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ORIGINAL ARTICLE

Investigation of the accuracy of BeiDou, QZSS and QZSS/BeiDou satellites configuration for short, medium and long baselines in the Asia-Pacific regions

Atinç Pirti [1*]

[1]Department of Geomatic Engineering, Yildiz Technical University, 34220 Esenler, Istanbul, Turkiye

*atinc@yildiz.edu.tr

Abstract

The field of satellite navigation has seen significant advancements due to the fast development of multi-constellation Global Navigation Satellite Systems (GNSS). Around 150 satellites will be in service when all six systems – GPS, GLONASS, Galileo, BeiDou, QZSS, and NAVIC – are launched by 2030, offering both enormous potential and advantages for research and engineering applications. This study used an experiment on the accuracy, particularly for short, medium, long baselines (Wide Lane ambiguity solution) of the BeiDou, QZSS and QZSS/BeiDou combinations. It showed that with the integration of BeiDou/QZSS static measurements in the study region millimetre-centimetre accuracy for short, medium, and long baselines can be attained. Based on the results of this study, it can be concluded that the 1st (QZSS/BeiDou), 2nd (BeiDou), and 3rd (QZSS) strategies feature different horizontal accuracies for all categories. The obtained results with different satellite configurations for the Fixed-Wide-Lane integer ambiguity solution are compared with each other. Accuracy at the short baseline (BeiDou, QZSS, and BeiDou/QZSS satellites) was obtained in the range of 0.5–0.7 cm. For the medium baseline, it was computed around 1.8–82 cm. For the long baseline, the accuracy was 5.6–13.3 cm.

Key words: BeiDou, accuracy, precision, improvement, QZSS, QZSS/BeiDou

1 Introduction

The China National Space Administration owns and operates the radio navigation system known as the BeiDou Navigation Satellite System (BDS), which is based on satellite technology. This worldwide system can obtain a BDS receiver position and time information from four or more BDS satellites in an unobstructed line of sight anywhere on or near Earth. It does not need the user to send any data, and it works without the need for Internet or phone coverage, however, these technologies may make the BDS positional data more valuable. Three satellites that provide regional location services constitute the first-generation BeiDou system, or BeiDou-1, whose primary function since its launch in 2000 was to provide navigation services within China alone. BeiDou-1 ceased operations in December 2012 due to the expiration of its envisaged design life. The BeiDou-2 (second-generation BeiDou), composed of six geostationary satellites, six inclined geosynchronous orbit satellites, and four medium earth orbit satellites, started offering regional positioning services to customers in the Asia-Pacific area in November 2012. The GPS is not as precise in the area as BeiDou. The third-generation BeiDou system, or BeiDou-3, includes three different orbits for the satellites: three inclined geosynchronous orbits, which cover the Asia-Pacific region, three geostationary orbits, which cover China, and twenty-four medium-circle orbits, which cover the entire planet. In December 2023, within the BeiDou-3 system forty-four satellites were operational. With post-processing, BeiDou-3 achieved ac-

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curacy to the millimetre in 2016. The four frequency bands used by BeiDou are: E1, E2, E5B, and E6, and they overlap with Galileo frequencies. In 2009 China's BeiDou satellites were to have had main rights to the E1, E2, E5B, and E6 bands, where they would have began broadcasting before the European Galileo satellites (Quan et al., 2016; Odolinski et al., 2015; Hu et al., 2022; Wolf and Ghilani, 2012; Yang et al., 2020).

Primarily consisting of satellites in quasi-zenith orbits, Quasi-Zenith Satellites System (QZSS) is a satellite positioning system developed in Japan. To determine the location, satellite positioning systems employ satellite signals. The American Global Positioning System (GPS) is one well-known example. The QZSS is also referred to as the "Japanese GPS." Although positioning with four or more satellites is possible, the most reliable positioning data are obtained with a higher number of satellites. Meanwhile, GPS satellites are less discernible in hilly and metropolitan areas because of obstruction caused by trees, buildings, and other structures that might hinder the steady gathering of positioning data. Three of the four satellites in the QZSS (Michibiki) constellation, which began operating in November 2018, are always visible from areas in Asia and Oceania. When combined with GPS, QZSS may provide a steady, highly accurate location data, as theses two systems use a sufficient number of satellites. Since QZSS are GPS-compatible and inexpensive to purchase, it is anticipated that position data enterprises that make use of geographical and spatial data will emerge (Hauschild et al., 2012a,b; Quan et al., 2016; Odolinski et al., 2014; Odijk et al., 2017; Japan Aerospace Exploration Agency, 2024; Wolf and Ghilani, 2012).

