resulting ionosphere-free observations equations, for each GNSS, for pseudorange P and carrier-phase L, between station i and satellite j, are:

$$P_i^{j,GPS} = \rho_i^j + \nu^j \Gamma_i + c\left(\delta t_i - \delta t^j\right) + \varepsilon_{P_i} \tag{1}$$

$$L_i^{j,GPS} = \rho_i^j + \nu^j \Gamma_i + c\left(\delta t_i - \delta t^j\right) + a_i^j + \varepsilon_{L_i} \tag{2}$$

$$P_i^{j,GLO} = \rho_i^j + \nu^j \Gamma_i + c\left(\delta t_i - \delta t^j + ISB_i^{j,GLO}\right) + \varepsilon_{P_i}^j \tag{3}$$

$$L_i^{j,GLO} = \rho_i^j + \nu^j \Gamma_i + c\left(\delta t_i - \delta t^j + ISB_i^{j,GLO}\right) + a_i^j + \varepsilon_{L_i}^j \tag{4}$$

$$P_i^{j,GAL} = \rho_i^j + \nu^j \Gamma_i + c\left(\delta t_i - \delta t^j + ISB_i^{GAL}\right) + \varepsilon_{P_i}^j \tag{5}$$

$$L_i^{j,GAL} = \rho_i^j + \nu^j \Gamma_i + c\left(\delta t_i - \delta t^j + ISB_i^{GAL}\right) + a_i{}^j + \varepsilon_{L_i}^j \tag{6}$$

$$P_i^{j,BEI} = \rho_i^j + \nu^j \Gamma_i + c\left(\delta t_i - \delta t^j + ISB_i^{BEI}\right) + \varepsilon_{P_i}^j \tag{7}$$

$$L_i^{j,BEI} = \rho_i^j + \nu^j \Gamma_i + c\left(\delta t_i - \delta t^j + ISB_i^{BEI}\right) + a_i^j + \varepsilon_{L_i}^j \tag{8}$$

where:

- ρ_i^j is the geometric distance between station and satellite, assuming relevant corrections, such as antenna phase center corrections or phase wind-up, have been already accounted for.
- $\nu^j \Gamma_i$ is the wet tropospheric delay between station and satellite, where Γ_i is the tropospheric zenith delay and ν^j is the associated elevation-depending mapping function. The dry component of the tropospheric delay is removed from the observations using an a-priori model.
- δt_i and δt^j are the epoch-wise receiver and satellite clock offsets, respectively. Following this notation, it has been assumed that there is a single receiver clock common to all observables from different GNSS. GNSS-differences are accounted for in the intersystem-bias terms.
- c is the speed of light.
- $ISB_i^{j,GLO}$ is the GPS-Glonass intersystem-bias term. It is to be noted that this bias depends on each station i and satellite j, due to the Frequency Division Multiple Access (FDMA) scheme implemented by Glonass, which induces receiver- and satellite-dependent interchannel biases. As shown in Reussner and Wanninger (2011), each frequency (satellite) encounters a slightly difference delay in the receiver.
- ISB_i^{GAL} and ISB_i^{BEI} are the GPS-Galileo and GPS-BeiDou intersystem-biases, respectively. Contrary to Glonass, it is to be noted that these are satellite-independent, as Galileo and BeiDou have adopted the Code Division Multiple Access (CDMA) scheme, meaning that all satellites from the same constellation use the same carrier-frequency. Significant biases appear though depending on the receiver model,

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but might depend also on the digital signal processing (firmware) happening inside the receiver. It needs to be mentioned that the new generation of Glonass satellites (Glonass-K) is expected to implement CDMA as well.

- a_i^j is the ambiguity term between station and satellite, associated to the carrier-phase measurements. For the ionosphere-free linear combination, this term is in general not integer, due to non-integer nature of the combination coefficients, and the presence of satellite and receiver hardware delays (Laurichesse et al. (2009)).
- $\varepsilon_{P_i}^j$ and $\varepsilon_{L_i}^j$ are unmodelled effects, such as thermal noise and multipath, for pseudorange and carrier-phase, respectively. It is to be noted that, for GNSS measurements, $\varepsilon_{L_i}^j \ll \varepsilon_{P_i}^j$.

4 Orbit and clock estimation

4.1 Processing strategy

For estimation of orbit and clocks, NAPEOS (Springer and Dow (2009)) software package has been used. The software has been extended to process BeiDou, on top of the existing capabilities for GPS, Glonass and Galileo. The processing strategy, depicted in Fig. 2, will be described next.

