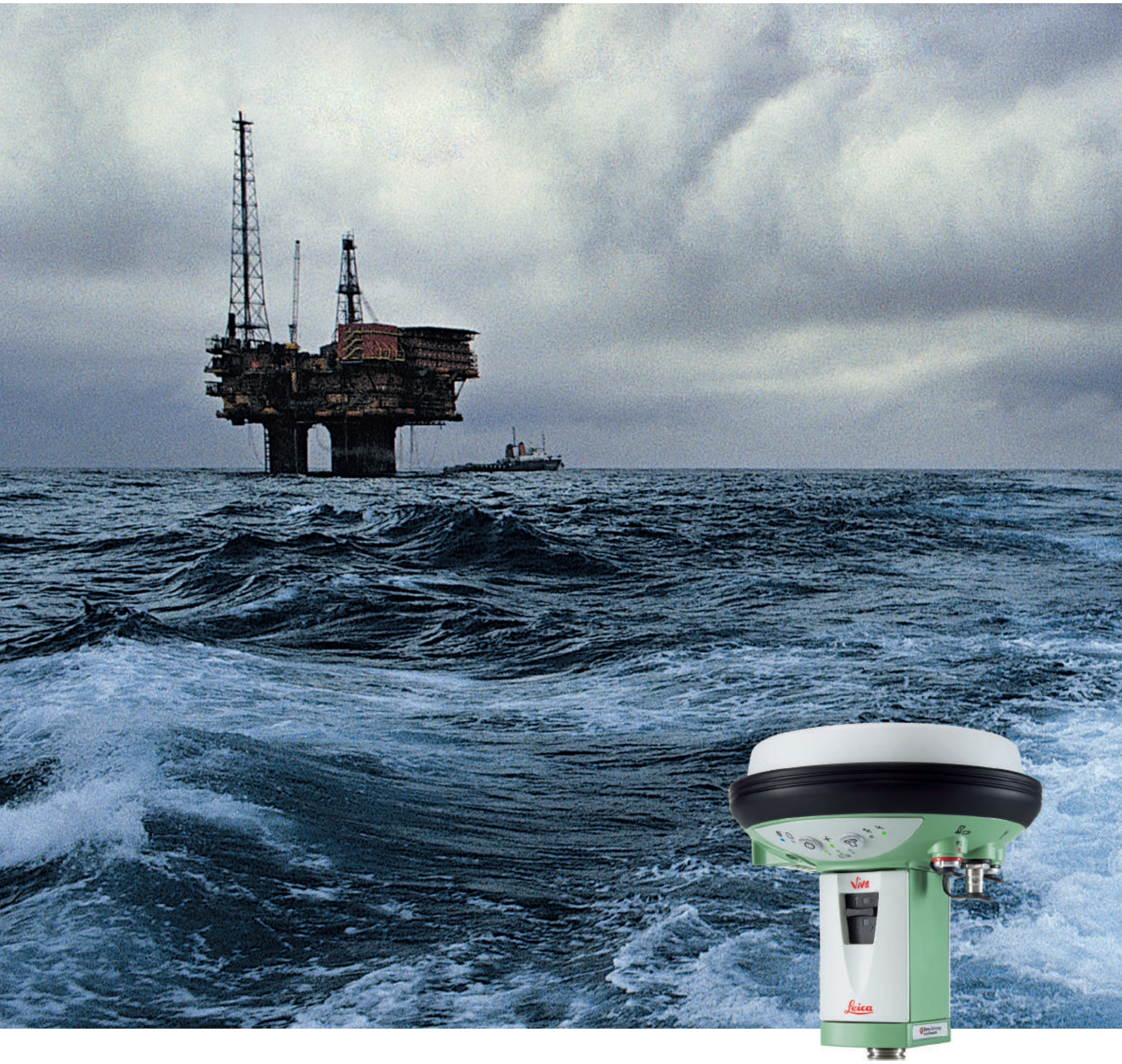
New Systems, New Signals Providing BeiDou Integration

Technical literature



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Leica Geosystems

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New Systems, New Signals, New Positions – Providing BeiDou Integration

Abstract

Leica Geosystems is a world leader in GNSS positioning and in utilizing innovative methods for providing high precision GNSS solutions. With new GNSS such as BeiDou and other signals and regional systems providing a significant increase in satellite availability, new methods are required to fully realize the potential benefits of these additional GNSS constellations.