Since only extremely high elevation satellites can be visible in Japan's many metropolitan canyons, the main goal of QZSS is to make GPS more easily accessible there. Performance augmentation, which proposes precision and dependability of GPS-derived navigation solutions, serves a supplementary purpose. The GPS L1C/A signal, as well as the updated GPS L1C, L2C, and L5 signals, are all compatible with the signals sent by quasi-zenith satellites thus limiting the necessary alterations to current GPS receivers. By transmitting the submeter-class performance improvement signals L1-SAIF and LEX from QZSS, the combined systems GPS+QZSS provide improved positioning performance, when compared to solo GPS. Through failure monitoring and warnings of system health data, it also increases dependability (Hauschild et al., 2012a,b; Quan et al., 2016; Odolinski et al., 2014; Odijk et al., 2017; Japan Aerospace Exploration Agency, 2024; Wolf and Ghilani, 2012).

Numerous studies have covered all relevant aspects from QZSS signal transmission to POD (Precise Orbit Determination) and location since the first QZSS satellite was launched. Hauschild et al. (2012a,b), Montenbruck et al. (2015, 2017), Ansari et al. (2021) and Ansari (2023) describe investigations of the satellite's attitude and orbit. In 2017, QZSS also released the official satellite information and control mode, which was extremely helpful in determining QZSS orbit (Japan Aerospace Exploration Agency, 2024). According to the analysis in Montenbruck et al. (2017), the SISRE (Signal in Space Range Error) may descend below 0.6 m and is equivalent to that of the GPS. Using authentic data, Quan et al. (2016) evaluated the QZSS signal quality in conjunction with other GNSS systems, while Odolinski et al. (2014, 2015) examined the effectiveness of long-baseline and single frequency QZSS-assisted Real-Time Kinematic (RTK). A number of other GNSS systems are used to estimate the QZSS Inter-System Biases (ISB) (Odijk et al., 2017). Owing to its constellation nature, QZSS's service cover an area restricted to the Asia-Pacific region. The primary focus in this research is to establish whether BeiDou and QZSS satellites contribute to the Asia-Pacific region. The study used commercial software (Topcon Magnet Tools 8.2.0 Software) to analyse the accuracy of BeiDou, QZSS, BeiDou/QZSS satellite combinations on short, medium, and long baselines.

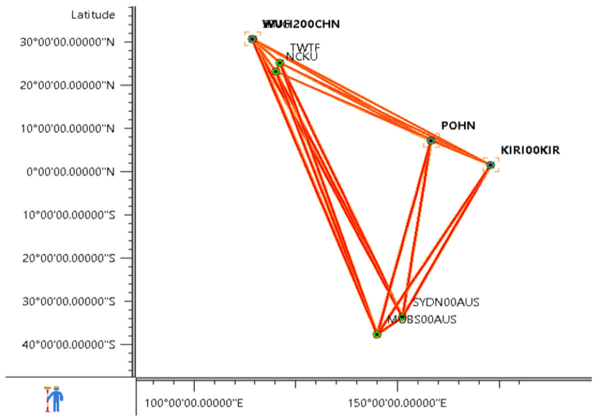

Figure 1. Distribution of IGS stations in the study region

2 Study Region

The eight stations were selected for this study (NCKU, TWTF, JFNG, WUH2, KIRI, POHN, MOBS, and SYDN) are – in China, Indonesia, and Australia (Figure 1) – based on their satellite configurations (observed BeiDou/QZSS satellites), and their base lengths, are between approximately 13 km and 1741 km. The GNSS data of these points were obtained with a recording interval of 30 seconds on January 30, 2024 from IGS webpage (http://garner.ucsd.edu/pub/rinex/2024/).

