The Design and Implementation of Global Navigation Satellite System Remote Docking Test Platform

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Abstract. The global navigation satellite system (GNSS) includes satellites of multiple types, ground facilities with multiple functions, and various user terminals. The docking test of multiple systems in ground is an important part for managing the design, construction, and deployment of the satellite navigation system. To achieve efficient parallel docking of multiple systems, this paper designs a platform for remote docking test. Specifically, the architecture, operating process, and functional performance of the docking test platform are designed according to the task and characteristics of the docking test for satellite navigation. Besides, some key techniques are also analyzed including the management of command and dispatch for multi-node system as well as the interconnection of remote fiber. This paper implements the effective interconnection between the simulation verification system and real engineering system, and realizes command control and timing scheduling with high-precision. The designed platform has the capability of full coverage test for signal and information projects, and the capability of remote docking test for multi-systems that work in parallel. By applying our platform, the docking efficiency can be improved, the docking cost can be reduced, and the implementation of high-density networking for satellite can be promoted.

Keywords: GNSS · Remote docking

1 Introduction

GNSS is a complex and large-scale system in aerospace engineering area. It consists of dozens of satellites, dozens of ground stations, some control centers, a management center (for inter-satellite link operations), and various user terminals. These components need to closely cooperate with each other in order to realize the centralized management

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between the satellite and the ground, and to provide high-precision and highly reliable positioning-navigation-timing (PNT) services for users. The satellite navigation system can provide various services as well as fast network deployment, and its design is usually very complicated.

To demonstrate the pre-designed schemes and protocol algorithms for the satellite navigation systems, supporting simulation systems are usually required. Some supporting simulation systems have been developed for the major satellite navigation systems in the world. The US GPS system has carried out many simulations and experiments in terms of positioning, operating modes, system control, and key algorithms. Such as GPS simulation system, satellite navigation software toolbox (NavTK) [1, 2], GIANT software [3–6], etc. The European Galileo system has attached great importance on the use of simulation software at beginning for overall design and system verification. Many hardware and software platforms are developed for constellation configuration demonstration, technical system design, navigation signal design, key indicator allocation, technical base evaluation, and performance indicator verification. For instance, Galileo system simulation software (GSSF) [7, 8], Galileo system test bed (GSTB) [9, 10], software simulation verification environment (GRANADA platform), and software simulation plan (Polaris plan) [11, 12].

GNSS will carry out the satellite-ground docking test in the initial and normal stages of satellite development. The major departments of the GNSS project will develop their own devices, and move their devices to the satellite plant to conduct docking tests for specific functions. The content of the test mainly includes: 1) verify the status between the interface of systems, including the signal format interface, signal level interface, and information layout interface for the satellite-ground devices; 2) verify the procedures of the information transmission and processing between the major systems, including the accuracy of the information transmission procedures between the satellite-ground transmission and between the satellite- satellite-ground transmission; 3) check the performance for the realization of key indicators such as anti-interference and delay.

The verification implementation of this docking mode is incomplete, which cannot represent the true state of the system. Besides, it cannot verify system-level functions such as inter-satellite links and autonomous navigation. As a result, it takes a lot of time to carry out on-orbit test after the satellite is in orbit, which wastes the effective life of the satellite. Once such on-orbit tests need to be repeated, the cost will be particularly huge, and the project construction may face high risks.

Therefore, in order to change the situation of long-term lack of a system-level test environment in the field of satellite navigation, this paper builds a system-level simulation system for satellite navigation system, which is multi-level flexible and can approximately represent the real state of the GNSS. In addition, the high-performance interconnection between the simulation test system and the real engineering system is achieved by the remote optical fiber. The presented simulation system can carry out the design verification of the system scheme, business processes, key technologies, inter-system interfaces, indicators, signal flows, information flows, and time flows under the state of the whole satellite navigation system. Using our simulation system can improve the docking efficiency, save the docking cost, and promote the implementation of high-density networking for satellite.

2 Architecture of Test Platform

The remote docking test platform for GNSS includes the space section, ground control section, and user terminal. These sub-systems represent the technical status of the project. To cooperate with the above sub-systems and improve the test scheme, environment segment simulation sub-system, control and comprehensive support sub-system, global system simulation software, performance evaluation software, information management system software are also inserted. The remote optical fiber system is added for connecting satellite plant signals to the system. The platform composition is shown below (Fig. 1).

