Chapter 2
Application of BeiDou Navigation Satellite System on Attitude Determination for Chinese Space Station

Sihao Zhao, Cai Huang, Xin Qi and Mingquan Lu

Abstract BeiDou Navigation Satellite System (BDS) offers service to space-based users. The future Chinese Manned Space Station (CSS) orbits inside the service area of the future global BDS, and can utilize BDS to perform its attitude determination. This contribution first analyzes the constellation situation of the global BDS during the operation phase of the CSS. The results show that the global BDS can provide positioning and attitude determination service to the CSS. Second, the principles of the carrier phase based attitude determination technique are presented and the characteristics of the CSS are discussed, based on which the technical conditions required for BDS-based attitude determination for the CSS are analyzed. An attitude determination scheme which requires three antennas to be installed on the three CSS' component cabins respectively is proposed. Next, simulations and analysis on the roll, pitch and yaw angle measurement errors when the CSS is orbiting are conducted. The results indicate the feasibility of applying BDS on the attitude determination for the CSS, and the root mean square errors of the measured attitude angles can reach about 0.05° for roll and pitch, and 0.04° for yaw respectively, provided the condition of two linearly independent 10 m level baselines formed by three BDS receiving antennas.

Keywords BeiDou navigation satellite system · Chinese space station · Multi-baseline · Attitude determination · Application

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2.1 Introduction

BeiDou Navigation Satellite System (BDS) is a Global Navigation Satellite System (GNSS) developed and implemented by China which has achieved its regional service ability covering China and its surrounding areas since the end of 2012 [1] and would form a global constellation comprised of geosynchronous orbit (GEO) and non-geosynchronous orbit satellites by 2020 [2, 3]. The Chinese Space Station (CSS) program has entered its implementation phase, and around 2020, it is planned to complete a large scale manned space station comprised of multiple cabins which will conduct long term on-orbit operation with crew members on it [4]. The operation period of CSS concurs the global service time of BDS. Therefore, it is of theoretical and practical significance to explore the applications of BDS on such influential engineering projects as manned space programs.

GNSSs have been widely adopted by manned spacecraft. For example, the space shuttle determined its position with the Global Positioning System (GPS) operated by USA [5, 6], GPS is adopted as one of the relative measurement methods for spacecraft rendezvous and docking missions [7], and the Chinese manned spacecraft also equips with GNSS devices [8, 9]. It is worth mentioning that the International Space Station (ISS) not only uses GPS for positioning, but also utilizes 4 GPS receiving antennas which form a 1.5 m × 3 m rectangle to determine its attitude along with gyro data and the post processing precision reaches 0.5° (3-σ root mean square) [10].

BDS has already achieved a regional service ability, however, is still not able to provide a full-orbit coverage for manned spacecraft due to its limited service area. The forthcoming global BDS constellation will be a good complement or/and substitute for GPS and other GNSSs and will offer unintermittent service to manned space vehicles such as CSS [11]. At present, inertial measurement units, sun sensors, star sensors and etc. are widely adopted for attitude determination by spacecraft while GNSS devices are mainly used to measure the absolute and relative position/velocity of the vehicle as well as support the ground based orbit determination tasks. The CSS requires extremely high safety and reliability during on-orbit operation. With multiple BDS antennas and receivers installed on it, the existing attitude determination methods can be supplemented and augmented. At the same time, BDS can be used for deformation surveillance of the rigid multi-cabin assembly of CSS so as to increase the safety of on-orbit operation.

It is proposed that the CSS will further utilize the service of the BDS to support orbit determination and rendezvous and docking missions [12], which implies that each cabin may be equipped with its own BDS receiver, and consequently, makes it possible to utilize BDS to determine the attitude of the multi-cabin CSS as a whole. It is notable that the CSS will become the largest Chinese earth orbiter ever and one of the largest space vehicles around the world, which enables a superior measurement precision over other spacecraft as a result of the possible longer baselines between antennas.

In this paper, the service ability of the global BDS during the period of the CSS on-orbit operation is firstly simulated and analyzed. Then, the carrier phase double-differencing attitude determination technique is presented based on which the technical conditions required for CSS attitude determination are discussed. An attitude determination scheme using three antennas installed on CSS cabins is proposed. Next, the roll, pitch and yaw angle errors of the CSS measured using the proposed scheme is analyzed based on simulation. The main conclusion and outlook for next-step work are proposed in the final part.