3 Results

All static GNSS surveys were processed using Topcon Magnet Tools version 8.1.0 and Bernese 5.2 Software. There are four ambiguity resolution strategies implemented in program GPSEST of the Bernese GNSS Software Version 5.2: ROUND, SIGMA, SEARCH, and QIF (Quasi-Ionosphere-Free) which may be selected (Dach and Walser, 2015). Theory of QIF, for longer baselines (up to approximately 2000 km), it is possible to process both carriers together and to resolve both (L1 and L2) ambiguities in the same run. The recommended strategies are QIF for long sessions and baselines of almost arbitrary length, and SEARCH for short sessions and short baselines. Different algorithms use different combinations of the L1 and L2 observations. For the QIF strategy, both L1 and L2 observations are required, that the SEARCH strategy leads to the best results also depending on observations on both frequencies, and that the remaining strategies ROUND and SIGMA work actually with one carrier (or one linear combination) only. It is possible to use two linear combinations in one run, but the ambiguity resolution is performed independently on both carriers. The latitude, longitude and ellipsoidal height values of eight points were obtained using Bernese 5.2 and Topcon Magnet Tools Software v.8.2.0 on 30.01.2024. The precise ephemeris and Niell Mapping function were used with meteo model GPT (Global Pressure/Temperature). GPT model is based on spherical harmonics up to degree and order nine, and provides readings of pressure and temperature at any site in the vicinity of the Earth's surface. Input parameters of GPT are the station coordinates and the day of the year, which also allows for modelling of the annual variations of the parameters. Data processing was made using: elevation mask of 15 degree, datum ITRF2020 and confidence level: 95%. The standard deviation values of the latitudes and longitudes of the eight IGS points obtained, as

Table 1. Standard deviation, coordinates (ITRF2020, Epoch 2024.1) of the eight IGS points by processing static GNSS data (Bernese version 5.2)

Name	Latitude	Longitude	h [m]	Std Lat [m]	Std Lon [m]	Std h [m]
JFNG	30°30'56.03144"	114°29' 27.68269"	71.291	0.010	0.008	0.016
KIRI	1°21'16.51400"	172°55' 22.38451"	36.159	0.009	0.006	0.013
MOBS	-37°49'45.84353"	144°58' 31.23126"	40.574	0.005	0.006	0.010
NCKU	22°59'47.96809"	120°13' 21.31054"	98.274	0.009	0.008	0.015
POHN	6°57'35.81490"	158°12' 36.37176"	90.669	0.008	0.007	0.012
SYDN	-33°46'51.13125"	151°09' 01.37931"	85.576	0.006	0.006	0.013
TWTF	24°57'12.82889"	121°9' 52.22456"	201.509	0.009	0.008	0.013
WUH2	30°31'54.04371"	114°21' 26.16852"	28.145	0.010	0.008	0.017

shown in Table 1, were between 5–10 mm. The standard deviation values of the ellipsoidal heights of the IGS points obtained were between 10 mm and 17 mm, as presented in Table 1.

This study used satellite configurations like BeiDou, QZSS, and BeiDou/QZSS and integer ambiguity strategies like Wide-Lane and Fixed Iono-Free. These methods use dual frequency measurement codes and carrier phase measurements for the baselines' lengths falling from 30 km to 1500 km. In the initial stages of processing dual frequency measurements, integer ambiguity resolution is achieved using the Wide Lane combination. The final solution type of the processed observation is "Fixed Wide Lane" and "Float Wide Lane," which is solved at all baselines using BeiDou, QZSS, and BeiDou/QZSS satellites. The fix success rate of the fixed likelihood (FL)-approach was verified with simulation and real GNSS data. The numerical results indicate that the success rate of the FL-approach achieves >98% while the failure rate is <1.5 %.

