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METHODS

Integrated Navigation and Communication Service for LEO Satellites Based on BDS-3 Global Short Message Communication

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ABSTRACT Massive global Low Earth Orbit (LEO) constellations have been developed rapidly with the characteristics of larger number and shorter orbital periods of LEO satellites in recent years. The increasing requirements of real-time orbit determination and emergency data transfer in full arc can hardly meet the traditional strategies based on regional ground stations. An integrated communication and navigation service architecture based on the third phase of the BeiDou system (BDS-3) Global Short Message Communication (GSMC) is proposed, which enables global coverage and random access. The GSMC downlink single-frequency signal is used for real-time orbit determination, and is further combined with B1C navigation signal for real-time dual-frequency high-precision orbit determination. Considering fast moving of LEO satellites and short burst of uplink messages, the uplink BDS-3 satellite selection strategy based on carrier-to-noise ratio, and uplink high-precision compensation of frequency shift are adopted to increase the communication success rate. The service architecture proposed can improve the precision of the autonomous orbit determination and enhance the capability of real-time command transmission of LEO satellites even without the traditional ground stations involved. Integrated communication and navigation service has been validated by simulation and on-board BDS-3 GSMC test data. The precision of single-frequency real-time orbit determination can reach 2.86m, and the precision of dual-frequency can reach 0.26m. The average time delay of communication is about 11.45s, and the success rate is about 99.8%. The method may provide alternative means of real-time high-precision orbit determination and emergency data transfer of LEO satellites.

INDEX TERMS BDS-3, global short message communication, LEO satellites, orbit determination, communication.

I. INTRODUCTION

In recent years, the development of global Low Earth Orbit (LEO) constellations, such as Starlink and OneWeb, has been booming rapidly. The number of these new LEO constellation satellites has increased from dozens to tens of thousands compared with the traditional LEO constellation satellites. In addition, meteorological satellites and resource satellites draws more attentions from worldwide countries [1], which has led the continuous launching events all over the world benefiting from the progress of space technology [2]. With the increasing number of satellites, there is a growing demand for remote control, telemetry and other operation management, as well as the burst service data transmission [3]. Ground stations are traditionally used in the management of constellation and service. Normally, the on-board data and control demand of LEO satellites can be transferred and received only when the satellites can be technically connected by

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the ground stations [4]. Due to the orbit characteristics of the LEO satellites, there exists long data gap between two successive visible arcs, and the longest invisible interval may be over 10 hours for a certain ground station. In order to manage satellites and provide service in near real-time way, it is necessary to build numerous ground stations globally, which will substantially increase the complexity and maintenance cost of the ground system.

Space-based method is one of the ways to solve this problem, because it is independent of the distribution of ground stations [5]. However, the present space-based method is also limited by some factors. For instance, the relay satellites located at Geostationary Earth Orbit (GEO) are unable to cover the poles of the Earth and are hard to manage the LEO constellation due to relevant resource application [6]. Additionally, the LEO mobile communication satellite system is incapable of delivering service of communication and orbit determination for other LEO satellites [7].

Global Short Message Communication (GSMC) is one of the newly featured services of the third phase of the BeiDou system (BDS-3) and is mainly based on the Medium Earth Orbit (MEO) satellites [8], [9]. It has been studied to transmit information worldwide in many fields [10], [11], [12], [13], [14], [15].

With GSMC, an integrated communication and navigation service for LEO satellites is proposed in this paper. Due to the integrated B2b downlink signal structure of communication and navigation of GSMC, it can support rapid positioning, orbit determination and high-precision timing. Additionally, the data of LEO satellites can be transferred to ground stations in near real-time way with GSMC, while the commands of remote control from ground stations can also be transferred to the LEO satellites for fast response. Meanwhile, in order to increase success rate of short-burst uplink messages, the uplink BDS-3 satellite selection strategy based on carrier-to-noise ratio, and uplink high-precision frequency shift compensation are adopted.

This paper introduces the service framework of BDS-3 GSMC for the LEO satellites in section II,and evaluates the performance of orbit determination and data transfer in section III, then gives simulated analysis and on-orbit measured results in IV, finally draws several conclusions.

II. SERVICE ARCHITECTURE

A. SYSTEM STRUCTURE

As shown in Fig. 1, the BDS-3 service architecture of integrated communication and navigation for LEO satellites mainly contains the BDS-3 satellites configured with GSMC payload, BDS-3 ground stations, LEO satellites and the LEO ground stations.

The BDS-3 with GSMC service contains user uplink receiving payload and user downlink broadcasting payload. The user uplink receiving payload has been installed at 14 MEO satellites, and is used to receive user uplink Code-Division Multiple Access (CDMA) signals which supports random access. The user downlink broadcasting payload has been installed at 3 Inclined GEO Synchronous Orbit (IGSO) satellites and 24 MEO satellites, and is used to broadcast the downlink B2b Time Division Multiple Access (TDMA) signals. Both uplink and downlink signals can achieve seamless global coverage.