In order to obtain an a-priori orbit, broadcast ephemeris can be used for GPS and Glonass. For Galileo, test ephemeris started in March 2013, but satellites are still unhealthy meaning that this data might not always be reliable. For BeiDou, MGEX stations are at the moment not providing any ephemeris. For these reasons, Two Line Elements (TLEs) are used, for both Galileo and BeiDou, in order to obtain an a-priori orbit initialization. The accuracy of this a-priori orbit is at sub-kilometer level. TLEs can be downloaded from www.space-track.org, which also includes the format description. In a first processing step, a least-squares estimation using only pseudorange observations is performed, in order to improve the TLE-derived orbits and to obtain a-priori satellite clocks for Galileo and BeiDou. After this step, the orbit accuracy is around meter-level, similar to what is obtained for GPS and Glonass via broadcast ephemerides.

In a second step, both pseudorange and carrier-phase observations are used, in order to benefit from the precision of the carrier-phase measurements. Estimated parameters are the satellite state vectors, solar radiation pressure parameters, wet tropospheric delays, satellite and station clocks, intersystem-bias terms and carrier-phase ambiguities.

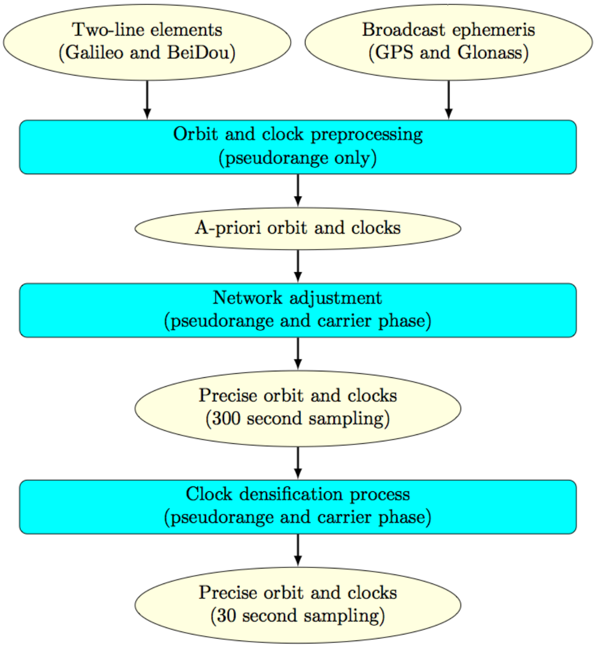

Fig. 2. Processing strategy for generation of orbit and clocks, including Galileo and BeiDou.

Finally, in order to obtain suitable clocks for PPP at 30 seconds sampling, a final clock densification process is performed. In this final step, only station and satellite clocks are estimated. All other parameters are kept fixed to the previous estimates.

4.2 Modeling for Galileo and BeiDou

A summary of the models being used for all constellations is presented in Table 2. Being relatively new constellations, BeiDou and Galileo have a number of modeling limitations compared to more mature systems, such as GPS and Glonass. The impact of these limitations will be addressed in the current section.

GPS and Glonass precise antenna phase center corrections (Schmid et al. (2007)) have been made available as part of the IGS activities via the Antenna Exchange (ANTEX) format, both for transmitting and receiving antennas. These precise corrections are not available yet for either Galileo or BeiDou. For satellite antennas, the MGEX project has released approximate values for the distance between the satellite center of mass and the antenna phase center. These are [0.2, 0, 0.6] m for Galileo and [0.6, 0, 1.1] m for BeiDou, XYZ in the satellite body-fixed reference frame. It

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Table 2. Summary of models used for multi-GNSS processing.

	GPS	Glonass	Galileo	BeiDou
Observation sampling	**30 seconds**			
Elevation cut-off	**10 degrees**			
Signal selection	**L1/L2**		**E1/E5a**	**B1/B2**
Antenna phase-center corrections	**IGS Antex file**		**A-priori values**	
Tropospheric modeling	**GPT/GMF Boehm et al. (2007)**			
Ionospheric modeling	**First order removed by linear combination**			
Solar Radiation Pressure	**CODE Empirical Model with 5 parameters**			

is expected that these values have an uncertainty around decimeter level. Nadir- or azimuth-dependent corrections are not available for these constellations so far.

