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Editorial

An Overview of a Special Issue on Upcoming Positioning, Navigation, and Timing: GPS, GLONASS, Galileo and BeiDou

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In recent decades, global navigation satellite systems (GNSSs) have experienced significant changes. The BeiDou Navigation Satellite System (BDS), Galileo Navigation Satellite System (Galileo), and Quasi-Zenith Satellite System (QZSS) have been newly deployed in China, the European Union, and Japan, respectively. Furthermore, modernization of USA's Global Positioning System (GPS) and restoring of Russia's Global Navigation Satellite System (GLONASS) have been accomplished. It is expected that integration of these GNSSs data can provide more accurate positioning and timing results because there has been a significant increase in both the number of satellites and frequencies. However, it is necessary to analyze and evaluate the quality of signals transmitted from the newly developed GNSS to support geodetic applications [1–3]. Moreover, system-related errors, such as biases between systems and between tracking channels, should be determined with sufficient accuracy for the applications that require undifferenced GNSS measurements [4–8]. The Precise Point Positioning (PPP) technique, which uses undifferenced GNSS measurements, has been widely used because of its simplicity in the modeling of observations [9,10]. The satellite orbit and clock information provided by the analysis centers are also important factors for PPP, and their accuracies need to be evaluated for GNSS users [11,12]. Improved observation redundancy enhances positioning quality and reliability only when the functional and stochastic models of observations are properly designed [13,14]. It also offers enhanced accuracy and availability in navigation solutions when integrated with other sensors, such as inertial measurement units (IMUs) [15]. In this overview paper, new issues and challenges of additional GNSSs are introduced based on the papers published in a Special Issue on upcoming positioning, navigation, and timing: GPS, GLONASS, Galileo, and BeiDou. More details on the contributions of each paper are given in the following paragraphs.

Most traditional approaches for the orbit determination of GEO satellites are based on ground-based ranging systems. However, navigation solutions using onboard GNSS receivers are an attractive alternative owing to their cost-effectiveness and autonomy. Ref. [1] analyzed the signal characteristics of observations collected from an onboard GNSS receiver in the GEO satellite, that is, TJS-5. They then generated kinematic and dynamic orbit solutions from the GNSS observations. The signal characteristics of GPS and BDS were analyzed in terms of the number of observations, availability, position dilution of precision (PDOP), and observation accuracy. The results showed that the noise levels of the BDS code and phase observations were lower than those of the GPS observations. Finally, they showed some comparative results of orbit determination with accuracy.

The construction of a 3rd generation of BDS, that is, BDS-3, was completed in July 2020. BDS-3 consists of a GEO, geosynchronous satellite orbit (IGSO), and medium Earth orbit (MEO). Hence, analysis of the new signals from BDS-3 should be performed to reliably utilize the full BDS. Comprehensive assessments of the new observations were performed according to the orbital types and signal strengths of BDS-3 expressed by the carrier-to-noise ratio (C/N) [2]. The authors also presented the accuracy of carrier-phase observations using zero-baseline solutions.

The signals transmitted from GNSS satellites are weak near the Earth's surface and limit GNSS satellite availability in the presence of signal interference and jamming. Recently, many studies have reported signal blocks owing to personal privacy devices (PPDs) and their impact on GNSS-based positioning. Ref. [3] examined the effects of GNSS signal jamming on positioning with a single-baseline and network RTK. The jamming effects on the carrier phase observations are the primary concerns in this study and were investigated through the Testbed in the Aarhus for Precision Positioning and Autonomous Systems (TAPAS) GNSS network. The authors showed that the TAPAS network to jamming was robust owing to its multi-frequency and multi-GNSS capabilities.

The ionospheric delay measured from GNSS observations is inherently affected by both differential code bias (DCB) and inter-satellite code bias (ISCB). Hence, the determination of biases with high accuracy is a challenging topic in ionospheric modeling. Until recently, many studies have focused on the estimation of DCB, mainly for GPS, GLONASS, and Galileo. However, the characteristics of the DCBs of BDS have not been examined in depth, especially BDS-3. Ref. [4] presented an ISCB estimation algorithm and analyzed the clustering code bias characteristics of BDS-2 and BDS-3. In addition, a self-calibration method, together with improved results, is presented.

The BDS developed by China began to provide positioning, navigation, and timing (PNT) services on 31 July 2020. BDS satellites can be categorized into three stages: demonstration systems (BDS-1), regional systems (BDS-2), and global systems (BDS-3). Each system has its own characteristics of orbits and transmitting signals owing to the different modulation types. The hardware delay bias that exists between the systems should be determined with reasonable accuracy to use the full BDS constellation. Ref. [5] estimated ISBs and analyzed their impact on BDS-2 and BDS-3, combined with precise time and frequency. Four different stochastic models were tested, and then, the random constant and random walk were recommended as optimal and sub-optimal models, respectively.

Many studies have shown that the fractional part of inter-system bias (F-ISPB) can be ignored when the receiver types of the reference and rover are the same in the double-differencing observation model. However, it cannot be ignored if different types of receivers are used for the constitution of the baseline. Therefore, it is necessary to accurately estimate the value of F-ISPB for precise positioning. The particle swarm optimization (PSO) algorithm can be used to estimate F-ISPB. Ref. [6] proposed an improved PSO algorithm to overcome the limitations of the standard PSO algorithm. The main idea of the proposed algorithm is to transform the search space so that the F-ISPB value, which is close to the boundary of the search space, can be located near the center region. A numerical test was performed to validate the proposed algorithm, and the results showed better performance than that of the standard PSO.