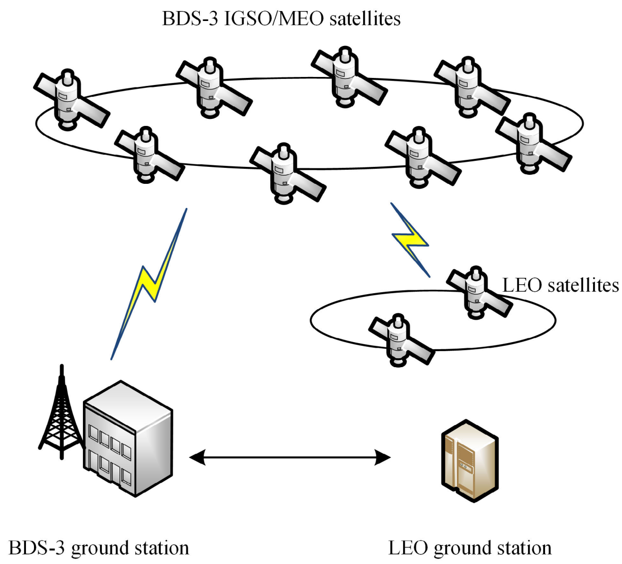

FIGURE 1. **The GSMC service architecture of the LEO satellites.**

The 24 BDS-3 MEO satellites have an orbital altitude of 21528km and an orbital inclination of 55°, adopting the Walker 24/3/1 constellation configuration. The three IGSO satellites have an orbital height of 35786km and an orbital inclination of 55°. They are evenly distributed on the orbits with an ascension point of 118° and an orbital inclination of 55°. The BDS-3 ground stations mainly manage the GSMC service, monitor its technical status and ensure the stable operation of the GSMC system.

The LEO satellites mainly refer to the satellites with global monitoring, operation and control requirements. By installing GSMC transceiver terminals, the LEO satellites can receive operation management and remote control information from the ground stations, and send telemetry and other relevant information to the ground stations. Autonomous orbit determination can be achieved by receiving downlink signals. Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor (GECAM) LEO satellites successfully use GSMC terminals for Gamma Ray burst data transmission for the first time [16], [17].

The LEO ground stations are mainly responsible for operation and management of LEO satellites, including monitoring satellites status and regularly uploading remote control information.

B. ON-BOARD TERMINAL

An integrated on-board module of BDS-3 GSMC communication and navigation for LEO satellites is shown in Fig. 2.

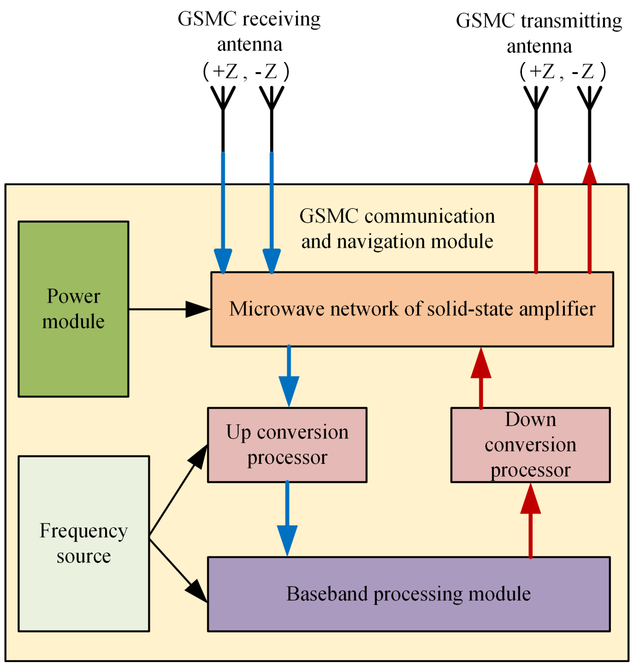

FIGURE 2. On-board GSMC terminal.

The on-board GSMC terminal mainly performs signal processing, and the service and telemetry data are interacted with on-board computer through serial ports and data bus interface. Two receiving antennas on the +Z and –Z planes are used to ensure the B2b signal can be received even under extreme situation of satellite flipping. The corresponding phase offsets should be measured on the ground before the launch of the LEO satellite, thus this correction can be calculated with the offsets and satellite attitude model during the real-time orbit determination. The microwave network of solid-state amplifiers is responsible for signal amplification and distribution. The solid-state amplifier module amplifies the small signal of the received short messages, and the cavity filter suppresses the out-of-band signal to improve the electromagnetic compatibility problem in this system. The up and down conversion processor performs up and down conversion independently. The baseband processing module realizes digital intermediate frequency processing of B2b downlink and uplink signals of short messages. Besides the power supply module provides the secondary power for the entire module to work.

III. ORBIT DETERMINATION AND DATA TRANSFER

A. ORBIT DETERMINATION

GMSC downlink channel shares B2b frame with BD3 navigation message by TDMA. Thus, the positioning of LEO satellites can be achieved by installing the short message communication terminal and receiving the downlink B2b signal of short message communication of several visible BDS-3 satellites.