2.2 Analysis on Service Ability of Global BDS for CSS

BDS is comprised of the space constellation, the ground control segment and the user segment, and has achieved its regional coverage. The forthcoming global BDS constellation will consist of 5 GEOs, 3 inclined geosynchronous orbit satellites (IGSO), and 27 medium earth orbit satellites (MEO). The GEOs will locate at 58.75°E, 80°E, 110.5°E, 140°E and 160°E respectively. The 3 IGSOs which will orbit at an altitude of 36,000 km, are distributed evenly on three orbital planes with an identical inclination of 55° and a phase shift of 120°. They share the same 8-shaped ground track which intersects at 118°E. The 27 MEOs will be evenly distributed on 3 orbital planes with an altitude of 21,500 km [2]. The simulated global BDS constellation is shown in Fig. 2.1.

The assumed orbit of CSS is near-circular which has an inclination of 42°–43°, and an altitude of 340–450 km [4]. Table 2.1 lists the orbital elements of Tiangong 1 target vehicle observed from ground [13] which are assumed to be used by CSS, and the ground track of this orbit is shown in Fig. 2.2 [11]. The CSS flight attitude is assumed to be three-axis stable which means that the BDS antenna always points to the zenith as illustrated in Fig. 2.3. The half pitch angle of the antenna field of view is set to 80° which blocks off the BDS signals outside this angle.

A simulation scenario with a total length of 6 days and an epoch step of 1 min is established in Satellite ToolKit (STK) based on the above-mentioned configurations.

The number of visible BDS satellites and their time percentages from the simulation are listed in Table 2.2.

The results indicate that at least 4 BDS satellites can be viewed at any place of the manned space orbit which guarantees an absolute positioning service to CSS [11]. Furthermore, the number of visible satellites for CSS is actually no fewer than 6 which enables a carrier phase differencing technique for high precision relative measurement should more than one BDS receivers/antennas be installed. Therefore, the global BDS is able to provide a full-course coverage for CSS to meet the high precision measurement demand. More specifically, if no fewer than 3 BDS receivers and antennas are installed to form 2 or more linearly independent baselines, attitude determination for CSS can be achieved.

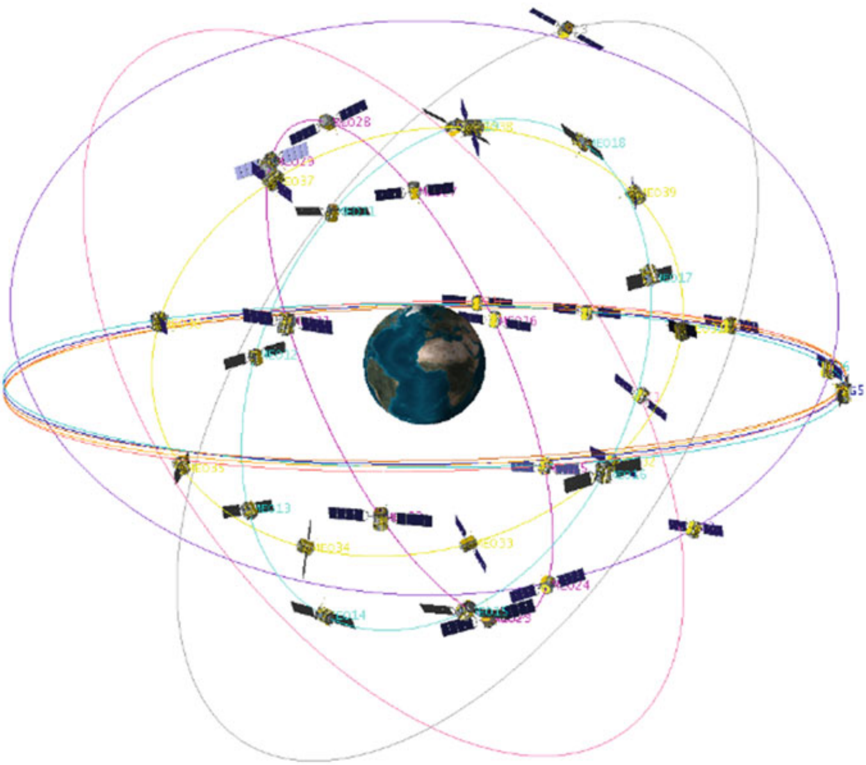

Fig. 2.1 Simulated global BDS constellation

Table 2.1 Orbital parameters of CSS for simulation

Orbital element	Value
Time (UTC)	2014/03/01 12:28:00
Semi-major axis (km)	6753.800
Eccentricity	0.000947
Inclination (°)	42.686
Right ascension of ascending node (°)	241.312
Argument of perigee (°)	20.204
True anomaly (°)	76.347

