TRIPLE-CONSTELLATION DUAL-FREQUENCY RTK: INCLUDING BEIDOU

João Viana, Frank Boon, Jean-Marie Sleewaegen (Septentrio)

Evan Bollard (GlobalPos)

BIOGRAPHIES

João Viana holds a M.Sc. in aero-space engineering from Instituto Superior Técnico in Portugal. He is currently a GNSS research engineer at Septentrio in Belgium. His main area of expertise is high precision GNSS with emphasis on RTK.

Frank Boon is head of Septentrio's research department. He received his M.Sc. in aero-space engineering from Delft University of Technology. He is responsible for the design and implementation of positioning algorithms in the firmware of Septentrio's GNSS receivers. His research interests include error models of GNSS measurements and optimization of positioning algorithms for high dynamic applications.

Dr. Jean-Marie Sleewaegen is responsible for the GNSS signal processing, system architecture and technology development at Septentrio Satellite Navigation. He received his M.Sc. and Ph.D. in electrical engineering from the University of Brussels. He received the Institute of Navigation (ION) Burka award in 1999.

Mr Evan Bollard is a GNSS solutions specialist with GlobalPos Pty Ltd. He received his Bachelor of Surveying degree from The University of Newcastle, Australia. He has over 25 years' experience in the integration of GNSS systems in multiple applications.

ABSTRACT

When GLONASS reached full operational capability several years ago, surveyors experienced that RTK equipment could be used in environments where GPS-only equipment failed to deliver sufficient availability. With the rapid deployment of BeiDou, an even further increase in positioning accuracy and availability is expected.

This paper presents an assessment of the benefits of including BeiDou in a multi-constellation dual-frequency RTK engine (GPS+GLO+BDS) using data recorded within the coverage area of BeiDou constellation. The performance of RTK positioning is evaluated for various combinations of constellations. In particular, it is shown that with three GNSS constellations continuous RTK performance is ensured even in the event of a total failure of one GNSS constellation.

INTRODUCTION

The current BeiDou constellation (BDS) is in a mature operational status. With almost as many BDS satellites in view as GPS in the Asia-Pacific sky, BeiDou is currently able to function as a sole satellite navigation system at least in this region. It currently features 14 active satellites emitting in three frequencies: B1, B2 and B3 (35 satellites are planned for the full constellation). Unlike GPS and GLONASS constellations, which use only one type of orbit (MEO), BeiDou satellites orbit the Earth along three distinct types of orbits: geosynchronous orbits (GEO, 5 satellites), medium earth orbits (MEO, 4 satellites), and inclined geosynchronous orbits (IGSO, 5 satellites) [1]. The purpose of combining different types of orbits is to ensure reliable 24/7 coverage in the Asia-Pacific region by using IGSO and GEO satellites which always have high elevations in this region. Septentrio pioneered the use of BeiDou signals in commercial receivers. The first signal tracking was reported in 2007 [2], while the first stand-alone (SA) positional solution was reported in 2012 [3], [4]. Septentrio has access to the Asia-Pacific region through co-operation with GlobalPos in Australia. Two PolaRx4/S Septentrio receivers featuring triple carrier tracking capabilities were used to develop and validate B3 signal tracking capabilities for the next generation Septentrio receivers in the context of this paper.

The paper begins with the description of the measurement collection campaign followed by the analysis of the BDS measurement quality. B1 pseudorange noise and multipath (MP) is assessed via the pseudorange multipath linear combination [5].

Afterwards, the performance of the new BDS-capable RTK engine is presented. The benefits of including BeiDou in a triple-constellation dual-frequency RTK engine (GPS+GLO+BDS) are evaluated. To better assess the benefits of BeiDou, performance of different GNSS constellation configurations are compared: GPS+BDS RTK versus GPS+GLO RTK, as well as BDS-only RTK versus GPS-only RTK. Performance figures are shown in the form of planimetric and vertical precision error and covariance figures, as well as time to first RTK fix comparison (TTFF) with a high elevation mask. TTFF and the availability of RTK are estimated with a high elevation mask as a way to simulate the performance of RTK in an urban canyon environment. Planimetric and vertical positional deviations and variances are also presented.

MEASUREMENT COLLECTION

Field observations were made at the east coast of Australia, in a benign rural environment with very few obstructions (some low trees) in locations where the errors caused by multipath are expected to be relatively low. Conventional survey methods were used whereby each antenna was placed on a survey tripod or a bipod-supported range pole. Two receivers were used: PolaRx 4 PRO (ser# 3000954) and PolaRxS PRO (ser# 2003865) with custom firmware which allowed the tracking of all the BDS signals including B3. These two receivers were connected to two antennas: Septentrio's Choke Ring MC #5099 and a Javad's GrAnt-G3T respectively. The data was collected in hourly files over two consecutive 24 hour periods at a 1 Hz data rate during the days 53 and 54 of 2014. The baseline length was approximately 16.5 km with an altitude difference of 240m.

MEASUREMENT ANALYSIS

The performance of a multi-constellation RTK engine significantly depends upon a proper noise modeling for each constellation. Optimal relative weighting of constellations due to correct models for thermal noise and multipath errors of carrier phases as well as of pseudorange measurements is particularly important (modeling of atmospheric delays is common for all constellations). Underestimating the thermal noise and the multipath error will negatively impact the reliability and accuracy of the RTK solution. Overestimating of these errors will de-weight the contribution of a constellation to be added: in the extreme case of measurement variances being too high, the engine will behave as if the constellation in question is not present.