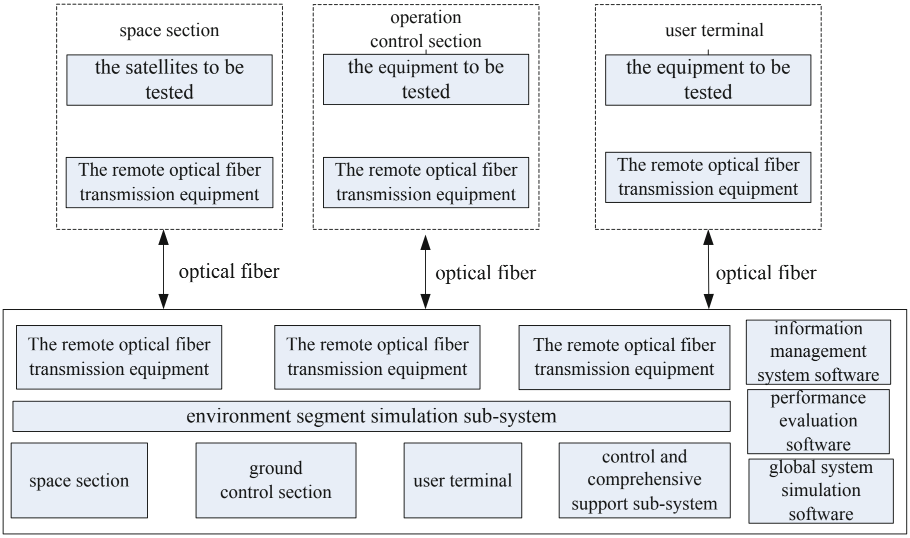


Fig. 1. Composition of the remote docking test platform of GNSS

The space segment subsystem represents the technical status of the GNSS, has the functions of satellite payload and platform control subsystem. It has the ability to parse commands between the ground operation control, measurement control, and inter-satellite link operation management systems. It is capable of inter-satellite data transmission and measurement, integrity monitoring and autonomous operation.

The ground control section forms a ground operation control network composed of a main control station, an injection station and a monitoring station, and realizes inter-system interfaces and business processes related thereto. It has functions such as navigation business processing, operation management and control, satellite-to-ground data transmission and measurement, etc. At the same time, it has functions such as constellation management in various space segment states such as constellation networking stage, constellation normal operation stage and constellation supplementary network stage.

The user terminal subsystem represents the technical status of typical application terminals. It has functions such as navigation and positioning, timing, and speed measurement based on the global system's downlink navigation signals. It verifies the signal system, system service performance indicators, and terminal algorithms.

The environmental segment analog subsystem is connected to the space segment subsystem, the ground control section and the user terminal subsystem in a matrix of multiple inputs and multiple outputs. It is responsible for multiple satellites and multiple stations on the ground. The radio frequency signals between multiple users and between satellites are superimposed with various dynamic characteristics such as various relative motions, transmission channels, environmental effects. It converts static signals into dynamic signals.

The control and comprehensive support subsystem realizes the unified monitoring and scheduling of test verification tasks and the operation service support for completing test tasks. It has functions such as power supply and distribution guarantee, reference time-frequency signal, channel delay calibration, communication network construction, test task management, and test data processing and analysis.

The global system simulation software completes the modeling, integration and simulation tests of the core system of the global system in the form of software. It conducts comprehensive integration verification and evaluation of key algorithms of information transmission, satellite-ground integrated control management, and navigation system to simulate the complete closed-loop operation of the system.

Performance evaluation software evaluates system service performance based on test data.

The information management system software manages information such as files, data, and task records of the entire system.

3 Process of Platform Operation

As a full-scale equivalent simulation system of GNSS, the test platform can operate independently, carry out simulation research and design verification of the core technology system of the system, and promote innovation and development. It can carry out comprehensive test verification of system operation control and interface between systems, confirm the technical status of the system, and support project construction. It can carry out the equivalent operation test of the system, support the abnormal or problem investigation of the GNSS, and ensure stable operation. On the other hand, the satellites to be tested and the ground test verification system are interconnected through the remote optical fiber and the radio frequency signal transmission technology by using the radio frequency signal remote transmission technology. The satellites to be tested in the test platform can be equivalent to one set of space segment satellite simulators, which are interchangeable with other satellite simulators of the space segment subsystem. Together with other subsystems in the test platform, the GNSS Equivalent Simulation Verification System is formed to carry out a multi-star multi-station system-level integrated docking test involving multiple real satellites.