The validity of BDS for high precision relative positioning is proved by ground tests using carrier phase differencing techniques [14–16], and the root mean square (RMS) error lies within 1 cm under an approximate 10 m baseline condition [15, 17]. In the manned space orbital area, the atmosphere is extremely thin which greatly alleviates the tropospheric delay frequently experienced in a ground application and thus is beneficial to a higher precision. In addition, the fast

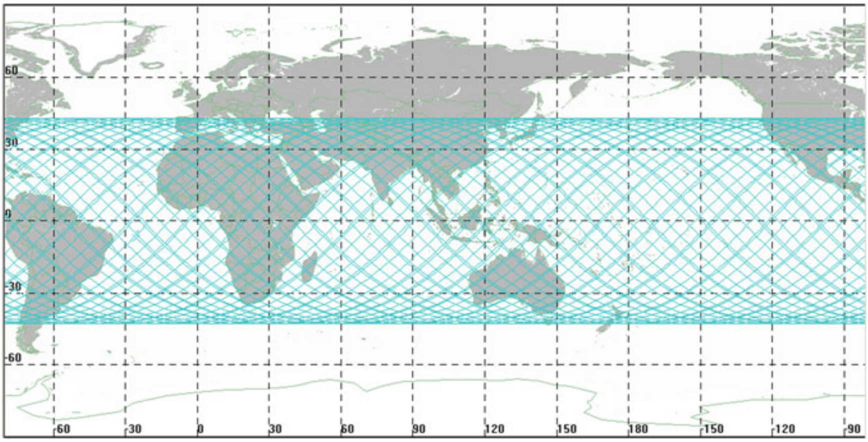

Fig. 2.2 Simulated ground track of CSS

Fig. 2.3 Flight attitude and antenna setup diagram [11]

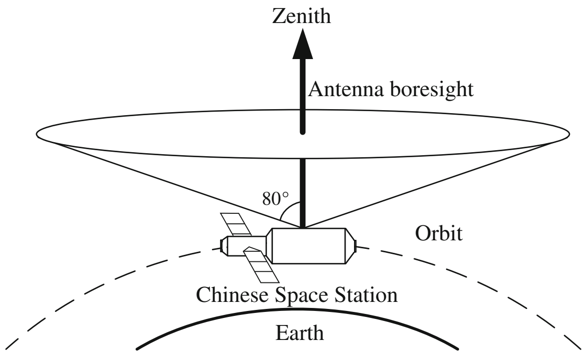

Table 2.2 Statistics of number of visible BDS satellites for CSS

Item	Value
Maximum number	19
Minimum number	6
Average number	10.3
≥9 time percentage (%)	65.1
≥8 time percentage (%)	78.3
≥7 time percentage (%)	90.5
≥6 time percentage (%)	100.0
≥5 time percentage (%)	100.0
≥4 time percentage (%)	100.0

maneuver of the spacecraft is helpful to shorten the convergence time of real-time high precision solutions. From the test and simulation results, we know that BDS has the ability to provide high precision measurement to the CSS.

2.3 Carrier Phase Based Attitude Determination

A vehicle's relative attitude information in a certain coordinate frame can be obtained by measuring the relative relationship between the known baseline vectors and the coordinate frame if there are more than one linearly independent baselines. For example, if **C** is denoted as the rotation transformation matrix between the body coordinate frame (b frame) and the navigation coordinate frame (n frame), then **C** can be written as the following equation.

$$\mathbf{C} = \begin{bmatrix} \cos p \cos y & \cos r \sin p \cos y - \cos r \sin y & \sin r \sin y + \cos r \sin p \cos y \\ \cos p \sin y & \cos r \cos y + \sin r \sin p \sin y & \cos r \sin p \sin y - \sin r \cos y \\ -\sin p & \sin r \cos p & \cos r \cos p \end{bmatrix} \tag{2.1}$$

where r, p, and y are the roll, pitch and yaw angles respectively.