The B2b signal supports high-precision pseudorange and carrier phase measurement, broadcasts regularly navigation messages at some timeslots and transmits GSMC downlink short message at other timeslots. The basic types of B2b navigation type 10 and 30 are broadcasted in turn, the type 40 is broadcasted once per 60s. Specifically the type 10 contains ephemeris parameters while the type 30 contains the information of time, ionosphere and Earth Orientation Parameters (EOPs). These navigation types provides the necessary broadcast ephemeris that can be used to calculate BDS-3 satellite orbit for LEO satellite positioning.

The ionosphere is the outer space with vertical height from 50km to 1000km. The BDS-3 global ionosphere correction model is only for the users on the ground and the corrected time delay refers to the delay caused by whole ionosphere. However, the LEO satellites are almost located at the middle range of the ionosphere, thus the ionospheric parameters broadcasted by the Global Navigation Satellite System (GNSS) broadcast ephemeris are unable to correct the ionospheric signal delay of the LEO satellites. Although there are literatures that put forward International Reference Ionosphere 2012 (IRI2012) ionosphere correction model to solve this problem [18], but the parameters have to be obtained based on ground observations which cannot be transferred to the LEO satellites in real-time way. When the single-frequency positioning for the LEO satellites is carried out, the corresponding positioning error would be larger due to the inaccuracy of ionospheric correction. As the result, the dual-frequency ionosphere-free linear combination of B2b and B1C is implemented for the LEO satellite high-precision positioning in the rest of this paper.

1) PSEUDORANGE AND CARRIER PHASE OBSERVATION EQUATION

The pseudorange observation equation of a LEO satellite and BDS-3 satellite j at a specific frequency channel can be expressed

$$\rho_L = |\vec{r} - \vec{r}_j| + c(\delta t_r - \delta t_s) + \varepsilon \tag{1}$$

where ρ_L is the pseudorange observation at a specific frequency channel, $\vec{r}$ is the spatial position of the receiver, $\vec{r}_j$ is the position of the j-th GNSS satellite, δt_r is the clock error of the receiver, δt_s is the satellite clock error and ε is the sum of the other error during the signal propagation. The error sources which affect pseudorange and carrier phase observations consist of ionospheric refraction error, atmosphere refraction error, signal transmission time delay, clock error of satellites and receivers, the phase center offsets of satellites and receivers, the receiver displacements caused by plate motion and solid Earth tides, the relativistic effects.

Similarly, the carrier phase observation equation is

$$\rho_\Phi = |\vec{r} - \vec{r}_j| + c(\delta t_r - \delta t_s) + \lambda N + \varepsilon \tag{2}$$

where ρ_Φ is the carrier phase observation at a specific frequency channel, λ is the corresponding wavelength, N is the integer phase ambiguity.

2) IONOSPHERE-FREE LINEAR COMBINATION

The ionospheric error is an important error source for pseudorange and carrier phase observations and it's too large to be ignored. For single-frequency orbit determination, the ionosphere correction model can be used to eliminate one part of the ionosphere influence to orbit determination. Because the ionosphere time delay is inversely proportional to the square of frequency, the ionosphere-free combination is able to eliminate the first order of ionosphere influence while the higher order of ionosphere influence still remains. Note that the combined phase ambiguity is no longer an integer and the measurement noise will be amplified to 3 times the original level based on the law of error propagation. For dual-frequency orbit determination, the ionosphere-free combination of $L1$ and $L2$ can be expressed as

$$P_3 = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 P_1 - f_2^2 P_2\right) \tag{3}$$

$$L_3 = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 L_1 - f_2^2 L_2\right) \tag{4}$$

where f_1,f_2 are two different carrier frequencies, P_1,P_2 are the corresponding carrier phases at the receiving moment and L_1,L_2 are the pseudoranges, P_3 is their combination carrier phase and L_3 is combination pseudorange.

3) ALGORITHM AND FLOW OF ORBIT DETERMINATION

According to the dynamic models of precise orbit determination, the perturbative acceleration $\vec{A}$ is

$$\vec{A} = -\frac{GE}{R^2}\frac{\vec{R}}{R} + \vec{P} \tag{5}$$

where the first term on the right side is the center gravity force of Earth, $\vec{P}$ is the acceleration caused by other perturbative forces, GE is Earth's gravitational constant. $\vec{R}$ is the position vector of satellite, R is the distance from satellite to Earth's center.

In dynamic models, the perturbative forces which should be considered consist of Nbodies perturbation, relativistic perturbation, solar radiation pressure perturbation, repeated RTN perturbation. The dynamic models used in precise orbit determination for LEO satellites are shown in Table 1 [19].

The parameters to be estimated in precise orbit determination contain the parameters appeared in the satellite motion equation, such as the initial orbit parameters of satellites, the parameters of solar radiation pressure and the parameters of empirical acceleration, along with the clock error parameters. The flow of the dual-frequency precise orbit determination is shown in Fig. 3.