The differences between the baselines obtained using Bernese 5.2 and Magnet Tools ver. 8.2.0 (JFNG-WUH2, ~13 km) ranged from 0.5 cm (BeiDou/QZSS) to 0.8 cm. For the other baselines, (NCKU-TWTF, ~237 km), the differences are calculated to be between 1.8 cm (QZSS/BeiDou) and 10.1 cm (BeiDou) and for the other baseline (MOBS-SYDN, ~716 km) the differences are calculated to be between 5.8 cm (BeiDou) and 81.8 cm (QZSS). Visibly, the BeiDou/QZSS satellite configurations are effective in solving the Fixed-Wide Lane integer ambiguity for short, medium and long baselines. The signals used by BeiDou and QZSS satellites show both strong and robust characteristics.

Figure 2 illustrates skyplot in the study region. The number of BeiDou satellites is between 15 and 43, whereas the number of QZSS satellites is between 2 and 4 (Figure 2).

Two satellites were visible at NCKU and TWTF points. Since QZSS satellites are not observed sufficiently to solve NCKU-TWTF baseline, this baseline was not solved and analysed for this situation (Table 2).

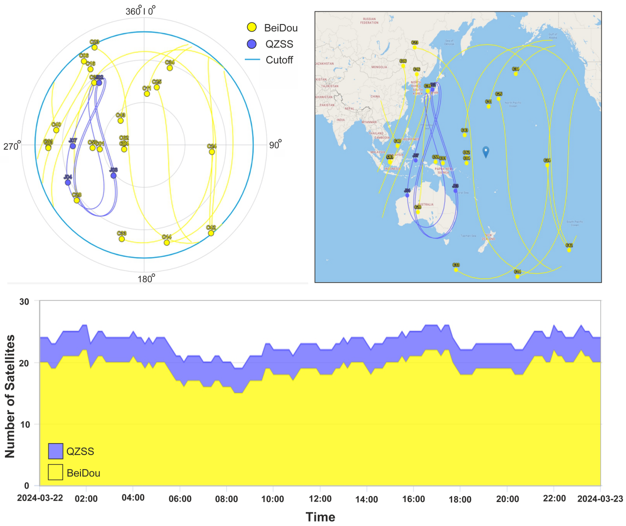

Figure 2. Skyplot in the study region and number of QZSS and BeiDou satellites

4 Analysis of fixed baseline surveys

"Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques" is a handbook created by the US Federal Geodetic Control Subcommittee (FGCS) explaining the national standard for data quality. The National Standard for Spatial Data Accuracy (NSSDA) (Positional Accuracy Handbook, 1999) contains instructions for the measurement and reporting of positional accuracy of features found within a geographic data set, while recognizing the growing need for digital spatial data and provides a common reporting. The Positional Accuracy Handbook offers practical information on applying the standard to a variety of data used in geographic information systems. It is designed to facilitate the interpretation of the NSSDA, using the standard more confidently and help relay information about the accuracy of data sets more clearly. It is also intended to help data users understand the meaning of accuracy statistics reported in data sets more fully. It is meant to function as a manual for organizing, conducting, and categorizing geodetic surveys using GNSS relative positioning techniques. It can be used to verify the ppm values in column (Table 2) for the specified order of accuracy for the survey. The FGCS rules provide additional requirements for various orders of accuracy in relation to repeated baseline observations, in addition to the ppm requirements. Once again, the FGCS guidelines or the manufacturer-provided accuracy level specifications may be used to calculate the acceptability of the line. The procedure used for evaluating the consistency of the observed data and in preventing errors, repeated observations of certain baselines, involves different observing sessions followed by comparing the results. Significant differences in repeat baselines indicate issues with field procedures or hardware (Wolf and Ghilani, 2012; Positional Accuracy Handbook, 1999).