Due to the similarity of the signal structure, it is expected that the code thermal noise and multipath errors of BeiDou resemble that of GPS. This paper focuses on the behavior of the pseudorange multipath (in the future, the phase multipath will also be studied). The pseudorange multipath linear combination [5] for the B1 pseudoranges was computed in order to assess the combined noise and multipath error in the pseudoranges - Figure 1.

The average standard deviation of the multipath and noise is 0.213 m for the MEO satellites, 0.498 m for the IGSO satellites and 0,614 m for the MEO satellites.

The GEO satellites at this observation location have lower standard deviation as they are virtually static in the sky at a high elevation. Hence their observations do not show the typical increase of the error dispersions typical of rising and setting satellites which have low elevations (as seen for IGSO C08 in Figure 5, 12 to 15 h). The standard deviation observed for the IGSO and MEO satellites are comparable to the levels typically observed for the GPS satellites (0.665 m in this data set).

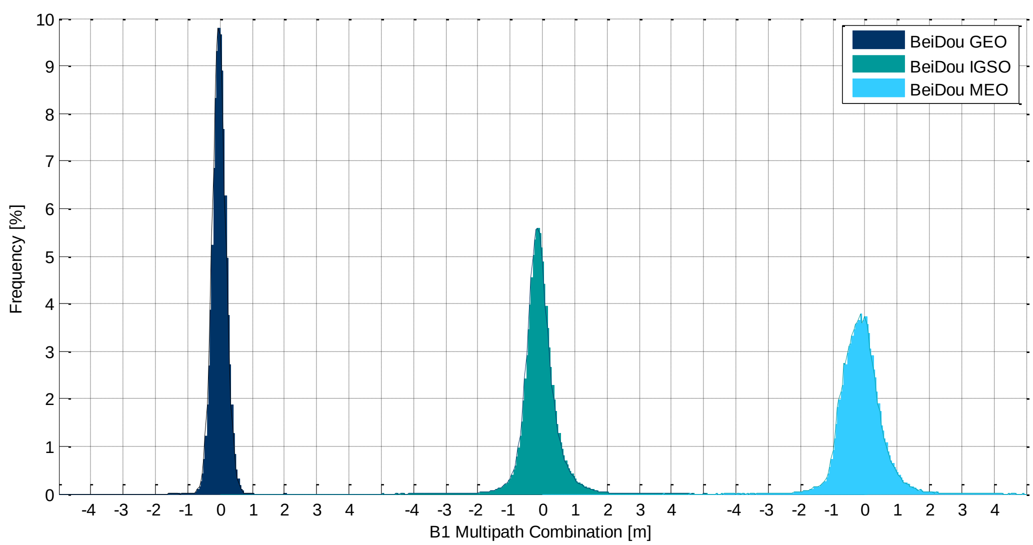

Figure 1 - Histogram of the B1 MP combination.

As an example, Figure 2 to Figure 7 show the code multipath and noise for the four active GEO satellites over a full day.

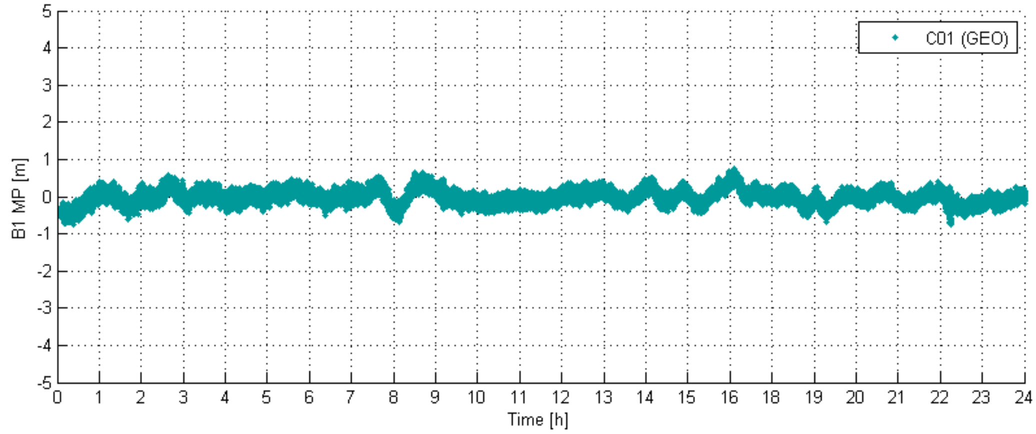

Figure 2 - B1 multipath combination for GEO C01.