4 Management of Comprehensive Control

The test platform is a large-scale test system with strong comprehensiveness, complex structure, wide professional coverage, and diverse test contents. It has the characteristics of "systematic", "authenticity", "completeness", and "flexibility". Therefore, it requires very high requirements for the comprehensive control of the system.

Comprehensive control management takes task planning management and operation control as the main line, based on test business and monitoring business, and uses delay calibration as a means. It designs the collection, transmission, storage and processing system of test data according to the standard of dynamic data management center. It builds the system network hardware and software platform according to the maximum equipment scheduling capability and task planning operation capability of full-speed operation. It can meet the needs of stable operation of the test platform, configurable tasks, easy integration, and flexible expansion. The comprehensive control management of the test platform is realized by the control and comprehensive support subsystem, including four parts: "time-frequency network subsystem", "test standard stator system", "software and communication subsystem", and "power supply and distribution subsystem". The time-frequency subsystem is responsible for generating high-precision 10 MHz, 1PPS, B code, NTP and other signals, providing a unified standard time and frequency signal for the entire test platform. The test calibration stator system is mainly used for high-precision equipment time-delay calibration of equipment in the space section and operation control section. The software and communication subsystem is responsible for the management control, business processing, data processing and system monitoring of the test platform. The power supply and distribution network subsystem, as an important part of the control and comprehensive support subsystem, provides a safe, reliable, and continuous power supply capability for the entire ground test verification system equipment. Among them, how to realize the high-precision time reference and time synchronization of the test platform and provide the test platform with high-precision, high-performance and high-stability time-frequency signals is the key to the operation of the test platform.

The time base of the test platform is controlled by the time and frequency subsystem of control and comprehensive support. The subsystem is controlled by atomic clock equipment, reference signal distribution equipment, space section time and frequency distribution equipment, ground control section time and frequency distribution equipment, user segment time-frequency interface, environment segment time-frequency distribution interface, monitoring hall time-frequency equipment, star-ground clock difference automatic measurement equipment, GNSS time traceability equipment (Fig. 2).

The working principle of the time-frequency subsystem is as follows:

(1) Atomic clock group equipment is a reference signal generation equipment: high-precision 10MHz, 1PPS, B code signals are generated by atomic clocks, time-frequency selection switches, digital clocks, and other equipment; the standard time is obtained through the coarse synchronization of the GNSS timing user machine based on the standard BDT; the counter records the time difference information of

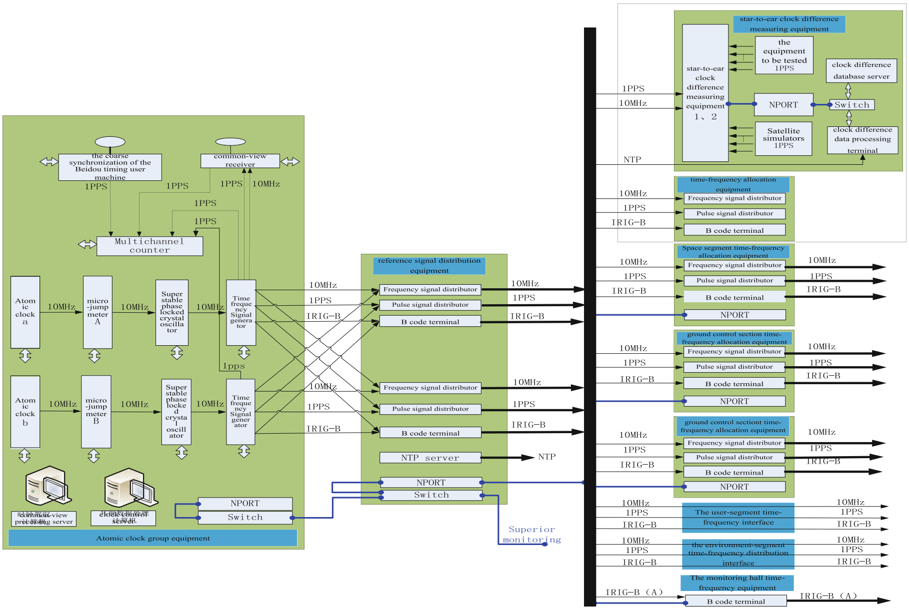


Fig. 2. The architecture diagram of time frequency subsystem.

two atomic clocks in real time; in addition, it also has the function of monitoring the integrity of the clock group equipment.