If $\mathbf{v}_{1\mathrm{b}}$ and $\boldsymbol{v}_{2\mathrm{b}}$ are two known vectors in b frame, and their expressions can be defined as $\mathbf{v}_{1\mathrm{n}}$ and $\mathbf{v}_{2\mathrm{n}}$ in n frame, then

$$\begin{aligned} \mathbf{v}_{1n} &= \mathbf{C}\mathbf{v}_{1b} \\ \mathbf{v}_{2n} &= \mathbf{C}\mathbf{v}_{2b} \end{aligned} \tag{2.2}$$

The values of y, p and r are the solution of this non-linear equation set.

The expressions of the vectors in b frame can be obtained by measuring the vectors directly in b frame. The vectors need to be measured in n frame in order to solve the attitude angles in Eq. (2.2). We use BDS carrier phase based technique to measure the baseline vector in n frame. Figure 2.4 demonstrates the relationship between the carrier phase and the baseline vector.

The two end points of a baseline vector are denoted as b and r respectively, and then the measurement equation of navigation signal carrier phase are given as follows.

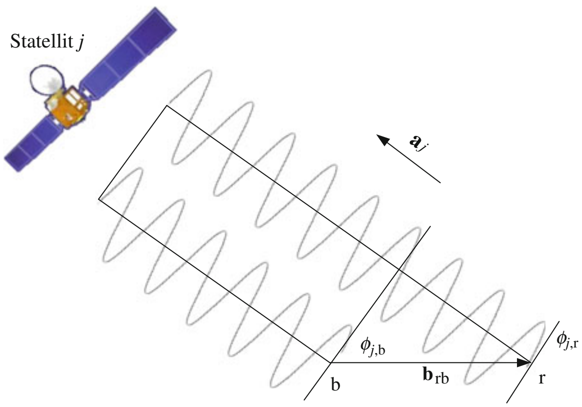

Fig. 2.4 Relationship between carrier phase and baseline vector

$$\phi_{j,\mathrm{r}} = \lambda^{-1}\left(d_{j,\mathrm{r}} - I_{j,\mathrm{r}} + T_{j,\mathrm{r}}\right) + f\left(\delta t_{\mathrm{r}} - \delta t_{j,\mathrm{r}}\right) + N_{j,\mathrm{r}} + \eta_{j,\mathrm{r}} \tag{2.3}$$

$$\phi_{j,\mathrm{b}} = \lambda^{-1}\left(d_{j,\mathrm{b}} - I_{j,\mathrm{b}} + T_{j,\mathrm{b}}\right) + f\left(\delta t_{\mathrm{b}} - \delta t_{j,\mathrm{b}}\right) + N_{j,\mathrm{b}} + \eta_{j,\mathrm{b}} \tag{2.4}$$

where ϕ represents the carrier phase (in carrier cycle), λ is the carrier wavelength (in m), d is the true geometrical range between the navigation satellite and the user (in m), T is the troposphere delay (in m), I is the ionosphere delay (in m), f is the carrier frequency (in Hz), δt_r and δt_j are the user and the satellite clock biases respectively (in m), N is the carrier cycle integer ambiguity, ε and η are measurement errors of pseudorange and carrier phase, and the subscript j is the visible satellite number.

The I and T terms can be eliminated via double differencing between r and b and then satellite i and j, provided a short range or baseline between r and b, and Eq. (2.5) is then formed.

$$\phi_{ji,\mathrm{rb}} = \lambda^{-1} d_{ji,\mathrm{rb}} + N_{ji,\mathrm{rb}} + \eta_{ji,\mathrm{rb}} \tag{2.5}$$

Equation (2.5) is the carrier phase double-differencing measurement model under the short baseline condition. The baseline vector of interest is buried in the double-differenced range $d_{\mathrm{ji,rb}}$ which can be expanded about the estimate positions of b and r with the first order terms remained as shown in Eq. (2.6).

$$d_{ji,\mathrm{rb}} = -\lambda^{-1}\left(\mathbf{a}_{j,\mathrm{r}} - \mathbf{a}_{i,\mathrm{r}}\right)^T \mathbf{b}_{\mathrm{rb}} \tag{2.6}$$

where, $\mathbf{a}_{\mathrm{r,j}}$ is the normalized line-of-sight (LOS) vector pointing from the receiver at r to the jth satellite with the assumption that the counterpart LOS vector of b is identical with that of r, i.e. $\mathbf{a}_{\mathrm{r,j}}$ equals $\mathbf{a}_{\mathrm{b,j}}$, and $\mathbf{b}_{\mathrm{rb}}$ is the baseline vector from b to r.