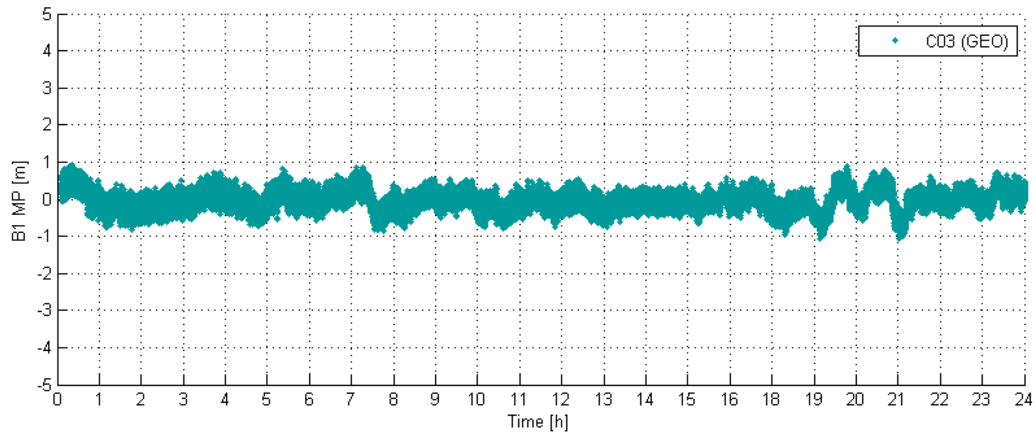

Figure 3 - B1 multipath combination for GEO C03.

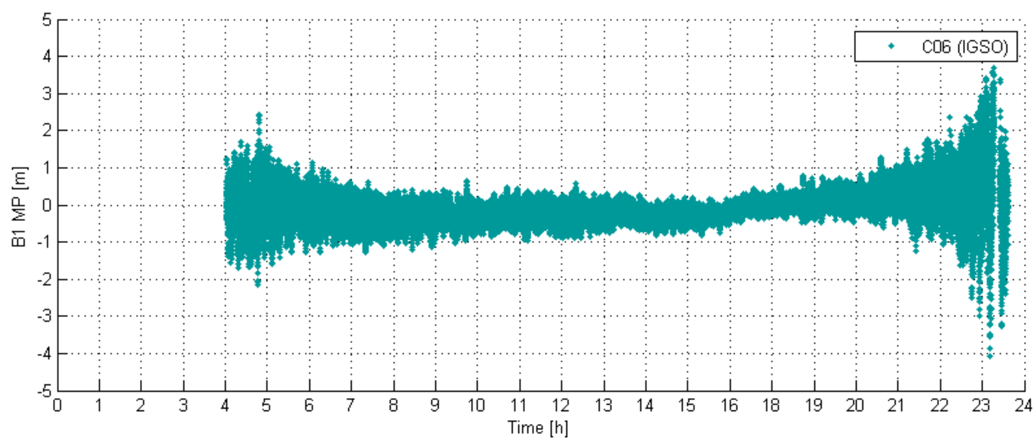

Figure 4 - B1 multipath combination for IGSO C06.

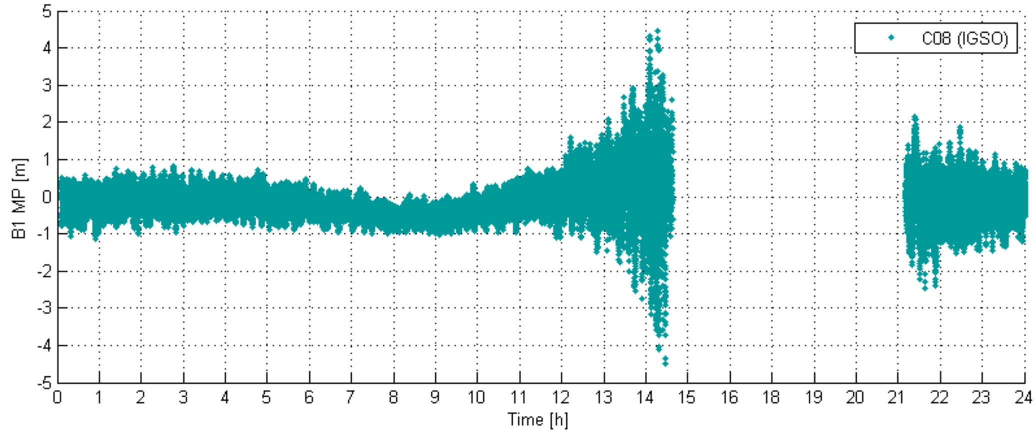

Figure 5 - B1 multipath combination for IGSO C08.

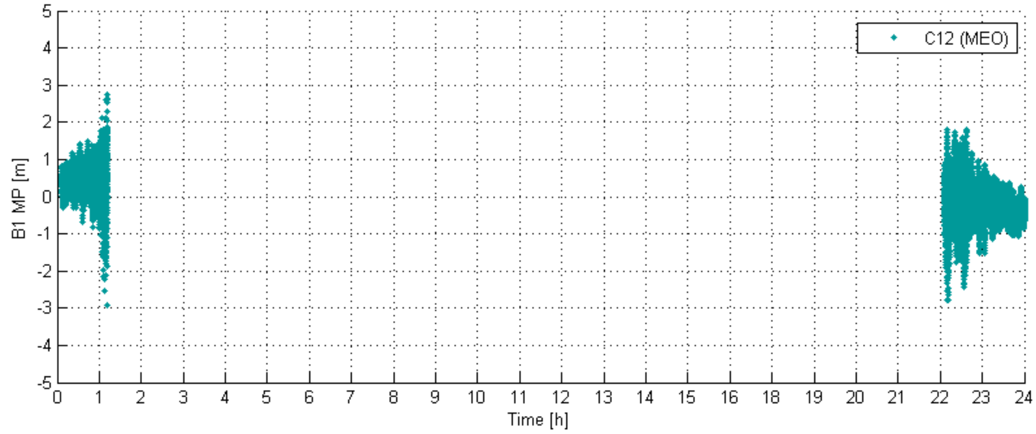

Figure 6 - B1 multipath combination for MEO C12.