Inter-system bias (ISB) is a bias between observations from different GNSSs, and it is caused by hardware delay and known to be affected by receiver and antenna types. ISB is one of the most important factors to be estimated or modeled precisely for precise positioning and ionospheric modeling using GNSS. There has been an attempt to resolve this issue by introducing ISB parameters into the observation equations and estimating ISBs for GLONASS, Galileo, BDS-2, and BDS-3 with respect to GPS [7]. When the effect of receiver type on the short- and long-term stability of ISB was analyzed, no significant variations were observed. In addition, a feasibility test on the positioning was performed by introducing the predicted ISB as a priori constraint.

The PPP technique has been widely used because it is a relatively simple and independent solution that can be obtained; that is, it does not require a reference station. Therefore, much research has been conducted on PPP with GNSS observations. Currently, five satellite systems are almost in full operation and provide both positioning and timing services, resulting in improved observation redundancy. Hence, the accurate and precise modeling of observations from multiple systems is a crucial part of PPP. Ref. [8] presented the positioning performance of a five-system integrated PPP in both static and kinematic modes. The results showed that significant improvements in the static positioning accuracy were not observed. However, improved performance in terms of convergence time in both the static and kinematic modes was achieved.

Galileo, developed by the European Space Agency (ESA), was designed to transmit five-frequency signals to provide precise positioning and timing services. Multi-frequency signals can improve the redundancy in observations and consequently, positioning accuracy. Many studies have been conducted on precise positioning and ambiguity resolution (AR) using Galileo multi-frequency signals. However, most previous studies have focused on precise dual-, triple-, and quad-frequency positioning and time-frequency transfer. Ref. [9] presented mathematical models for precise positioning using five-frequency Galileo signals. To demonstrate the performance of the proposed mathematical model with observations, data collected from five stations from the multi-GNSS experiment (MGEX) network were processed, and the results were compared with those from the dual-frequency observation combination.

The PPP technique requires precise modeling for all error sources, including orbit and clock errors. However, real-time precise orbits and clock information of GNSS satellites are generally not available and limit the use of PPP in real-time applications. To overcome this limitation, ultra-rapid orbits with clock products are frequently used. Ref. [10] presented a new strategy and method, that is, combined parallel threads (CSPT), to improve stability, latency, and accuracy. Availability and reliability were verified by comparing the results with the reference orbit and clock products, respectively.

Satellite clocks play an important role in PNT services for GNSS users. Therefore, a comprehensive analysis on GNSS satellite clocks should be performed, especially when new GNSS satellites are launched. BDS-3 is a new satellite system developed by China and has been operating fully for more than one year. Ref. [11] analyzed the precise clock products for BDS-3 from GeoForschungsZentrum and showed the characteristics and performance in terms of clock bias, frequency, drift rate, fitting residuals, periodicity, and frequency stability.

Earth-observing techniques using low Earth orbit (LEO) satellites are considered efficient because they provide global coverage and periodic observation capability. Many Earth observation missions focus on real-time applications, and precise orbit determination, especially in real time, has been one of the main issues. In general, real-time orbit determination (RTOD) is performed using data, such as broadcast ephemeris, collected from onboard GNSS receivers. Ref. [12] proposed a new RTOD algorithm for LEO in a multi-GNSS environment and presented numerical results based on the algorithm. The proposed algorithm mainly focuses on the absorption of orbit and clock offset errors in the line of sight (LOS) and is applied to the GPS/BDS measurements obtained from the FngYun-3C satellite. A comprehensive analysis of the optimal stochastic model for pseudo-ambiguity was performed to validate the proposed algorithm.

To determine the attitude of a vehicle, gyroscope data from an inertial navigation system (INS) are frequently used. However, this has disadvantages in that the cost of INS is relatively high and accumulates errors as the elapsed time increases. Therefore, attitude determination using a GNSS receiver with multiple antennas could be an alternative because it is relatively inexpensive and free of error accumulation. Ref. [13] proposed a single-difference (SD) approach to retain the advantages of SD observables and a one-step ambiguity substitution technique to separate ambiguities from SD uncalibrated phase delay. The proposed method was validated in both static and kinematic modes, and the results were consistent with the reference attitude data.

The double-difference (DD) relative positioning technique can eliminate the most common errors in the observations of the reference and rover stations. However, it is difficult to mitigate multi-path errors because it is affected by signal-reception environments. In general, sidereal filtering is applied to remove or mitigate the multi-path effects. Ref. [14]

proposed an algorithm to generate an SD multi-path hemispherical map that can retain flexibility in the construction of a DD observation model. The SD multi-path can be obtained from the DD multi-path by applying "zero mean" constraint. The numerical test results showed that multi-path effects were successfully modeled, resulting in an improvement in positioning accuracy.

GPS-only attitude determination is not applicable when the GNSS receiver is in unfavorable conditions; for example, the number of visible satellites in urban areas is sometimes insufficient to solve unknowns. To compensate for the weakness of the GNSS-only approach, a low-cost microelectromechanical system (MEMS) can be incorporated and integrated to achieve reliable solutions. Ref. [15] presented a new tightly coupled model that uses a single filter to obtain optimal estimates such as attitude drift, gyro biases, and ambiguities. In addition, a MEMS-attitude-aided quality control method is proposed, and the corresponding numerical test results are shown with an improvement in the ambiguity resolution success rate.

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