However, before the potential of these new systems can be fully realized, we must first understand what advantages they can provide when being used in a high precision GNSS solution. Leica Geosystems' previous leading-edge work on GLONASS observation interoperability showed that there are many challenges involved with incorporating new GNSS constellation into a position solution, and careful evaluation needs to be carried out to understand the behaviour and characteristics of these systems (Takac, 2009).

This paper presents some results from integrating BeiDou into Leica Geosystems' GNSS technologies from SmartTrack through to RTK positioning and SmartCheck. The BeiDou signal strength is analysed, and the code and phase tracking performance is assessed in terms of multipath and noise. Further findings show considerable GNSS positioning improvements that can be gained through the assimilation of BeiDou data, as well as some challenges that need to be addressed in order to generate the highest quality GNSS position solution in all environments without compromising on reliability. Leica Geosystems AG is leading the way in providing technologically innovative approaches to meet the demands of all high precision GNSS applications.

Introduction

The BeiDou Navigation Satellite System (BDS) program has been centred on improving the ground and space segments to create high accuracy positioning, navigation and timing services.

In December 2012, the China Satellite Navigation Office (CSNO) released the official Signal-in-Space Interface Control Document (ICD; ICD-BeiDou, 2012) and announced the system operability over the Asia-Pacific region.

The ICD release prompted Leica Geosystems to release software to fully support the BeiDou constellation in the Leica Viva GNSS technologies:

- Leica SmartTrack
- Leica SmartCheck
- Leica xRTK

These technologies form the basis of Leica Geosystems GNSS RTK performance. Leica SmartTrack technology guarantees the most accurate signal tracking. It is future proof and ensures compatibility with all GNSS systems today and tomorrow. Leica SmartCheck technology automatically performs permanent, independent checks during surveying activities and continuously verifies the RTK solution to achieve the most reliable positioning results (Fairhurst et al., 2011). At a slightly lower accuracy than a high precision RTK solution, Leica xRTK technology provides reliable, ambiguity-fixed positions with highest availability in difficult measuring environments such as urban canyons and dense canopy.

Previous work on the introduction of GLONASS into Leica Geosystems RTK positioning showed improved productivity, reliability, precision and accuracy, particularly in stressed observing environments (Takac and Walford, 2006). This indicates that the integration of BeiDou into the Leica Viva GNSS features may bring a number of performance benefits for high precision GNSS users. Together with GPS and GLONASS measurements, BeiDou observations are analysed in this paper to study the signal characteristics and the potential benefits for Leica Viva GNSS.

Beidou

BeiDou has been developed to provide high accuracy positioning, navigation and timing services globally by 2020. Currently, it covers the Asia-Pacific region with a constellation of five Geostationary Earth Orbit (GEO) satellites (PRN C1–C5), five Inclined Geosynchronous Orbit (IGSO) satellites (PRN C6–C10), and four Medium Earth Orbit (MEO) satellites (PRN C11–C14). The GEO satellites always stay over the Indian Ocean and the Pacific, while the IGSO satellites improve the availability of high elevation satellites in densely populated areas (Montenbruck et al., 2013). The use of GEO and IGSO satellites is a special feature of the BeiDou constellation, which enables regional services at the moment and enhances these in terms of satellite availability after the global system is fully in operation (Ge, 2013). However, for the South and North America continent, Antarctic and Arctic regions, the GEO and IGSO satellites are either below the observer's horizon or at low elevations (Greilier et al., 2007; Zhang et al., 2011).