(2) The reference signal distribution device is a first-level distribution device for time-frequency reference signals: it receives high-precision 10MHz, 1PPS, and B code signals provided by atomic clock equipment; it realizes the multiplex distribution of reference 10MHz, 1PPS, and B code signals; it uses 10MHz, The B code and 1PPS signal generate the NTP time service signal.

(3) Space segment time-frequency allocation equipment, ground control section time-frequency allocation equipment are second-level allocation equipment: they realize the distribution of reference time-frequency signals; they provide high precision 10MHz, 1PPS, B code signal for space segment, ground control section, respectively.

(4) The user-segment time-frequency interface and the environment-segment time-frequency distribution interface are a set of 10 MHz, 1PPS, B code signals directly transmitted from the reference signal distribution equipment.

(5) The monitoring hall time-frequency equipment realizes the multi-channel distribution of the reference B code signal and provides multiple B code signals for the monitoring hall.

(6) Automatic measurement system for clock error.
The star-to-ear clock difference automatic measurement system is composed of three parts, including the star-to-ear clock difference measuring equipment, the clock difference data processing terminal, and the clock difference database server. The satellite-to-earth clock difference measurement equipment completes the clock difference measurement of 1PPS and the 1PPS of the integrated time and frequency

system sent by the satellite simulator or the satellite workshop of the Fifth Hospital. It simultaneously completes the comprehensive security local time reference and GPS and GNSS clock time measurement to provide support for time traceability. The clock difference data processing terminal completes the analysis, storage, and reporting of the clock difference data, and it controls the autonomous operation of the star-to-ground clock difference system. Clock difference database server completes the local storage of clock difference data.

(7) GNSS Time Traceability Subsystem.

The GNSS time tracing subsystem is composed of a common-view receiver, a micro-jump meter, a common-view processing server, and a clock control server. The GPS time of the time-frequency subsystem is traced to the GPS time through the GPS common-view receiver. Time-frequency subsystem GNSS time traces to GNSS time through GNSS timing user machine.

5 Transmission of Remote Interconnection

Through the remote optical fiber transmission system, the GNSS Satellite and the test verification system are distributed in different locations. The time and frequency reference is unified to realize remote interconnection transmission. Its principle is shown in Fig. 3.

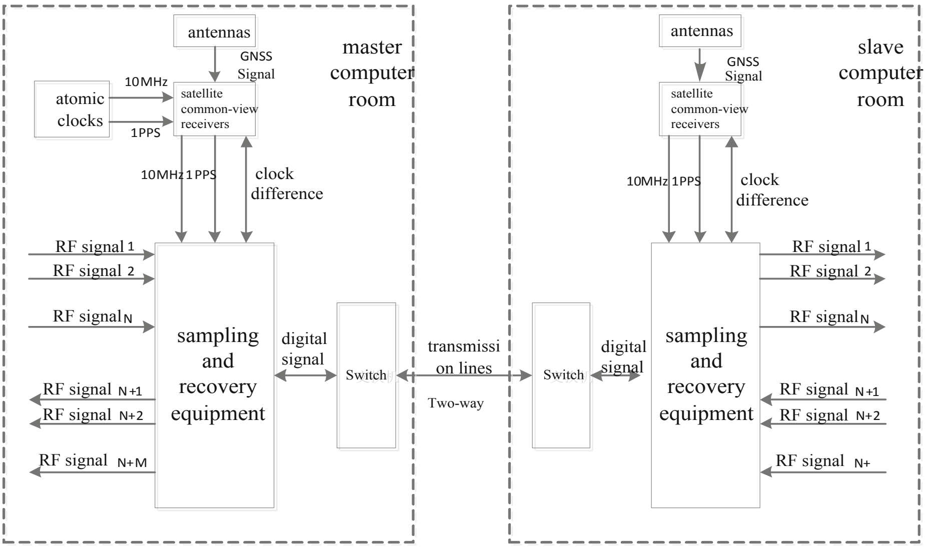


Fig. 3. Block diagram of remote interconnection.

The system includes sampling and recovery equipment in the master computer room, sampling and recovery equipment in the slave computer room, transmission lines (commercial data lines and switches at both ends), atomic clocks, satellite common-view receivers and antennas in the master computer room, satellite common-view receivers in the slave computer room, and antenna.