A high precision baseline vector can be obtained if the integer ambiguity N in Eq. (2.5) is solved by some ambiguity resolution method such as LAMBDA [18]. If more than one such linearly independent baselines exist, they can be solved respectively with a high precision based on the carrier phase double-differencing technique. Afterward, the attitude information can be extracted from the two baselines via some calculation such as shown in Eqs. (2.1) and (2.2).

As commonly adopted in ground applications, a joint processing is required for the independent carrier phase measurement outputs from the receivers at r and b. As a consequence, a data communication link or/and a centralized processing device is needed to double-difference the data from r and b as well as solve the attitude angles.

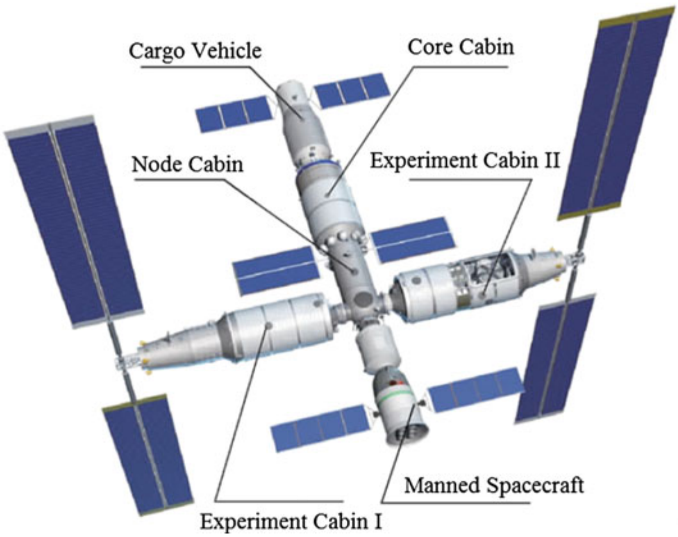

Fig. 2.5 Basic configuration of CSS [4]

2.4 Technical Conditions of BDS Based Attitude Determination for CSS

The CSS is a complex formed by the Core Cabin, the Experiment Cabin I and the Experiment Cabin II and this configuration is illustrated in Fig. 2.5 based on [4].
1. Linearly independent baseline vectors
The Core Cabin, Experiment Cabin I and Experiment Cabin II will form a rigid complex when operating on orbit. Two stable independent baselines as shown in Fig. 2.6 can be formed if there are one BDS receiver and antenna installed on each

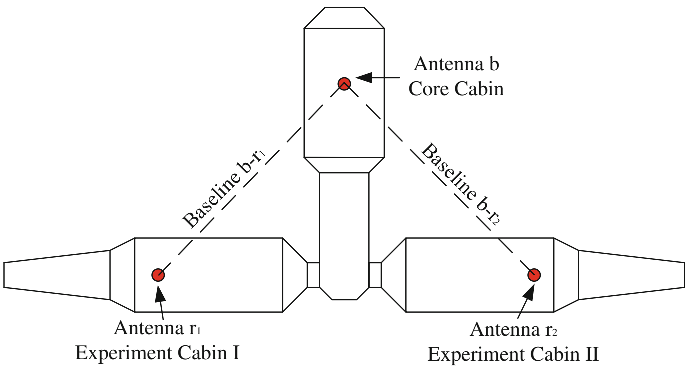

Fig. 2.6 Baselines between BDS antennas on Chinese space station

cabin respectively. We select the antenna b on the Core Cabin as the reference point for the attitude determination system along with which the antennas r_1 and r_2 on Experiment Cabin I and II can establish the two independent baselines.

2. High quality carrier phase measurements
The BDS antennas should be carefully designed so that interference such as multipath effects should be eliminated as far as possible. The receiver should properly handle the spacecraft dynamics and the weak signal reception to guarantee a high quality carrier phase measurement output.