The BeiDou satellites transmit signals on three frequency bands (B1, B2, B3), which share common features with GPS and Galileo, e.g., CDMA. The B1, B2 and B3 bands are close to the GPS L1, the GPS L5 and the Galileo E6 frequency, respectively (Ge, 2013). The current BeiDou rubidium clocks are competitive with older generations of GPS frequency standards and the GIOVE-A/B rubidium clocks (Montenbruck et al., 2013). Since the GEO and IGSO satellites have relatively limited orbital movements with respect to the GNSS sensor, accurate clock and orbit estimates are more challenging than MEO satellites. Within this context, Hauschild et al. (2012) found high temporal variations in the satellite clock solution, which reduce the accuracy of clock predictions and degrade the positioning quality of real-time users. He et al. (2013) showed that the BeiDou orbit quality is affected by the geometry of tracking networks, the involvement of MEO satellites and the fixing of integer ambiguities. Looking into the future, the BeiDou solutions and products will be improved with an increased number of MEO satellites, a rapid build-up of monitoring stations and the availability of more accurate antenna calibration parameters (Shi et al., 2013).

Data Collection

In practice, the inclusion of the BeiDou constellation into GNSS RTK processing is realised at several different stages; the key stage being the tracking of the raw observations and their integration into RTK positioning algorithms. To assess the tracking performance of the BeiDou signals, raw GNSS observations, along with their ephemeris and almanac information, were collected directly from the Leica Viva GNSS sensor without going through any pre-processing and smoothing stages. For the static test, a zero-baseline setup was used to eliminate common external error effects and to measure the raw noise of GNSS phase observations on a single difference level. In this experiment, two Leica Viva GS10 units were connected to a single Leica Viva AS10 antenna via a 4-way antenna splitter (Fig. 1a). 24 hours of GNSS data were collected from Shanghai test sites in open sky environments to obtain full passes of the BeiDou MEO satellites and to maximise the visibility of the GEO and IGSO satellites. In addition, an RTK test was carried out using a short baseline of 5 km, where 3 hours of GNSS data were observed by a Leica GS15 sensor in heavy canopy (Fig. 1b and c). By analysing measurements from difficult environments, the benefits of integrating the BeiDou constellation into the Leica RTK algorithms are evaluated in the position domain.

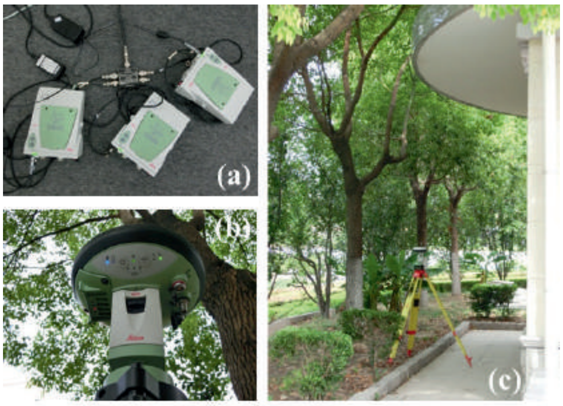


Figure 1 Static zero-baseline setup (a) and GNSS RTK test in heavy canopy environment (b and c).

Integrating Beidou Into Leica Viva GNSS Technologies

The performance of integrating BeiDou into the Leica Viva GNSS technologies and the effects on position availability and reliability are highlighted in this section.

SmartTrack

The quality of signal tracking is analysed by examining the measured signal strength, code multipath errors and single-difference phase residuals. Fig. 2 shows the BeiDou skyplot observed in Shanghai (Latitude 31.2 N and Longitude 121.6 E) on August 24, 2013. The GEO satellites C1–C5 are almost stationary in the second and third quadrants. The IGSO satellites C6–C10 exhibit incomplete "figure-8" ground tracks as the satellites below the horizon cannot be observed (Fig. 2a). The MEO satellites C11–C14 illustrate more variable orbital movements and reach the maximum elevation of 86.7° (C13 in Fig. 2b). The combination of GEO, IGSO and MEO allows simultaneous tracking of up to ten BeiDou satellites in open sky environment.