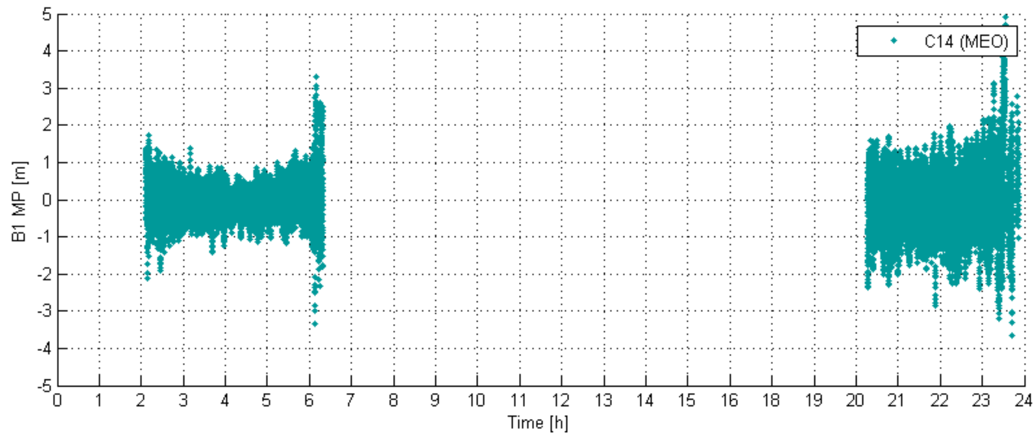

Figure 7 - B1 multipath combination for MEO C14.

RTK PERFORMANCE ANALYSIS

The collected data was post-processed with Septentrio's latest BDS-capable RTK. This software emulates the real-time receiver processing: no apriori assumptions are made about the rover position and dynamics (moving), differential corrections between base and rover receivers are not synchronized and no backwards processing is applied.

Septentrio's RTK engine is based on the colored-noise form of the Kalman filter which takes into account time correlation of measurements. Pseudorange multipath and carrier-phase ionosphere delay are modeled as first order auto-regressive processes and are estimated in real-time by the Kalman Filter. The troposphere delay is corrected a-priori by an offline model. Pseudorange and carrier-phase thermal noise error models use real-time carrier-to-noise information from the GNSS tracker. Further details about Septentrio's RTK engine can be found in previous work [6].

POSITION ANALYSIS

Different constellation configurations are studied to assess the contribution of BDS to the RTK positioning engine:

- GPS+GLO+BDS vs GPS+GLO (Figure 8 to Figure 10)
- GPS+GLO vs GPS+BDS (Figure 11 to Figure 13)
- GPS-only vs BDS-only (Figure 14 to Figure 16)

Inclusion of dual-frequency BeiDou measurements (B1 and B2), together with dual-frequency GPS and GLONASS (L1 and L2) enhances overall geometry, as observed in Figure 8. This improves float ambiguity convergence, reduces TTFF (as later shown in Figure 18) and improves overall reliability. The extra redundancy added to the system constrains the position solution to unprecedented levels, making it easier to detect unmodeled errors and biases and therefore strengthening the RAIM algorithms. As a result, the addition of BeiDou also enhances the use of GPS and GLONASS. This overall improvement leads to higher precision and reduced RMS even in benign environments, as demonstrated in Figure 9 and Figure 10. The observed improvement in position precision is somewhat limited but the real advantage of the triple-constellation engine is the increase in RAIM precision, which will make a significant difference in harsh environments, where the measurements are contaminated with unmodeled errors and biases.

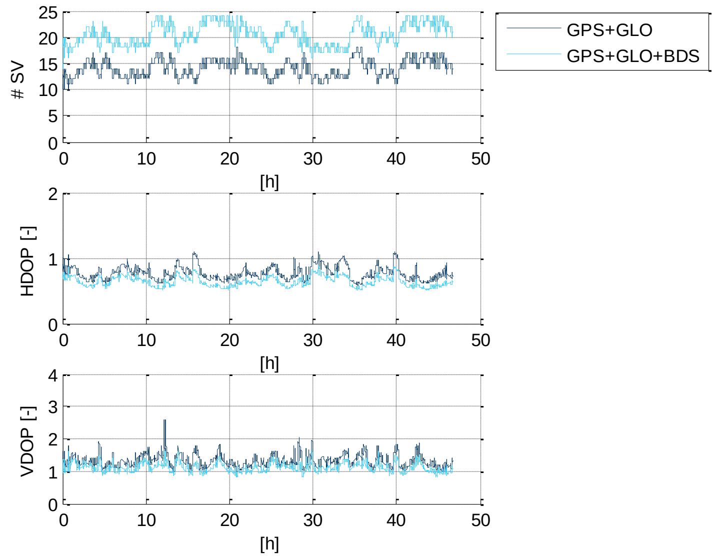

Figure 8 - Number of satellites used in RTK, HDOP and VDOP over 48 hours.