3. Transfer and processing of the measurement data
Besides three sets of antennas and receivers for the three cabins, a module to receive and process the measurement data from the three receivers is required. Therefore a data transfer link and/or a centralized processing device might be needed.

The following 4 preliminary schemes can be considered:

(1) The Experiment Cabin I and II receivers receive the measurement data from the Core Cabin receiver and solve the baselines b-r_1 and b-r_2, and then send the results to ground for attitude solution;
(2) The receivers of the Experiment Cabins send their data to the Core Cabin receiver to solve the attitude angles in a real time manner;
(3) A specialized device can be installed, for the purpose of receiving and processing the measurements from all the three receivers and real time completing attitude determination on-orbit;
(4) The three receivers send their own data down to the ground respectively. A ground based device takes the responsibility of calculating the attitude information.

2.5 Error Analysis for BDS Based CSS Attitude Determination

In this section, the attitude measurement errors of the proposed scheme in the previous section are analyzed via simulations. Three antennas are setup based on Fig. 2.6, and their positions in CSS body coordinate frame are set in Table 2.3.

The orbital elements of CSS are identical with Table 2.1. The CSS keeps a three axis stable flight attitude as set in Sect. 2.2. The simulation length is 6 days with 1 min step, and the total number of epochs is 8640. The three dimensional 3D position in earth-centered-earth-fixed (ECEF) frame of b, r_1 and r_2 at every

Table 2.3 Simulated positions for the three antennas in b frame

Position	Antenna b	Antenna r_1	Antenna r_2
X/m	0	−8	8
Y/m	8	0	0
Z/m	0	0	0

Table 2.4 Simulated true position data for the three antennas at one epoch

3D position	Antenna b	Antenna r_1	Antenna r_2
X/m	6061736.78515	6061731.92252	6061737.99753
Y/m	−2884357.11388	−2884367.32930	−2884357.70602
Z/m	−806299.27452	−806299.28819	−806288.04155

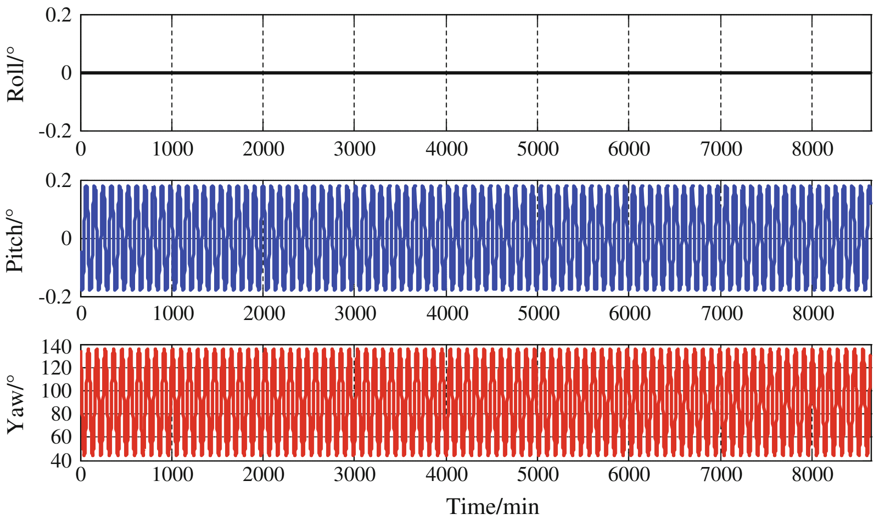

Fig. 2.7 Simulated true attitude angles

simulation epoch are obtained as the truth reference position. Table 2.4 lists the true positions of the antennas at one selected epoch.

We use STK to simulate the flight procedure of the CSS and obtained the true roll, pitch and yaw angles of all epochs in the simulation scenario as plotted in Fig. 2.7.

Random error with a standard deviation of 10 m is added on the true 3D position of the reference point antenna b in ECEF to simulate its positioning results using pseudorange measurements [1]. The standard deviation of the baseline measurement error of b-r_1 and b-r_2 is set to 1 cm.

The two baseline vector b-r_1 and b-r_2 are firstly transformed from ECEF frame to the north east down frame (NED) with b as the original point, and then Eqs. (2.1) and (2.2) are adopted to solve the attitude angles. The roll, pitch and yaw angle solutions are compared with the true attitude angles shown in Fig. 2.7 to generate the attitude errors. Figure 2.8 illustrates the attitude errors from one time simulation.