When the LEO location is calculated, the satellite uplink payload can transfer the result by GSMC so that the ground stations can know the accurate location of the satellite even it is invisible. The performance of the data transfer will be discussed below.

TABLE 1. The dynamic models for precise orbit determination.

Perturbation	Model	Note
Earth's gravity field	GGM02c model	150×150 degree
Solid Earth tides	IERS96 convention	McCarthy 1996
Ocean loading tides	CSR4.0	Eanes 1994
Nbodies perturbation	Gravitational perturbation by Sun and Moon	JPL DE/LE200 planetary ephemeris
Atmospheric resistance	DTM94 model	Piece-wise atmospheric resistance parameter Cd
Solar radiation pressure	Box-Wing	Rim 1992
General relativistic perturbation	IERS2003 convention	McCarthy and Petit 2002
Empirical acceleration	Empirical force towards TN direction	Piece-wise estimation

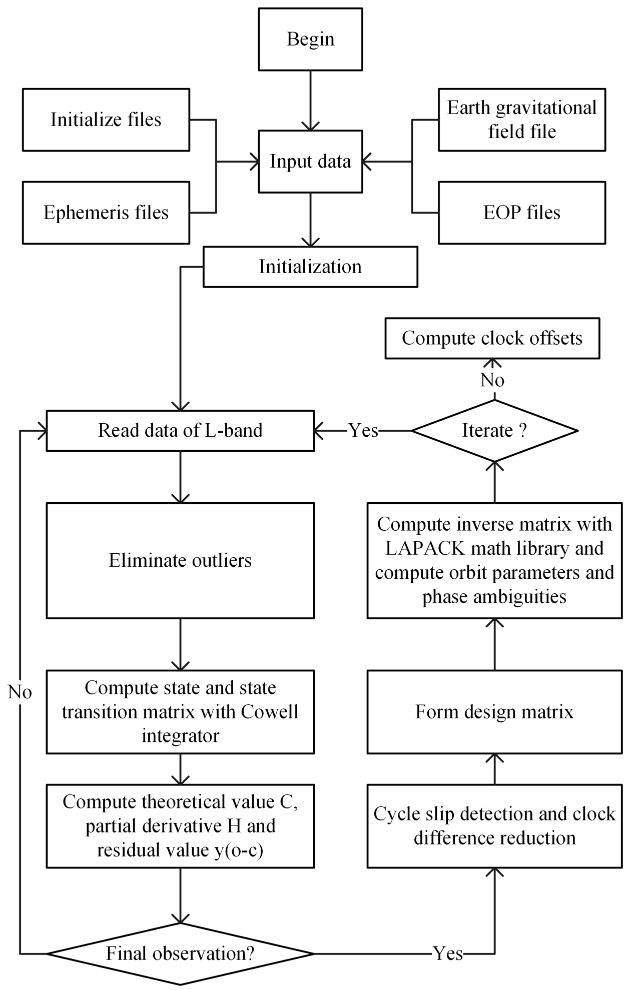

FIGURE 3. The flow of dual-frequency precise orbit determination.

B. DATA TRANSFER

The BDS-3 constellation GSMC uplink capacity is about 403,200 times per hour and downlink capacity is about 243,000 times per hour [8]. There is no remote measurement and instructions need to be transferred in normal circumstances. Assuming 95% LEO satellites transfer their position

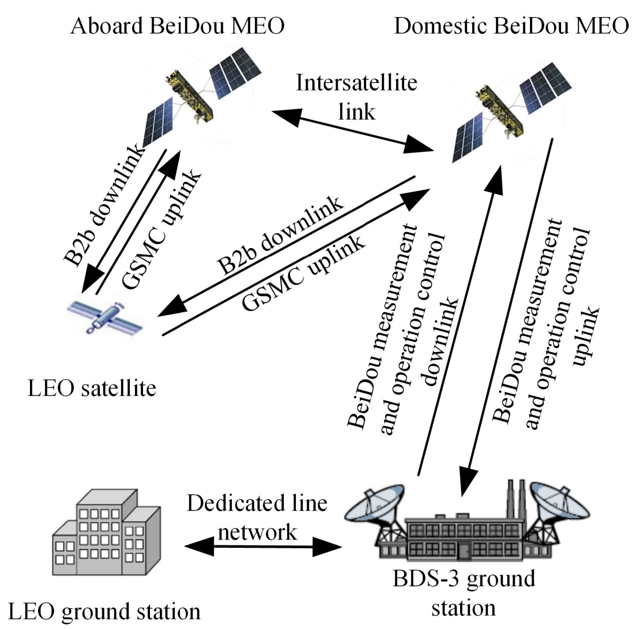

FIGURE 4. The uplink and downlink flow of BDS-3 GSMC.