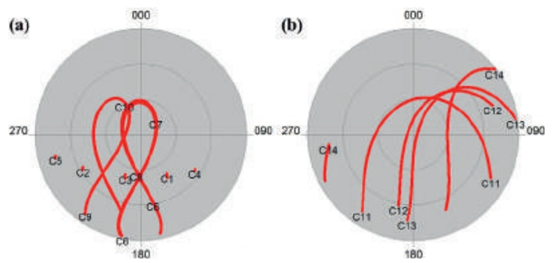


Figure 2 BeiDou skyplots at Shanghai on August 24, 2013 (a) GEO and IGSO satellites, (b) MEO satellites.

Signal Strength

As described in Luo (2013, Sect. 5.1), the received GNSS signal strength depends on various factors, such as the satellite and receiver antenna gain, the satellite-receiver distance, the elevation and azimuth of the incoming signal, etc. The signal-to-noise ratio (SNR) over elevation as measured by the Leica Viva GS10 receiver and AS10 antenna for GPS, GLONASS and BeiDou signals is depicted in Fig. 3a and b. The signal strength of G1 is lower than that of L1, and both are higher when compared to B1. This corresponds to the different minimum received power levels of −160 dBW (ICD-GPS, 1993, p. 13), −161 dBW (ICD-GLONASS, 2008, p. 16) and −163 dBW (ICD-BeiDou, 2012, p. 4) for L1, G1 and B1, respectively. Comparing Fig. 3a and b with each other, the GPS L5 signal exhibits larger SNR values than L1, particularly at low and medium elevations. This is due to the fact that the L5 signal has about twice the transmission power as L1 (Gao et al., 2010). In Fig. 3b, it is encouraging to observe that the high signal strength of GPS L5 can also be reached by the BeiDou B2 signal. Moreover, being advantageous to GPS L2, the BeiDou B2 code is not encrypted and can be accessed directly.

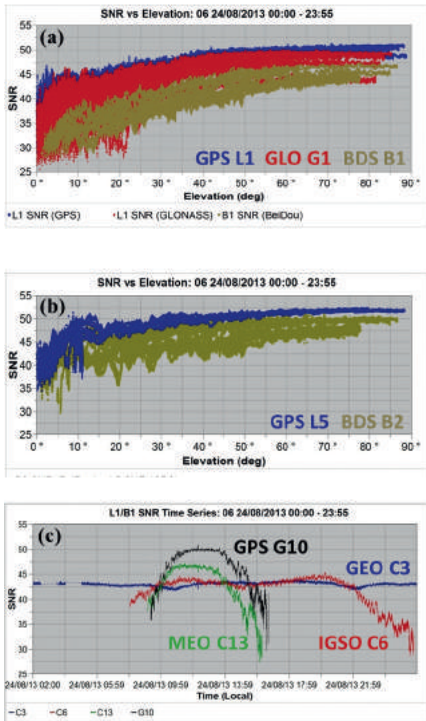


Figure 3 Signal-to-noise ratio (SNR in dB-Hz) for GPS, GLONASS and BeiDou signal tracking (Leica Viva GS10 receiver and Leica AS10 antenna, Shanghai, open sky environment, August 24, 2013) (a) SNR vs. elevation for L1/G1/B1, (b) SNR vs. elevation for L5/B2, (c) Examples of L1/B1 SNR time series.

In Fig. 3c, some representative SNR time series are shown, where the MEO satellites G10 and C13 have similar ground tracks. For the GEO satellite C3 that is almost stationary, the SNR measurements maintain a temporally constant level of about 43 dB-Hz. In contrast, the signal strength of the MEO and IGSO satellites varies strongly over time as the satellite-receiver geometry changes (Fig. 2). Significant SNR variations are visible at low elevations,

suggesting the presence of strong multipath effects (Bilich and Larson, 2007). In addition, no significant differences in the measured signal strength can be found between the GEO and IGSO satellites at common elevations, which coincides with the results shown in Montenbruck et al. (2013). However, the BeiDou MEO satellites provide larger SNR than the IGSO satellites at common elevations, e.g., about 3 dB-Hz larger at 50° for both B1 and B2. This can be explained by the different satellite altitudes (MEO: 21,528 km, IGSO: 35,786 km; ICD-BeiDou, 2012, p. 1). It should be noted that the signal strength characteristics presented here are hardware dependent and site specific.