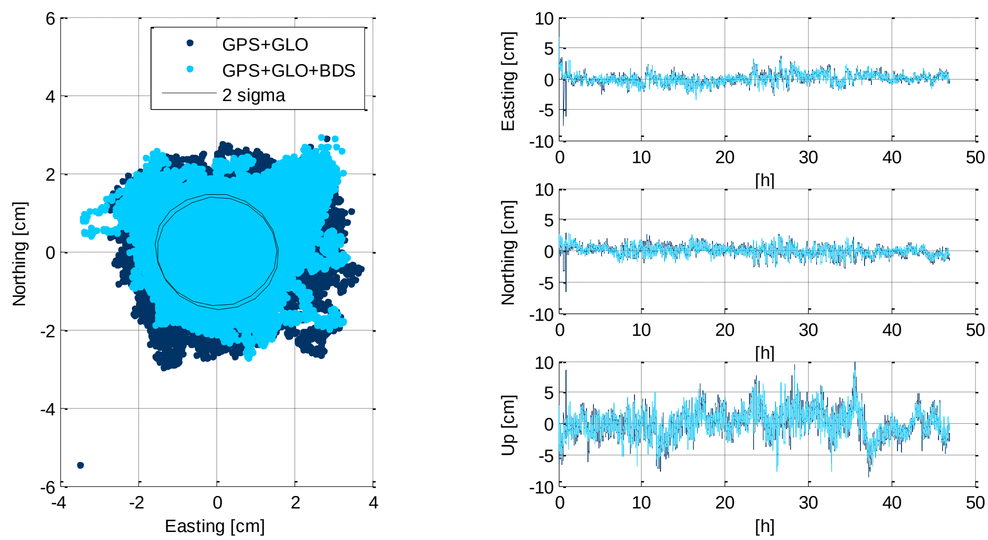

Figure 9 - RTK error over 48h (GPS+GLO+BDS vs GPS+GLO).

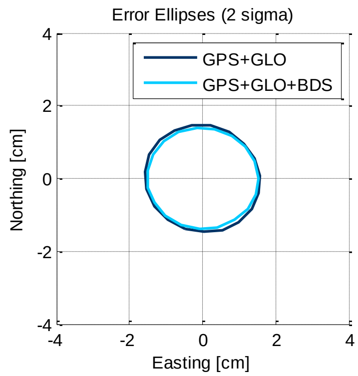

Figure 10 - 2-sigma planimetric error bounds (GPS+GLO+BDS vs GPS+GLO).

Figure 11 shows the number of satellites and overall geometry quality is quite comparable between a GPS+GLO and GPS+BDS configuration. In fact, RTK position error and RMS is very comparable between the two constellation configurations (Figure 12 and Figure 13). Figure 9 and Figure 12 suggest that including BeiDou not only improves the current dual-constellation RTK performance, but that it can also replace GLONASS (or even GPS) if needed. Hence it ensures continuous dual-constellation RTK performance. This will make a difference in events of a total disruption of a complete GNSS constellation, such as the recent event on April 2, 2014, when GLONASS broadcasted corrupted ephemeris for 11 hours.

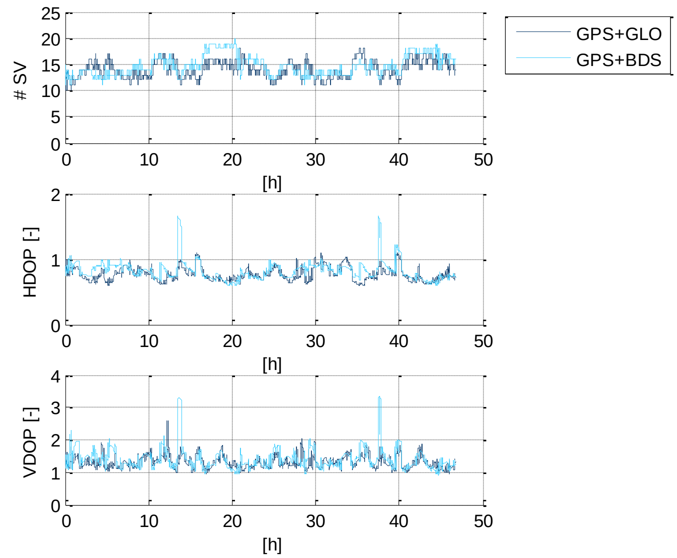

Figure 11 - Number of satellites used in RTK, HDOP and VDOP over 48 hours.