On the receiving antennas, the phase center offset and azimuth- and elevation-dependent variations for Galileo and BeiDou frequencies are expected to be slightly different (up to few centimeters) to the ones used for GPS, due to the different frequencies used by Galileo and BeiDou. At the time of writing, there are no publicly available calibrations for the antennas used in MGEX stations. For this study, GPS calibrations have been used for Galileo and BeiDou, which introduces an additional uncertainty below decimeter level.

Satellite attitude modeling is not fully known for the new constellations. Under nominal attitude, yaw-steering mode has been assumed for Galileo and BeiDou, in the same way as for GPS (Kouba (2008)). The behavior of the new satellites under eclipse seasons remains a topic for further research. A mismodelling of the satellite attitude in GNSS impacts the wind-up correction in carrier-phase measurements (Wu et al. (1993)), due to the relative orientation between transmitting and receiving antennas.

In order to limit the impact of this uncertainty in PPP, the very same models have been applied in the orbit adjustment and in the precise point positioning estimation.

4.3 Orbit quality

For the orbit estimation, two different sets of daily solutions have been generated, in order to assess the impact of the orbit arc length on the orbit accuracy. The first solution is based on 24 hours arcs, while the second is based of 72 hours, where the central 24 hours are extracted as daily solutions.

In order to estimate the orbit quality for GPS and Glonass, a comparison with IGS Final products has been performed. For the 3-day arc orbits, the monthly RMS is 1.7 cm for GPS, 3.9 cm for Glonass.

Regarding BeiDou and Galileo satellites, the orbit precision can be assessed measuring orbit differences between consecutive solutions at day boundaries. The monthly RMS values obtained for these day boundary differences, for both 1-day and 3-days arc solutions, for each Galileo and BeiDou satellite, are shown in Table 3. Sample GPS and Glonass satellites have been included for reference.

It can be observed that 3-day orbit solution improves significantly the orbit precision with respect to the 1-day solution, thanks to the better observability of the orbit dynamics over longer data arcs. Additionally, GEO orbit precision is typically lower than MEO and IGSO orbits, mainly on the along-track component. This could be explained by the fact that there is no geometry variation between the GEO satellites and the reference station network, which weakens the orbit estimation. Nevertheless, sub-decimeter level accuracy could still be achieved on the radial and cross-track components.

It is also interesting to note that the 3-day orbit solutions for IGSO satellites C07 and C10 are significantly worse than other IGSO satellites. The reason being that these satellites were under Earth eclipse periods during the first two weeks of August 2013. As mentioned earlier, precise attitude modeling for these satellites needs to be studied in order to obtain accurate orbits also during eclipse seasons.

For Precise Point Positioning, the 3-day orbit solution will be used, in order to achieve the highest possible accuracy. Additionally, the GEO satellites have been deweighted with a factor of 3 in PPP with respect to IGSO and MEO, in order to account for orbit uncertainty in these satellites.

5 Intersystem biases

When processing multi-GNSS observations, intersystem-biases need to be taken into account. For Glonass, these

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Table 3. Orbit day-boundary differences (RMS), during August 2013, for 24 and 72 hours orbit arcs. All units are centimeters.

Satellite Type	PRN	1-day orbit arcs			3-day orbit arcs		
		Radial	Along-track	Cross-track	Radial	Along-track	Cross-track
GPS	G01	4.5	4.6	2.7	0.6	0.5	0.5
	G25	1.7	5.3	2.3	0.4	0.5	0.5
GLONASS	R02	3.1	7.7	4.4	0.3	1.1	1.3
	R03	3.1	8.1	4.7	0.4	1.3	1.2
Galileo	E11	7.4	18.3	9.8	2.7	11.6	3.4
	E12	6.0	15.0	9.5	3.5	8.7	2.3
	E19	4.8	22.5	12.3	1.3	3.7	3.5
	E20	4.2	19.2	9.3	1.2	3.7	3.5
BeiDou GEO	C01	16.2	87.3	15.2	2.0	24.2	3.9
	C02	81.9	185.9	9.0	6.3	30.7	11.9
	C03	45.8	121.0	19.3	10.4	38.7	5.1
	C04	34.4	76.7	10.6	3.3	25.9	5.2
	C05	50.1	113.7	15.3	5.3	30.7	9.1
BeiDou IGSO	C06	58.9	22.4	16.9	3.0	4.3	2.7
	C07	24.7	22.1	24.3	15.4	60.5	11.8
	C08	22.8	12.8	16.6	1.8	4.7	2.5
	C09	17.0	10.9	10.2	1.0	2.2	1.8
	C10	24.6	15.3	17.6	13.1	35.1	9.6
BeiDou MEO	C11	4.5	44.8	11.5	1.2	6.6	2.6
	C12	4.2	54.3	10.6	1.4	7.3	2.8
	C13	5.0	48.5	16.2	0.9	7.9	4.8
	C14	5.2	50.2	17.7	0.9	8.2	5.2