Code Multipath

In order to assess code multipath, the multipath combination is applied, which eliminates the first-order ionospheric effect and the geometric range between the satellite and the receiver (Estey and Meertens, 1999; Shi et al., 2013). For each elevation interval of 5°, i.e., [0°, 5°), [5°, 10°), ..., [85°, 90°), the average multipath root mean square (RMS) is computed for GPS, GLONASS and BeiDou. The results over satellite elevation are shown in Fig. 4a for the respective L1, G1 and B1 frequency bands. The code multipath decreases with increasing satellite elevation, from about 1 m at low elevations to about 0.2 m at high elevations. Generally, the BeiDou B1 measurements illustrate stronger multipath effects than the L1 and G1 observations, which was also reported by Hauschild et al. (2012). Due to the inhomogeneous distribution of BeiDou data over elevation, the RMS values of B1 exhibit larger variations, especially at low and high elevations. Nevertheless, the inclusion of the GEO satellites C5 (13.9°–15.1°), C2 (31.6°–33.3°), C4 (34.4°–35.6°), and C3 (50.1°–53.4°) considerably reduces the RMS for the elevation intervals [10°, 15°), [30°, 35°) and [50°, 55°) (see black dots in Fig. 4a). Regarding the multipath skyplot shown in Fig. 4b, the IGSO satellites seem to be more strongly affected by multipath than the MEO satellites at common elevations. This was expected since the noise level of IGSO is generally higher when compared to MEO. Analysing GPS L5 and BDS B2 with respect to code multipath, similar conclusions can be drawn, where the B2 RMS reaches about 1.5 m at low elevations and about 0.5 m at high elevations.

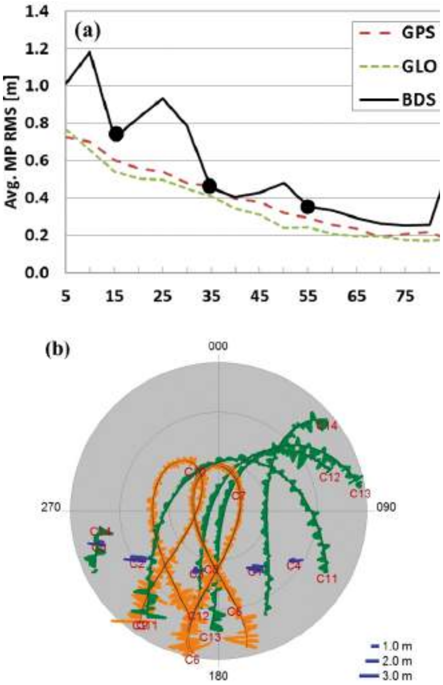


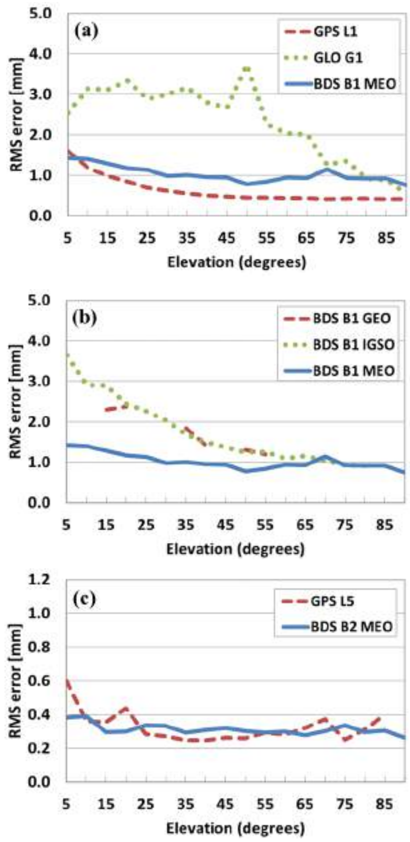
Figure 4 Comparison of code multipath (MP) error (Shanghai, open sky environment, August 24, 2013) (a) MP vs. elevation for GPS L1, GLONASS G1 and BeiDou B1, (b) MP skyplot for the BeiDou constellation.