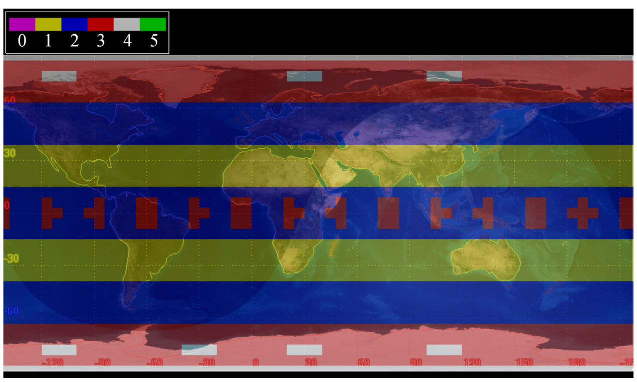

FIGURE 5. The minimum NSAT of uplink signal at the altitude of 500km.

information per 5 minutes which only use uplink channel, and 5% satellites transfer emergency instructions per minute which use both uplink and downlink channel. It can be calculated that GMSC can support over 18,000 LEO satellites.

As shown in Fig. 4, the BDS-3 GSMC uplink and downlink are in principle a pair of symmetric links and the only difference lies on the used channel for sending or receiving. For emergency remote measurement and instructions, the availability and performance of uplink determines when the satellites report their status to regional ground stations. The smaller the uplink latency, the faster the ground stations can know and deal with satellites' problems. Since the downlink signal is a broadcast signal, and the uplink signal is a short burst signal, the success rate of uplink determines the performance of GSMC.

1) UPLINK MESSAGE SENDING STRATEGY

The minimum number of visible satellites (NSAT) with uplink payload is shown in Fig. 5. It shows that NSAT for LEO satellite is over 2 at most of the time, which means LEO satellite usually chooses uplink satellite to access. When transmitting short messages, on-board terminal usually selects the BDS-3 satellite with higher elevation angle to ensure a higher transmission success rate. But the attitude of a LEO satellite will rotate during the flight, and the main lobe beam of the transmitting antenna is limited, the BDS-3 satellite with higher elevation angle maybe not within the main lobe range of the transmitting antenna. Considering that the downlink B2b signal carrier-to-noise ratio received can be used to infer the strength of the short message uplink signal, we select the carrier-to-noise ratio of downlink B2b signal as index in the satellite selection.

The BDS-3 satellites selection strategy for sending uplink message is selecting the satellite with the highest carrier-to-noise ratio in the available BDS-3 satellites. If a sending failure occurs, select the satellite with the highest carrier-to-noise ratio in the remaining available BDS-3 satellites.

The detailed strategy for sending uplink message as follows:

Step 1: Determine available BDS-3 MEO satellites with the GSMC function by receiving B2b downlink signals;

Step 2: Sort the available satellites by their carrier-to-noise ratios and generate the satellite series, select the satellite with highest carrier-to-noise ratio as the sending target;

Step 3: In order to confirm whether the message is sending successfully or not, a confirmation message may received by a B2b signal. Otherwise, step 1-step 3 is repeated until the sending times has reached the predefined repeating times.

2) HIGH PRECISION COMPENSATION OF UPLINK FREQUENCY SHIFT

As shown in Fig.6, the relative velocity of a GECAM satellite to a certain BDS-3 GSMC uplink satellite in one day is simulated. It shows that the relative velocity of the LEO to MEO satellite can reach nearly 7km/s, and the corresponding uplink doppler frequency shift is about 37kHz. It also shows that the LEO GSMC uplink signal has a very large doppler frequency shift range.

Considering that the uplink short messages are burst short signals, in order to reduce the capture pressure of the BDS-3 MEO satellites payloads and improve the success rate of fast acquisition of the uplink signals, the GSMC terminal can perform doppler precompensation. A method of precise uplink signal doppler compensation based on positions of LEO and BDS-3 MEO satellites is proposed. The uplink doppler compensation f_d^t can be calculated by

$$\begin{cases} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = \begin{bmatrix} x^s \\ y^s \\ z^s \end{bmatrix} - \begin{bmatrix} x^r \\ y^r \\ z^r \end{bmatrix} \\ \vec{l}^s = \frac{1}{\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} \\ f_d^t = \frac{(\vec{v}^r - \vec{v}^s)\cdot \vec{l}^s}{\lambda} = \frac{(\vec{v}^r - \vec{v}^s)\cdot \vec{l}^s}{c/f^t} \end{cases} \tag{6}$$

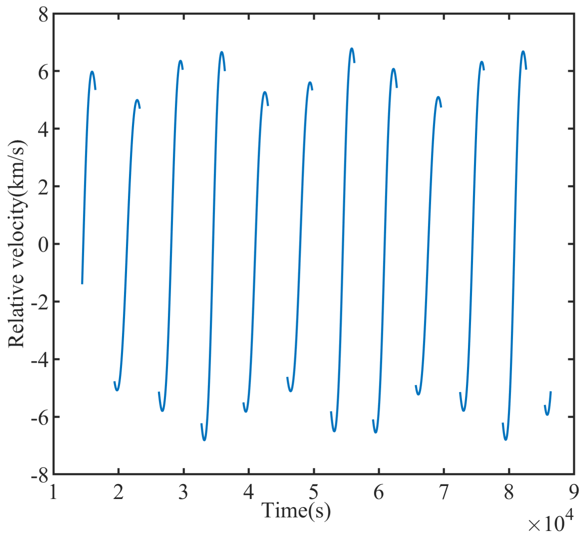

FIGURE 6. Relative velocity of a GECAM to BDS-3 MEO satellite in one day.