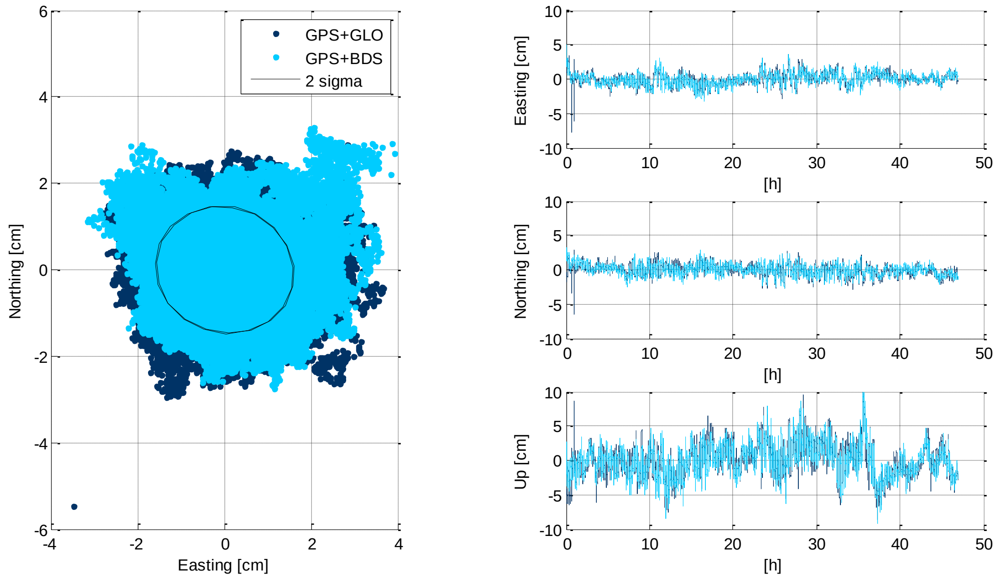

Figure 12 - RTK error over 48h (GPS+GLO vs GPS+BDS).

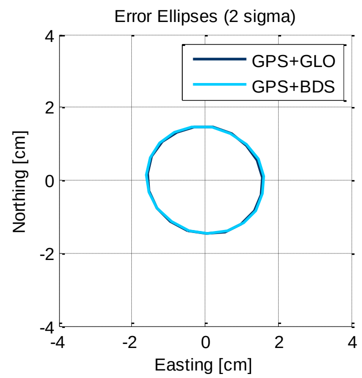

Figure 13 - 2-sigma planimetric error bounds (GPS+BDS vs GPS+GLO).

BeiDou-only RTK is currently feasible in the Asia-Pacific region. In Figure 15 and Figure 16, BeiDou-only RTK precision is compared to GPS-only RTK. Even though continuous ambiguity fixing and RTK operation is possible based solely on BeiDou, its precision falls behind that of the GPS-only configuration. Even though most of the time the number of satellites used is only slightly behind of GPS (Figure 14), the BeiDou-only geometry is at times suboptimal due to the large dependency on the IGSO and GEO SVs. This poor geometry leads to higher DOP values (Figure 14) and a bias in the north-west direction, at this observation location (Figure 15 and Figure 16). This problem is expected to be mitigated with time, as more MEO BeiDou satellites are deployed.

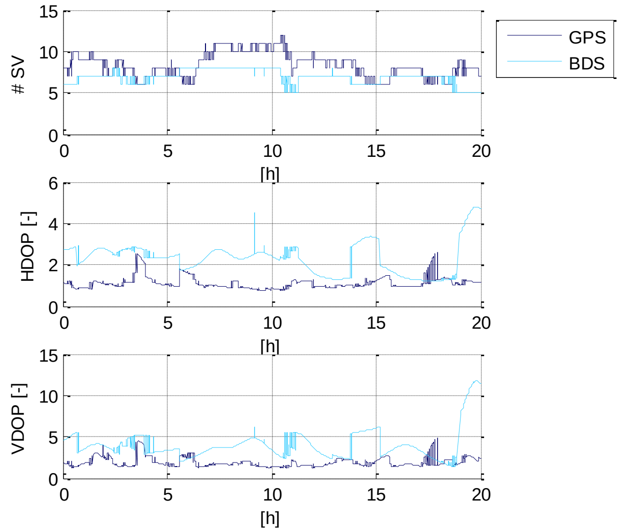

Figure 14 - Number of satellites used in RTK, HDOP and VDOP over 48 hours.

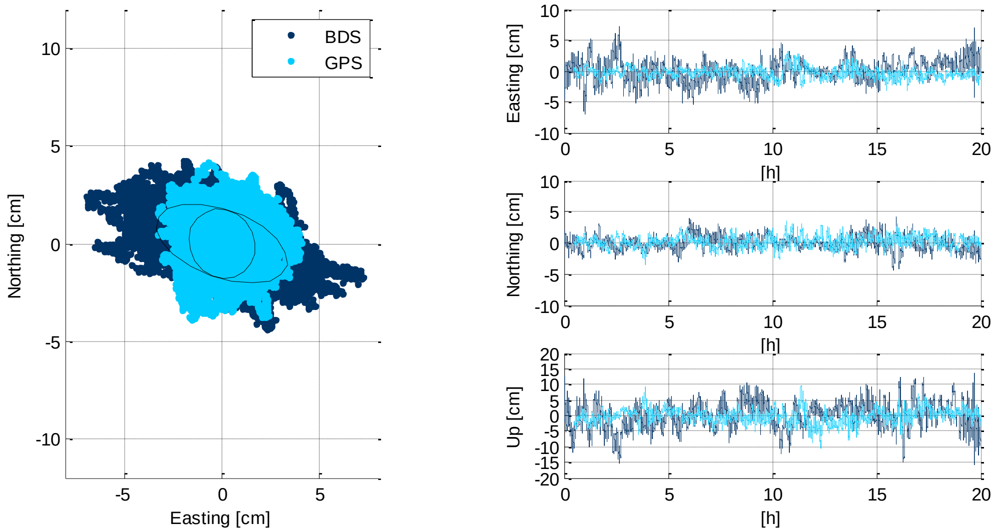

Figure 15 - RTK error distribution over 48h (BDS vs GPS).