biases have been extensively analyzed in the literature (Chuang et al. (2013); Wanninger (2012)), and this study will mainly focus on Galileo and BeiDou. As described in section 3, a single parameter per station and system (either Galileo or BeiDou) is enough to account for intersystem biases, as all satellites are using the same carrier frequency.

Additionally, in order to define the clock datum, a zero-mean condition has been applied to all intersystem-biases in the orbit and clock estimation process, for each constellation. This approach allows assessing relative differences in intersystem-biases between different receivers in the network.

The daily intersystem biases for each constellation are depicted in Fig. 3. Generally, a strong receiver-type dependency can be observed, with all stations with the same receiver model showing similar biases. An exception has been found in receiver WTZZ (Javad Delta G3T), which shows significant differences with respect to other Javad receivers. One possible explanation is that this receiver has a different architecture that allows it to track also BeiDou. It is also to be noted that the BeiDou intersystem-bias for WTZZ is different by more than 100 ns compared to Trimble or Septentrio receivers, meaning the effect is significant enough and cannot be ignored for precise applications. Additionally, it is noticeable that there are still small remaining differences with stations equipped with the same receiver type. This might be due to antenna- or cable-induced delays, or thermal effects between hardware installations at different locations.

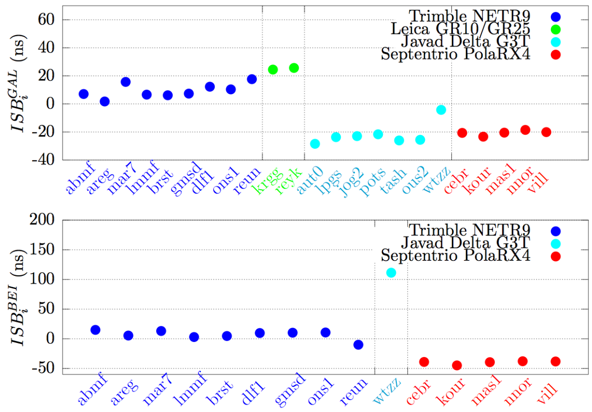

Fig. 3. Intersystem-bias estimates for several receivers in the MGEX network, for Galileo (top) and BeiDou (bottom).

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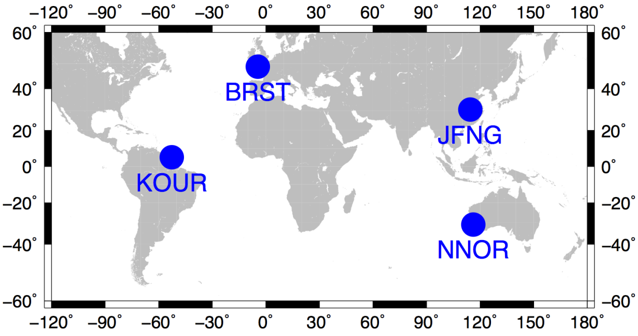

Fig. 4. MGEX stations selected for multi-GNSS PPP.

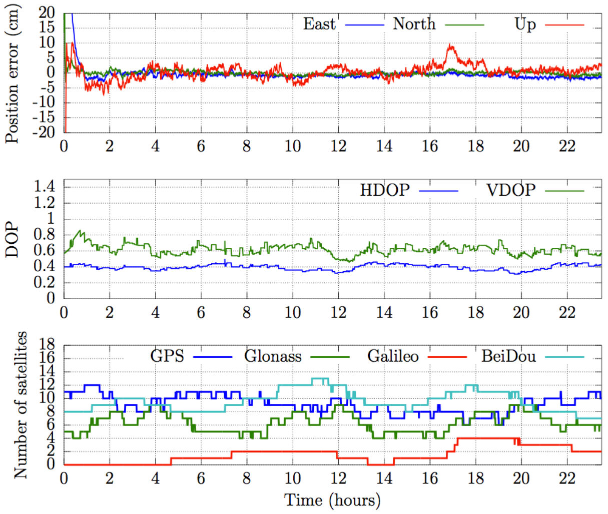

Fig. 5. PPP Kinematic results for station NNOR on August 26th, 2013.