where x^s,y^s,z^s are the position of MEO satellite and $\vec{v}^s$ is the velocity, obtained by calculating the ephemeris from the B2b signal. x^r,y^r,z^r are the position of LEO satellite and $\vec{v}^r$ is the velocity, obtained through B2b positioning. c is the speed of light. f^t is the carrier frequency of uplink signal.

3) UPLINK TIME DELAY

The uplink information transmission process is as follows: on-board LEO terminal—> (abroad BDS-3 MEO satellite—> inter-satellite link network) —> domestic MEO satellite—> BDS-3 ground stations.

The time delay of user terminal processing t0 is about 0.1s. The time delay of uplink short messages is divided into the spatial transmitting delay t_1 and information transmitting delay t_2. Assume that the orbit altitude of the LEO satellites is 500km and the minimum elevation angle for short message is 5°, then the minimum spatial distance from the LEO satellites to the BDS-3 MEO satellites is about 21028km and the maximum value is about 26467km. Thus, the spatial transmitting delay is about 0.070s–0.088s. Due to the fact that the length of GSMC information is variable, the information transmitting delay is 1s–2s.

The processing delay for a MEO satellite to relay the received message t_3 is about 0.1s. The message is transmitted back to a domestic satellite, and the transmitting delay of inter-satellite link t_4 includes link establishment and routing.

In addition, the time delay of the downlink of the BDS-3 domestic satellites t_5 is about 0.075s.

Therefore, the time delay of uplink $T1$ is

$$\begin{aligned} T_1 &= t_0 + t_1 + t_2 + t_3 + t_4 + t_5 \\ &= t_1 + t_2 + t_4 + 0.275(s) \end{aligned} \tag{7}$$

Because the position relationship between the LEO satellite and uplink BDS-3 satellite is changing, and the length of the short message is various, the uplink time delay $T_1 \in [1.345 + t_4, 2.163 + t_4](s)$.

Similarly, the downlink process is basically symmetric to the uplink, and the time delay is almost the same.

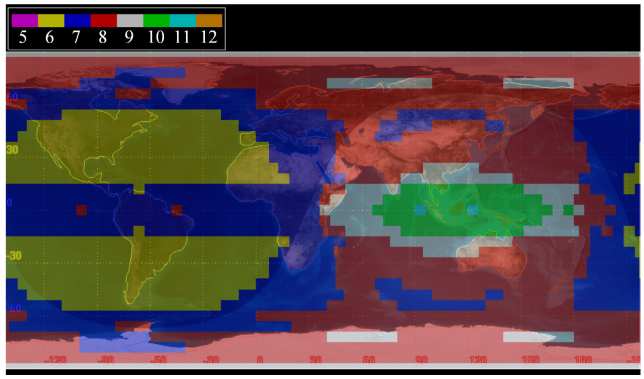

FIGURE 7. The minimum NSAT of downlink signal at the altitude of 500km.

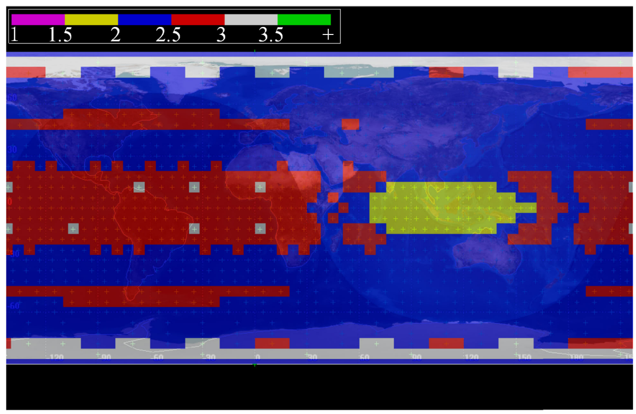

FIGURE 8. The maximum global PDOP distribution at the altitude of 500km.

IV. PERFORMANCE SIMULATION AND VALIDATION

A. PDOP DISTRIBUTION AND VISIBILITY ANALYSIS OF DOWNLINK SIGNALS

The NSAT of downlink signal determines availability of positioning and Position Dilution of Precision (PDOP) value affects positioning accuracy. The NSAT and PDOP distribution of downlink signals is analysed here.

The orbit of the BDS-3 satellites (3IGSO+24MEO) for 7 days is simulated using the STK software to investigate the global PDOP distribution of the B2b downlink signals. The altitude of interest is 500km and the cut-off elevation angle is 5°.The NSAT, maximum and average global PDOP distribution of the B2b downlink signals of BDS-3 satellites are shown in Fig.7, Fig.8 and Fig.9 respectively.