The attitude error in Fig. 2.8 indicates that the measured attitude angles using the proposed scheme are consistent with the true attitude. The RMS errors are 0.0498°, 0.0516° and 0.0357° for roll, pitch and yaw angles respectively. 100 time's Monte

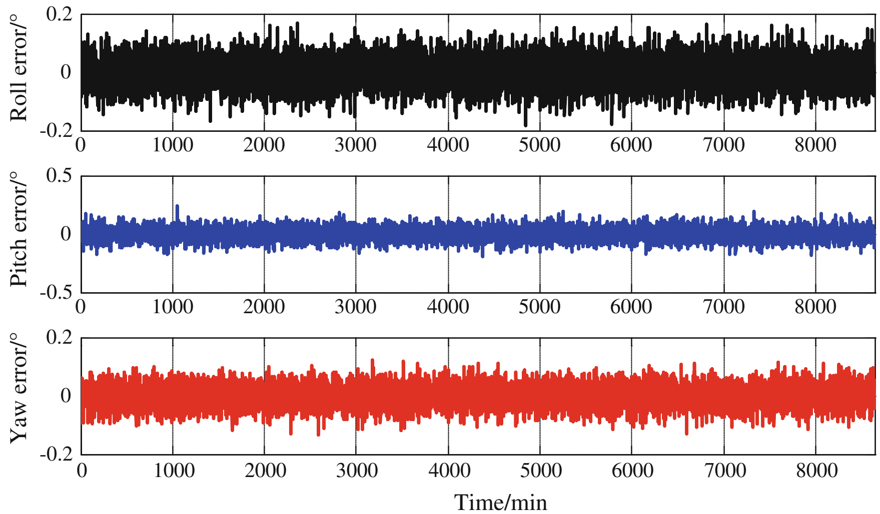

Fig. 2.8 Simulation results of attitude errors

Table 2.5 100 times Monte Carlo simulation results of attitude errors

	Roll	Pitch	Yaw
Average of RMS error/°	0.0506	0.0506	0.0359
Average of absolute error/°	0.0404	0.0404	0.0286

Carlo simulations are also conducted and the average RMS errors and absolute errors are listed in Table 2.5.

We should note that the above simulation only takes the measurement data of independent single epochs into account without employing any filtering methods to introduce any historical information. The error added to the measurements are also larger than that from the ground tests. As a consequence, the simulation results are more approximate to its lower performance boundary. In other words, an improved attitude determination precision can be expected in the practical operation of CSS, not to mention if other algorithms including filtering methods and constraints are adopted.

Additionally, the space environment of the CSS is expected to be better than the simulation conditions. For example, the manned space orbit is almost outside the atmosphere and the impact of air on the signal propagation is negligible. Apart from that, the BDS antenna for CSS can outperform those on the ground which may offer a higher quality of measurements. For those reasons, the on-orbit baseline measurement error tend to be less than 1 cm and a superior attitude determination performance over the simulated results can thus be expected.

2.6 Conclusion and Outlook

This work analyzes the BDS service ability during the on-orbit operation of CSS, discusses the technical conditions required for applying BDS on CSS attitude determination, and proposes a preliminary attitude determination scheme with a two 10 m linearly independent baselines formed by three BDS antennas distributed on the three cabins. It is feasible to employ BDS to support CSS attitude determination provided that multiple BDS antennas and receivers are installed on distinct cabins and data links and related measurement processing devices are equipped. The analysis and numerical simulation of the proposed scheme demonstrate RMS errors of about 0.05° for roll and pitch angles, and 0.04° for yaw angle which outperforms the existing GPS attitude determination system on ISS. In addition, the real on-orbit environment could be better than the simulation conditions and an improved performance can be expected.

BDS can be applied to offering full-course service to CSS attitude determination using the proposed scheme of multiple BDS devices on different cabins. It is an effective complement and augmentation for existing approaches which can also be used for deformation surveillance on the CSS and can provide better safety protection to the large space vehicle.

To establish a more solid foundation for the application of BDS on CSS attitude determination, the future work includes deeper investigation on constraints such as CSS operation environments, device configuration, and data link availability, further research on fast and reliable attitude determination algorithms with fixed baselines and more thorough analysis, simulation and verification on the performances.

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