In this study, BeiDou/QZSS, BeiDou and QZSS satellite configurations and Fixed-Wide Lane integer ambiguity solution for short, medium, and long baselines and ppm values were analysed using the FGCS guidelines (Positional Accuracy Handbook, 1999). Another remarkable finding of this study is that the four visible QZSS satellites were able to solve the JFNG-WUH2, MOBS-SYDN, KIRI-POHN baselines (QZSS configuration) with a difference of between 1 cm and 81.8 cm (Table 2). Meanwhile, ppm values of these baselines were computed to be between 0.03–0.54 ppm (BeiDou/QZSS), 0.07–0.62 ppm (BeiDou) and 0.08–1.14 ppm (QZSS).

Table 2. Comparison of satellite configuration, type of integer ambiguity solution, number of satellites (BeiDou/QZSS) and baselines, and ppm values in this study region

Baselines	Satellite Configuration	Solution Type	S_{TMTS} [m][1]	QZSS	BDS	$S_{BERNESE\ QIF}$ [m][2]	Diff. [m]	PPM
JFNG-WUH2	BeiDou/QZSS	Fixed, Wide Lane	12961.004	4	43	12961.011	-0.007	0.54
NCKU-TWTF		Fixed, Wide Lane	236983.918	2	15	236983.936	-0.018	0.08
MOBS-SYDN		Fixed, Wide Lane	715773.904	4	47	715773.966	-0.062	0.09
KIRI-POHN		Float, Wide Lane	1741104.538	4	48	1741104.482	0.056	0.03
JFNG-WUH2	BeiDou	Fixed, Wide Lane	12961.003		43	12961.011	-0.008	0.62
NCKU-TWTF		Fixed, Wide Lane	236984.037		15	236983.936	0.101	0.43
MOBS-SYDN		Fixed, Wide Lane	715773.908		47	715773.966	-0.058	0.08
KIRI-POHN		Float, Wide Lane	1741104.602		48	1741104.482	0.120	0.07
JFNG-WUH2	QZSS	Fixed, Wide Lane	12961.006	4		12961.011	-0.005	0.39
NCKU-TWTF		-	-	2		236983.936	-	-
MOBS-SYDN		Fixed, Wide Lane	715774.784	4		715773.966	0.818	1.14
KIRI-POHN		Fixed, Wide Lane	1741104.349	4		1741104.482	-0.133	0.08

[1] TMTS: Topcon Magnet Tools Software Version 8.1.0
[2] Bernese 5.2

5 Conclusion

The National Standard for Spatial Data Accuracy implements a well-defined statistic and testing methodology for positional accuracy of maps and geospatial data derived from sources such as: aerial photographs, satellite imagery, or maps. Accuracy is reported in ground units. The testing methodology is a comparison of data set coordinate values with those coordinate values from a higher-accuracy source for points that represent features easily visible or recoverable from the ground. While this standard evaluates positional accuracy at points, it applies to geospatial data sets that contain point, vector, or raster spatial objects. Data content standards, such as FGDC Standards for Digital Ortho-imagery and Digital Elevation Data, will adapt the NSSDA to given spatial object representations.

Based on the results of this study, it can be concluded that the 1st (QZSS/BeiDou), 2nd (BeiDou) and 3rd (QZSS) strategies feature different horizontal accuracies for all categories (13–1741 km) whereas horizontal accuracies are less than 6 cm. The obtained results with different satellite configurations for the Fixed-Wide-Lane integer ambiguity solution are compared with each other. In the statistical test-based investigations, the obtained differences of all baselines were calculated in ppm values. In this study, the effectiveness of BeiDou/QZSS satellites in the short, medium, and long baselines solution clearly evidenced. It will provide both enormous potential and advantages for research and engineering applications. This study was performed on experiment about possible accuracy, particularly for short, medium, long baselines (Wide Lane ambiguity solution) by using BeiDou, QZSS and QZSS/BeiDou combinations. It seems that the use with the integration of BeiDou/QZSS static measurements in the study region can ensure millimetre-centimetre accuracy for short, medium and long baselines.

Regarding the status and development of QZSS, the obtained results indicate that: In Asia-Pacific regions, QZSS enhances the visible satellite number. This study may contribute to expanding BeiDou's service area. QZSS would become an increasingly important component of BeiDou with its further development and formal operation.

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