Fig.7 shows that the minimum NSAT of downlink signal around world is 6, and the average is 7.41. It means that the LEO satellites can receive enough downlink signals anytime anywhere, which benefits positioning.

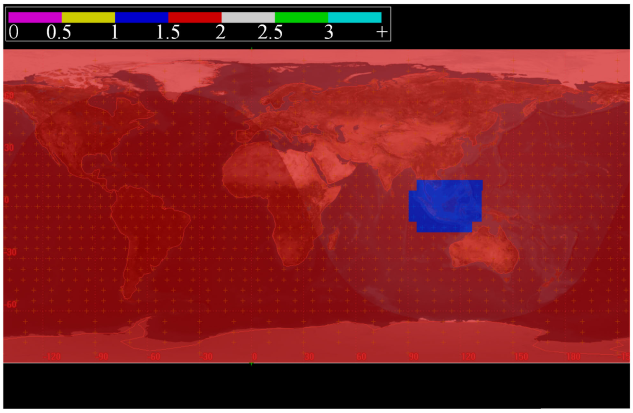

FIGURE 9. The average global PDOP distribution at the altitude of 500km.

TABLE 2. The detailed parameters in simulation of BDS-3 observations.

Item	Value
Constellation	BDS-3 navigation satellites
LEO satellite	Take SWARM-A as an example
SISRE of the BDS-3 spatial segment	0.44
Phase Center Offset (PCO)	igs14.atx
Phase Center Variation (PCV)	0
Ionosphere	Klobuchar model
Relativistic effect	Sagnec effect
The frequency channel of single-frequency orbit determination	B2b (1207.140 MHz)
The frequency channels of dual-frequency orbit determination	B1C (1575.42 MHz) B2b (1207.140 MHz)
The noise level of pseudorange measurement	0.47 m
The noise level of carrier phase measurement	2.7 mm

The simulation results indicate that the maximum PDOP value of global B2b downlink signals is about 1.5–3.5, and the average value is about 1.0–2.0. Additionally, the PDOP distribution within the Asia-Pacific region is improved due to the cover of IGSO satellites.

B. PERFORMANCE ANALYSIS OF ORBIT DETERMINATION

In the simulation of BDS-3 observations, the position of the LEO satellite, the orbit and clock errors of BDS-3 satellites are known, thus the geometric distance between the LEO satellite and the BDS-3 satellites can be calculated. Then based on given models, all the errors which occur during the signal propagation can also be calculated. After we add measurement noise, the simulated pseudorange and carrier phase observations are generated. In this simulation, only the ionosphere influence is considered. The detailed simulation parameters are listed in Table 2.

The ionosphere influence has to be considered in the simulation of the observations. Unlike the ionosphere influence on the ground, the altitude of the LEO satellites is generally about 500km, thus it has to be processed with the mapping functions to obtain the appropriate ionosphere influence. The corresponding ionospheric time delay correction T_{LEO} can be expressed as

$$T_{LEO} = \alpha T_{Klobuchar} \tag{8}$$

$$\alpha = \frac{e - \exp[1 - \exp(-z)]}{e - \exp[1 - \exp(h_0/H)]} \tag{9}$$

where $T_{Klobuchar}$ is the ionospheric delay calculated based on Klobuchar model, h is the altitude of the receiver, h_0 is the height of the assumed thin ionosphere which is set as 420km, H is the height of scale which is usually set as 100km and $z = (h - h_0)/H$.

In addition, the LEO orbit data is the orbit of the SWARM-A scientific satellite, provided by European Space Agency (ESA). Moreover, the GNSS precise products (orbit and clock offset) released by the Center for Orbit Determination in Europe (CODE) are used to simulate the BDS-3 observations to the SWARM-A satellite. Table 3 gives the detailed strategy of BDS-3 orbit determination of SWARM-A satellite.

TABLE 3. The detailed strategy of BDS-3 orbit determination of SWARM-A satellite.

Item	Value
On-board BDS-3 observation	Sampling interval of 30 s
BDS-3 orbit	Broadcast ephemeris
BDS-3 clock offset	Broadcast ephemeris
Ionosphere correction	Single-frequency correction / Ionosphere-free linear combination
PCO of BDS-3 antenna	igs14.atx
The sampling interval for data processing	30 s
Clock offset of the receiver	Epoch-wise estimation
Cut-off elevation angle	5°

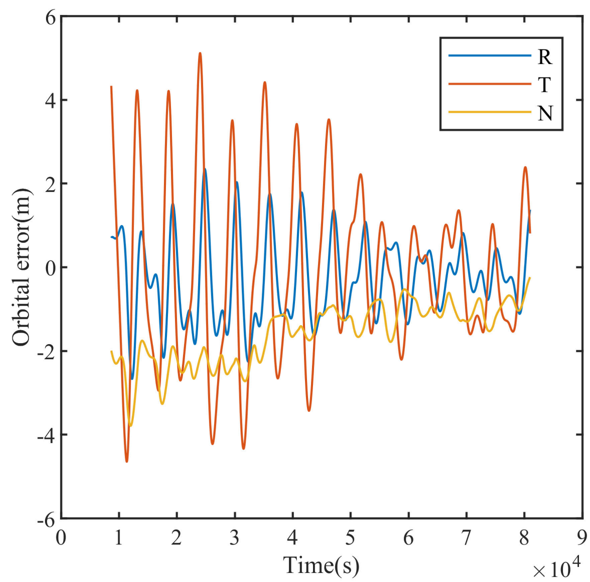

FIGURE 10. The results of single-frequency orbit determination.