6 Precise Point Positioning assessment

For multi-constellation Precise Point Positioning, a new kinematic PPP algorithm has been implemented in NAPEOS, based on sequential least squares, following the guidelines given in Kouba (2009), and the observation equations described in section 3.

In order to assess the effect of multi-constellation precise point positioning, some reference stations from the MGEX network have been selected. These are KOUR (Kourou, French Guyana), BRST (Brest, France), NNOR (New Norcia, Australia) and JFNG (Jiufeng, China). The station locations are indicated in Fig. 4.

All stations are tracking GPS, Glonass, Galileo and BeiDou MEO. In addition, JFNG and NNOR are also tracking BeiDou IGSO and GEO satellites, thanks to their geographical location.

Figure 5 shows kinematic multi-GNSS PPP results for station NNOR on August 26th, 2013. The 95% position error quantiles are 1.74, 1.16 and 3.95 cm, in the East, North and Up components, respectively, after removing the first two hours of convergence period.

It is interesting to notice the high number of satellites available for PPP when using all 4 constellations, resulting in a very stable geometry (Dilution of Precision-DOP). In order to assess the benefits of multi-GNSS PPP, daily kinematic PPP results have been obtained for the month of August 2013, for all four stations, in different configurations: GPS only, GPS+Glonass, GPS+Glonass+Galileo and GPS+Glonass+Galileo+BeiDou. The monthly average of the daily 95% position error percentile is summarized in Fig. 6. As shown in previous studies (Hesselbarth (2011)), the contribution of Glonass on top of GPS is quite significant in terms of kinematic positioning, thanks to the increased number of satellites available and improved geometry. For example, the NNOR vertical error is reduced by 36.3% when adding Glonass on top of GPS. Galileo further improves the vertical error by 3.5%, and the additional improvement with BeiDou is 6.7%. The contribution of Galileo on top of GPS and Glonass is relatively small, due to the small number of satellites available, which is visible from a station for limited hours per day. The contribution of BeiDou is slightly more important, especially in JFNG and NNOR, where IGSO and GEO also contribute to the positioning solution in those locations. Multi-constellation PPP is particularly suitable in situations with reduced sky

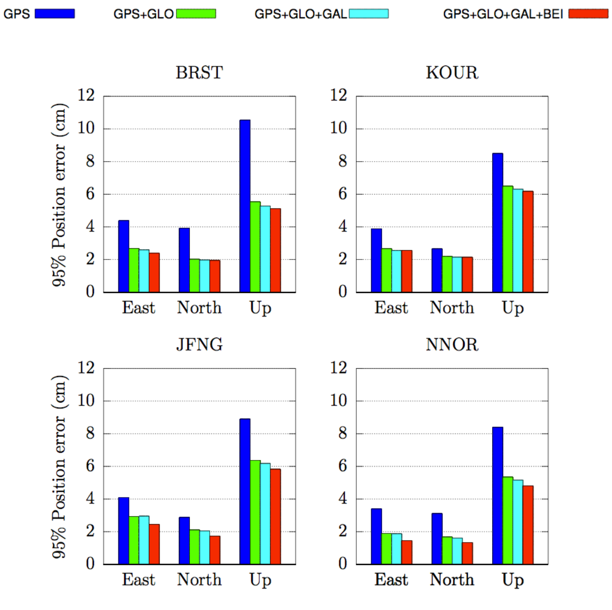

Fig. 6. Multi-constellation kinematic positioning statistics for several stations in MGEX.

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visibility, where the increased number of satellites allows to obtain a significant higher availability and accuracy compared to standalone GPS. In order to simulate this scenario, the PPP engine has been run with several elevation cut-off angles from 0 (full sky visibility) to 35 (reduced sky visibility) degrees. The results for station NNOR are depicted in Fig. 7, in terms of positioning accuracy and average dilution of precision. It can be observed how the accuracy of the GPS-only solution degrades rapidly with partial sky visibility. The multi-GNSS solution behaves significantly better in this condition, in particular the one with all four constellations, where sub-decimeter level accuracy can still be obtained even in the 35 degrees cut-off scenario, mainly thanks to the increased number of satellites visible for BeiDou, on top of GPS, Glonass and Galileo. In this case, Galileo improves the vertical accuracy by 12.6%, and BeiDou brings an additional 33.1% improvement. Figure 8 represents the position availability for stations JFNG and NNOR with different elevation cut-off angles. Position availability is here defined by the percentage of time when 5 or more satellites are visible with a Geometric DOP (GDOP) lower than 10.