Phase Noise

The objective of the static zero-baseline test is to examine the performance of the receiver and to study the noise characteristics of raw GNSS phase observations. By forming single differences (SD) with fixed known coordinates, common external error sources such as satellite-specific errors, atmospheric effects and site-specific multipath can be eliminated (Amiri-Simkooei and Tiberius, 2007). In analogy to the code multipath analysis, the RMS values of SD phase residuals are computed for each elevation interval of 5°. The results are presented in Fig. 5 with respect to GNSS constellation and BeiDou satellite component. Considering the frequency bands L1, G1 and B1 for GPS, GLONASS and BeiDou, respectively, the G1 phase observations show the highest noise level in Fig. 5a, which falls with increasing elevation from 3 to 0.5 mm. Compared to L1, the phase noise of the B1 measurements from the BeiDou MEO satellites is slightly larger but less elevation dependent. This indicates that the BeiDou MEO signals at low elevations can also be reliably observed by means of the Leica Viva SmartTrack technology. For the

different BeiDou satellite groups, Fig. 5b illustrates the B1 noise behaviour over elevation. The RMS of SD phase residuals is 1–3.6 mm for GEO and IGSO, and amounts to about 1 mm for MEO. Moreover, the RMS values for GEO and IGSO are considerably larger than those for MEO at low and medium elevations. This motivates advanced stochastic modelling that appropriately considers the group-specific noise characteristics of BeiDou phase observations. In Fig. 5c, the MEO B2 signal shows a similar noise level to GPS L5, with apparent improvements at low elevations. From Fig. 5d it can be recognised that the RMS of SD phase residuals is 0.4–1 mm for GEO and IGSO, and varies around 0.3 mm for MEO. Like B1 (Fig. 5b), the B2 noise also exhibits stronger elevation dependency for the GEO and IGSO satellites.

Taking the B1 frequency as an example, Fig. 6 depicts the SD phase residuals over elevation for the BeiDou GEO, IGSO and MEO satellites. These residuals are used to compute the RMS errors shown in Fig. 5b. The GEO satellites C5 and C2 illustrate lager variations in Fig. 6a, which can be explained by the smaller elevations. Moreover, significantly larger numbers of cycle slips are detected for these two GEO satellites (C5: 4478,



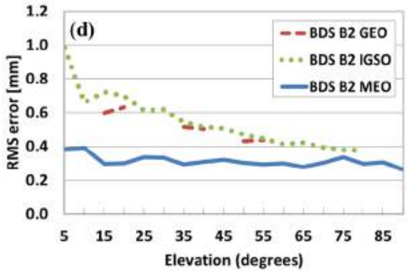


Figure 5 Comparison of single-difference (SD) residual RMS with respect to GNSS constellation and BeiDou satellite component (zero-baseline test in Shanghai, open sky environment, August 24, 2013).