The SWARM-A orbit can be determined using the methods discussed before. The results can be compared with the orbit of day-of-year 31 in 2022 released by ESA. For the full day

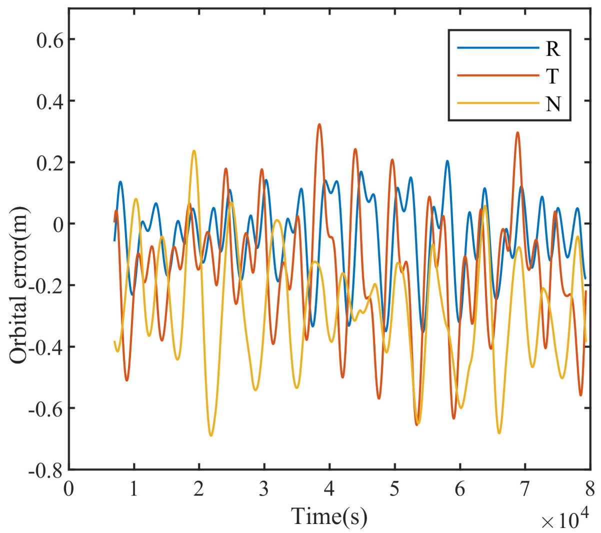

FIGURE 11. The results of dual-frequency orbit determination.

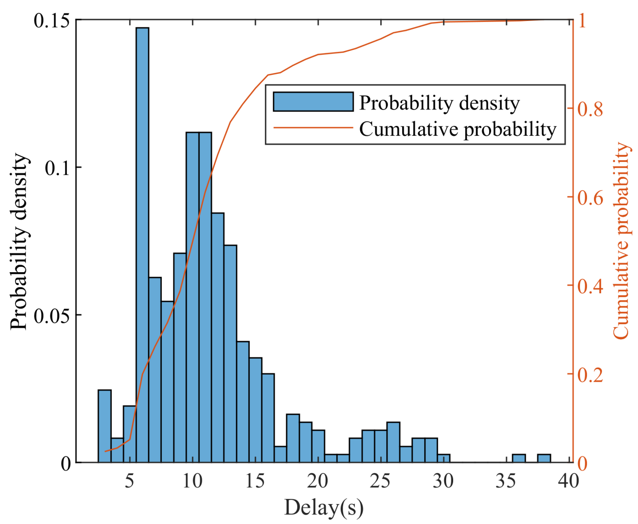

FIGURE 12. The probability density and accumulated probability distribution of the delay of the GSMC uplink.

results, the ones of the first and last one hour are excluded, and the rest results are compared.

For the single-frequency orbit determination as shown in Fig. 10, the Root Mean Square (RMS) of R, T, N direction is 1.0107m, 2.0247m, 1.7433m respectively, and the 3D RMS is 2.8566m.

Besides, for the dual-frequency orbit determination as shown in Fig. 11, the RMS of R, T, N direction is 0.1396m, 0.2565m, 0.3435m respectively, and the 3D RMS is 0.2602m. The orbit determination precision of the dual-frequency is much better than that of single-frequency because the ionosphere-free linear combination is able to eliminate most part of the ionosphere influence.

C. PERFORMANCE VALIDATION OF DATA TRANSFER

By counting the results of the uplink messages of GECAM LEO satellites, it can be found that the success rate is about 99.8%.

The uplink transmission delay distribution is shown in Fig. 12. The minimum delay is 3s, the maximum delay can reach 38s, and the average delay is about 11.45s. About 85% uplink delay is less than 15s, and about 90% is less than 18s. The on-board test data indicate that GSMC can support near real-time interaction of the measurement and operation control, along with low transmitting time delay and high transmitting success rate.

V. CONCLUSION

The BeiDou navigation satellite system has been built and provided service since July 2020. The service of global short message communication is one of its featured services which is capable of global coverage and random access for the first time, and is able to provide integrated communication and navigation services for the LEO satellites. In our research, the feasibility of this integrated service of communication and navigation for the LEO satellites has been validated based on simulation analysis and on-board test data. The new compact technique proposed with low complexity has a broad application prospect for the mega global LEO constellations with rapid development.

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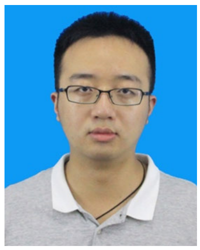

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