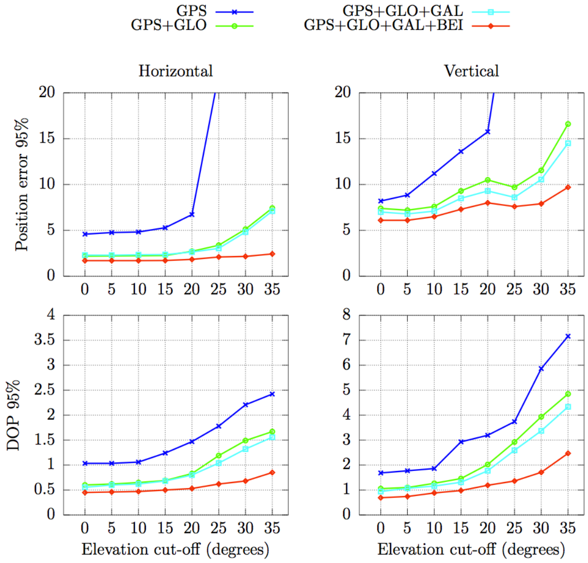

Fig. 7. Positioning statics and Dilution of Precision (DOP), for different stations and cut-off angles, for station NNOR on August 26th, 2013.

The solution with all four systems is significantly better. It needs to be mentioned that these results correspond to stations where BeiDou IGSO and GEO are available. In other regions of the world, the improvement is currently not so significant. A worldwide contribution will be achieved when Galileo and BeiDou MEO constellations will be fully deployed.

Regarding static PPP, it has been found that the addition of Galileo and BeiDou does not significantly improve the daily coordinate repeatability. The reason is that the quality of 24 hours GPS-only PPP is already at centimeter level, and the addition of new constellations does not improve significantly the accuracy. This was shown already for the case of Glonass in Hesselbarth (2011).

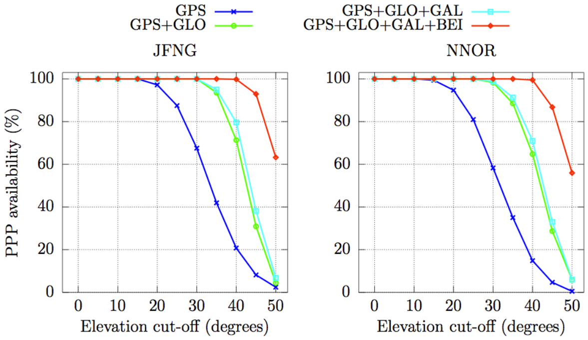

Fig. 8. PPP availability for stations NNOR and JFNG on August 26th, 2013.

7 Summary and Conclusions

The GNSS landscape is evolving rapidly, with the addition of emerging satellite systems on top of GPS and Glonass. In this study, precise orbit estimation results have been presented for Galileo and BeiDou. The achieved orbit precision is generally at sub-decimeter level for Galileo and BeiDou MEO and IGSO satellites. The orbit estimation for GEO satellites is challenging due to the lack of geometry variation with respect of the reference station network, and precision estimates are at few decimeter level. Satellite modeling remains an area for further research, in terms of antenna phase center corrections and precise attitude modelling.

Significant intersystem-biases differences have been detected between different receiver brands, which cannot be neglected for precise applications. Extended observation equations have been presented to accommodate these biases, both in network adjustment and PPP solutions.

Multi-GNSS PPP kinematic results show enhanced accuracy when using all four satellite systems together. However, the accuracy improvement is relatively small compared to the GPS+Glonass case under good sky visibil-

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ity. The improvement becomes more significant under reduced sky visibility conditions, where the increased number of satellites allows obtaining significantly higher accuracy and availability for the position solution. This is particularly visible in the Asia-Pacific area where BeiDou IGSO and GEO satellites are available for positioning. It can be expected that this level of performance will be extended worldwide with the further deployment of Galileo and BeiDou during this decade.

In this context, the data provided by the IGS MGEX campaign is highly valuable for the scientific community to get a better understanding of the new GNSS systems and signals. This study would not have been possible without such data. The authors are also grateful to Fugro for delivering the reference station data for scientific purposes.

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