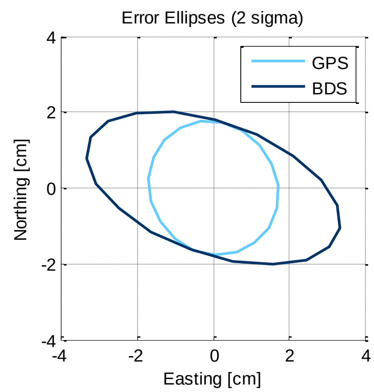

Figure 16 - 2-sigma planimetric error bounds (BDS vs GPS).

Carrier Phase Residuals

Carrier phase residuals of the triple-constellation RTK solution were analyzed for the three constellations; the histogram is presented in Figure 17. The mean and standard deviation of residuals are shown in Table 1. These results suggest that both B1 and B2 carrier phase measurements are high quality and are comparable to GPS for most BDS satellites.

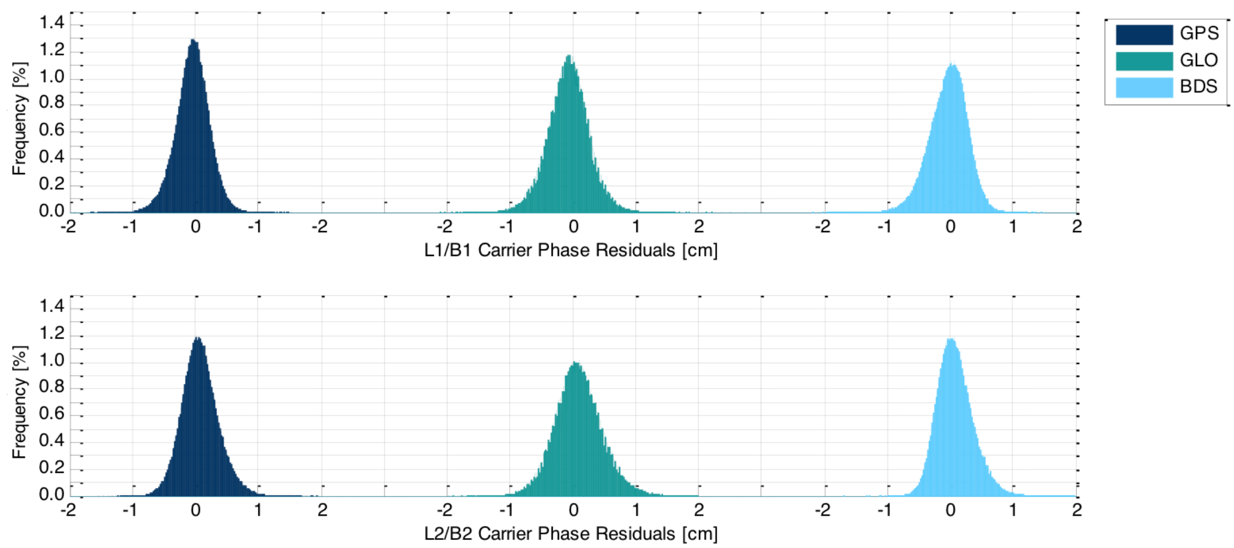

Figure 17 - Carrier phase residuals histogram from RTK solution over 48 hours period.

		GPS	GLONASS	BeiDou
L1/B1	μ [mm]	-0.62	-0.62	-0.26
	σ [mm]	2.71	3.41	3.06
L2/B2	μ [mm]	1.18	0.99	0.87
	σ [mm]	2.94	3.89	2.92

Table 1 - Carrier phase residuals statistics from RTK solution over 48 hours.

AVAILABILITY ANALYSIS

To evaluate the impact of including BeiDou satellites on the time to first RTK fix (TTFF), a dataset was recorded at the observation location described above, using the same Septentrio PolaRx4 GNSS receiver. A set of 44 data files was recorded with a duration of 10 minutes each, followed by a 10 minute off-period. These files were re-processed with different elevation masks and with different sets of GNSS constellation combinations. The elevation masks range from 10 to 50 degrees, with steps of 5 degrees.

For all data files the TTFF was calculated for each set of used constellations and elevation masks. Figure 18 shows the median TTFF from all the data files.