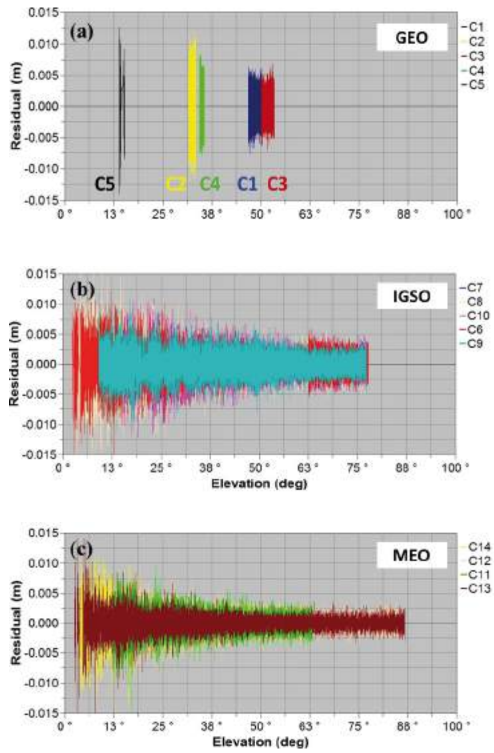


Figure 6 Single-difference (SD) phase residuals over elevation for the BeiDou B1 frequency (zero-baseline test in Shanghai, open sky environment, August 24, 2013).

C2: 1317 for receiver 1; C5: 3208, C2: 1020 for receiver 2). Comparing Fig. 6b and c with each other, it can be concluded that the phase observations from the IGSO satellites have a higher noise level than those from the MEO satellites. This coincides with the results from the SNR analysis (cf. Fig. 3), and may be caused by the different satellite altitudes. With mm-level noise, the GEO and IGSO phase measurements are clearly suitable for RTK

positioning. From Fig. 6 the maximum achievable elevations for the GEO, IGSO and MEO satellites are obtained as 53.4° (C3), 77.8° (C6) and 86.7° (C13), respectively (cf. Fig. 2).

SmartCheck and xRTK

In difficult measuring environments such as dense canopy and urban canyons, RTK position accuracy and availability can be constrained by full and partial blockages of the GNSS signals. Fig. 7 shows the GNSS visibility at the Shanghai heavy canopy test site over a 3 hour period on August 23, 2013 (Fig. 1b and c). The number of visible GNSS satellites varies from 8 to 21, as detailed in Table 1, depending on the constellation. The BeiDou constellation produces a smaller range of visible satellites [4, 8] when compared to the GPS constellation [3, 11] and contributes a higher number of satellites per epoch (mean 5.3) when compared to the GLONASS constellation (mean 2.7). The higher contribution of BeiDou can be attributed to the GEO and IGSO satellites and highlights the benefits of the regional system in comparison to the existing global systems, such as GPS and GLONASS.

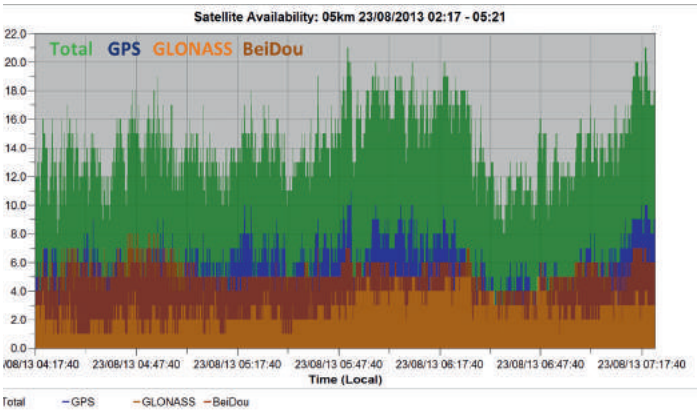


Figure 7 Availability of GNSS satellites (5 km baseline RTK test in Shanghai, heavy canopy environment, August 23, 2013).

Table 1 Statistics for the number of visible satellites (cf. Fig. 7).

Constellation	Mean	Min	Max
GNSS	14.3	8	21
GPS	6.3	3	11
GLONASS	2.7	1	5
BeiDou	5.3	4	8

Figur 8 compares the height errors of the RTK positions generated using the SmartCheck technology with different GNSS constellations. In this example, the inclusion of BeiDou into SmartCheck increases the high precision RTK position availability from 0.21% (GPS/GLONASS) to 20.82% (GPS/GLONASS/BeiDou) during the 3 hour period, as shown in Table 2. In the case of xRTK, the position availability is improved by about 10%, from 9.74% (GPS/GLONASS) to 18.47% (GPS/GLONASS/BeiDou). Considering the RTK results as a whole, the total position availability can be enhanced by about 30%, significantly increasing productivity in difficult observing environments.

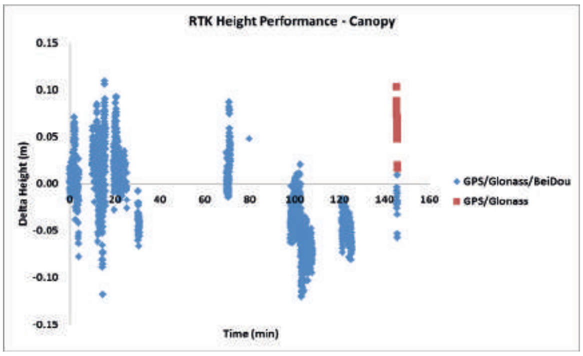


Figure 8 RTK height errors generated using different GNSS constellations (5 km baseline RTK test in Shanghai, heavy canopy environment, August 23, 2013).

Table 2 Position availability [%] achieved using different GNSS constellations (5 km baseline RTK test in Shanghai).

Constellation	RTK	xRTK	Total
GPS/GLONASS	0.21	9.74	9.95
GPS/GLONASS/BeiDou	20.82	18.47	39.29

Table 3 provides the precision and availability of GPS/GLONASS and GPS/GLONASS/BeiDou RTK positions achieved under dense canopy. The GPS/GLONASS RTK solutions produce very precise results, specifically in the height component. However, the low number of GPS/GLONASS RTK positions limits the sample to a single group of positions, restricting the effectiveness of a direct comparison (see time 150 minutes in Fig. 8). Considering the difficult measuring conditions, the GPS/GLONASS/BeiDou RTK positions are also precise in both the horizontal and height components.

Table 3 Precision [cm] and availability [%] of the RTK positions achieved using different GNSS constellations (5 km baseline RTK test in Shanghai).

GNSS constellation	Position precision N	E	H	Position availability
GPS/GLONASS	8.8	6.1	1.9	9.95
GPS/GLONASS BeiDou	9.6	9.6	4.1	39.29

Although the results presented in this example are site specific, they highlight the benefits of integrating the BeiDou constellation into the existing Leica Viva GNSS technologies. The increase in position availability is particularly advantageous for the RTK users who work in difficult measuring environments.

Conclusions

Following GPS and GLONASS, BeiDou is now providing positioning, navigation and timing services over the Asia-Pacific region. Upon the full system completion by 2020, it will play a very important role in high precision GNSS applications for worldwide users. To understand the potential benefits of the new constellation for Leica Viva GNSS technologies, this paper has shown some results from integrating BeiDou into SmartTrack, SmartCheck and xRTK. The main findings of this contribution can be summarised as follows:

1. Applying the Leica Viva SmartTrack technology, excellent signal strength can be achieved. The signal quality of the GEO satellites is temporally stable, while the MEO satellites provide larger SNR than the IGSO satellites at common eleva tions.

2. The BeiDou code multipath level is higher in comparison to GPS and GLONASS. The IGSO satellites are more strongly affected by multi path than the MEO satellites, particularly at low elevations.

3. The noise level of BeiDou single-difference phase observations is about 0.3–3.6 mm, where the B2 frequency shows better noise performance than B1. The MEO signals exhibit similar noise levels to GPS and less elevation dependent characteristics than the GEO and IGSO signals.

4. In the presented RTK test, the integration of BeiDou increases the number of visible satellites by 4–8. This enhances the efficiency of Smart Check by providing more fixed RTK positions, increasing availability and reliability.

5. In dense canopy, the inclusion of BeiDou observations into RTK and xRTK can improve the position availability by up to 30%.

Today, the GPS constellation still plays the most important role in GNSS solutions. The promising performance of BeiDou already indicates a more significant contribution than GLONASS on a regional scale. During the deployment of the BeiDou constellation, more advantages can be expected in the near future. The Leica Viva GNSS technologies are future proof, which guarantees the maximum benefits of BeiDou integration in both the measurement and position domains.

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