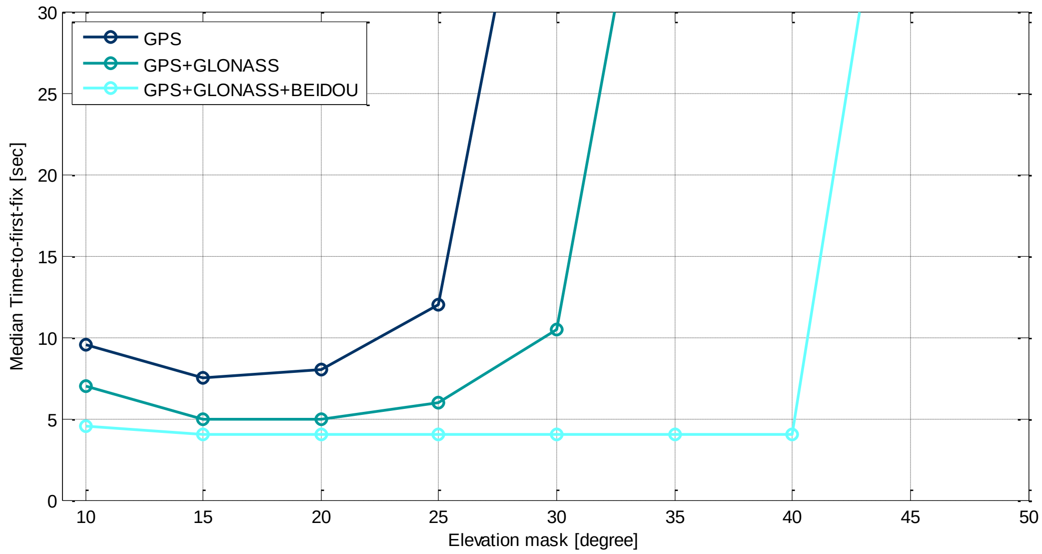

Figure 18 – Time to first RTK fix vs elevation mask analysis.

From 10 to 15 degrees there is a slight reduction in the TTFF trend for all constellations configurations. Removing low elevation satellites removes the observations most contaminated by errors such as multipath and ionosphere, hence reducing the TTFF. From 15 degrees on, as the elevation mask increases, the TTFF increases up to a saturation point where ambiguity fixing becomes very unlikely: >25 degrees for GPS, >30 degrees for GPS+GLO and >40 degrees for GPS+GLO+BDS.

The TTFF analysis indicates a clear superiority of the triple-constellation RTK engine over the other configurations. The presence of the GEO satellites brings an increase in availability for higher elevation masks, suggesting the triple constellation engine will perform better in environments where low elevation satellites are occluded (such as urban canyons).

CONCLUSION

The quality of BeiDou signals is in general high-grade and comparable to GPS. Having marked advantages in comparison with GLONASS (such as the use of CDMA instead of FDMA), BeiDou could replace GLONASS as the secondary constellation or contribute to the triple-constellation positioning strengthening the overall solution. At the time of writing this paper, BeiDou already benefits from the presence of high-elevation GEO and IGSO satellites, which ensures 24/7 availability in the Asian-Pacific region. Insufficient visibility of GPS and/or GLONASS satellites in challenging environments, e.g. in urban canyons, can be compensated with BDS, leading to unprecedented positioning availability. The use of three carriers (available for all BDS satellites, unlike GPS in its current status) provides for measurement redundancy and allows pre-processing quality control of phase measurements [7].

Preliminary performance analysis of RTK positioning highlighted significant advantages of including BeiDou in the navigation solution (GPS+GLO+BDS). With the use of BeiDou, accuracy, availability and reliability of the RTK solution increase. By introducing extra redundancy in the positioning algorithm, the RAIM algorithms become more effective, which strengthens the prevention of fixing errors. It was also shown that the performance of RTK with the combined GPS+BDS and GPS+GLO constellations is comparable. The addition of BeiDou not only strengthens current GPS+GLONASS algorithms, but will ensure continuous dual-constellation RTK performance in the event of a complete failure of an entire GNSS constellation.

At the time of this publication a data collection/survey campaign is taking place in the Asia-Pacific region. This data is already being used to further assess the real-time RTK performance of the new Septentrio's BeiDou-capable RTK engine in more demanding environments. Inter-receiver phase biases between receivers of different manufacturers have been identified when constructing double differences [8]. These biases, which may have ¼ and ½ cycle values, depending upon hardware and firmware of base-rover combinations, must be investigated for the sake of reliable RTK positioning with the use of BeiDou.

REFERENCES

[1] China Satellite Navigation Office, "BeiDou Navigation Satellite System Signal In Space Interface Control Document v2.0," 2013.

[2] de Wilde, W., F. Boon, J.-M. Sleewaegen and F. Wilms, "Tracking China's MEO satellite on a hardware receiver," *Inside GNSS*, July/August 2007.

[3] "Septentrio Demonstrates BeiDou+GPS+GLONASS Positioning," GPS World, 9 January 2013. [Online]. Available: http://gpsworld.com/septentrio-demonstrates-beidougpsglonass-positioning/. [Accessed 28 April 2014].

[4] "Septentrio Demonstrates BeiDou+GPS+GLONASS Positioning," Septentrio, 7 January 2013. [Online]. Available: http://www.septentrio.com/news/press-releases/septentrio-demonstrates-beidougpsglonass-positioning. [Accessed 28 April 2014].

[5] Teunissen, P. J. G., and A. Kleusberg, "GPS for Geodesy," Springer, Germany, 1988.

[6] Van Meerbergen, G., A. Simsky and F. Boon, "A Novel Decision Directed Kalman Filter to Improve RTK Performance," in *Proceedings of the 23rd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2010)*, Portland, OR, 2010.

[7] Simsky, A., "Three's the Charm - Triple-frequency Combinations in Future GNSS," *Inside GNSS,* July/August 2006.

[8] Nadarajah, N., P. J. G. Teunissen and N. Raziq, "BeiDou inter-satellite-type bias evaluation and calibration for mixed receiver attitude determination," *Sensors*, 2013.