The transmitting side uses the analog-to-digital (A/D) converter of the sampling recovery device to convert the analog RF signal to be transmitted into a digital signal, and transmits it in the long-distance data line. The receiving sides uses the digital-to-analog (D/A) converter of the sampling recovery device to restore the received digital signal to an analog radio frequency signal to realize the long-distance transmission of the radio frequency signal [13, 14]. The 10MHz and 1PPS signals output by both ends are synchronized by the satellite common-view method; the sampling recovery equipment at both ends uses the 10MHz and 1PPS output from the satellite common-view receiver as their own reference clocks to maintain the consistency of the master and slave clock frequencies.

Due to the influence of the routing path, the transmission delay of the remote optical fiber fluctuates, so the data buffer needs to be removed at the receiving end to remove the uncertainty of the data arrival time. The schematic diagram is shown in Fig. 4:

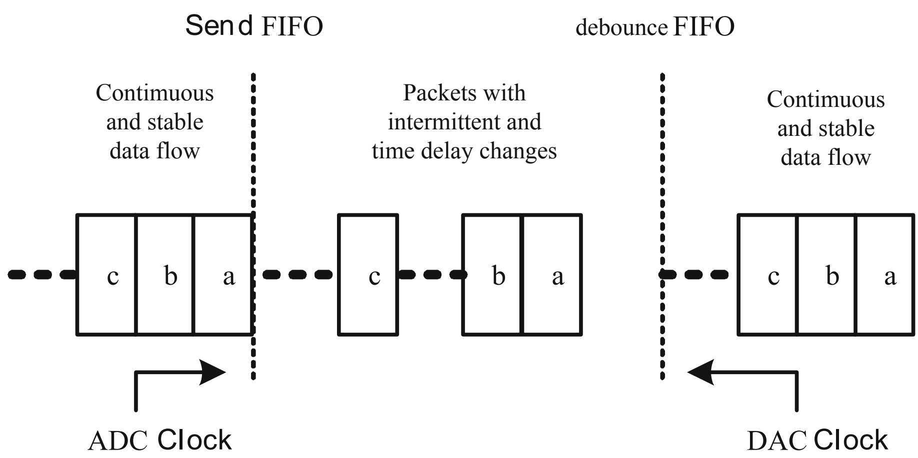


Fig. 4. Data transmission delay control

The receiving side first stores the received discontinuous data into the debounce FIFO, and after buffering for a certain time, reads the data continuously from the debounce FIFO. In the case of the same clock frequency of the ADC and DAC at both ends of the transceiver, when the buffering time is greater than the maximum transmission delay of the fiber, the number in the debounce FIFO will not be read empty. Therefore, the data after the debounce FIFO is continuous, and the uncertainty of the data arrival time caused by the fiber transmission is removed.

The delay of the data stream at both ends of the transceiver is determined by the time difference between the data transmission time and the reading time of the debounce FIFO. When the time difference is greater than the maximum transmission delay of the fiber, the data stream delay is not affected by the fluctuation of the fiber transmission delay. The time difference can be controlled by sending and receiving enable, as shown in Fig. 5:

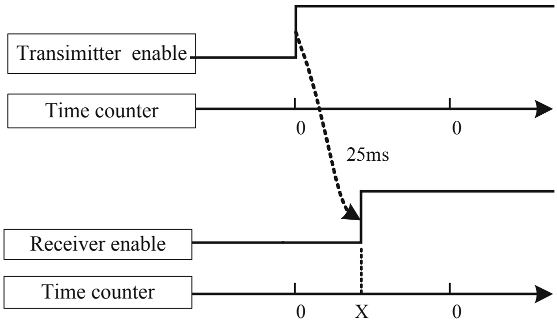


Fig. 5. Send and receive enable control

The time counters at both ends of the transceiver are counted by 10 MHz provided by the common-view satellite receiver, and cleared by 1PPS. Hence both ends of the transceiver use the same time reference. Set the delay between receiving enable and sending enable to 25 ms (greater than the maximum transmission delay of 20 ms between A and B). When the receiving time counter counts the corresponding value, enable the reading of the debounce FIFO. Therefore, the transmission delay of the off-site RF signal is $\tau = 25\text{ms} + \tau_{\text{d}} + \tau_a$, where τ_d is the delay introduced by digital circuits such as digital logic and digital-to-analog conversion at both ends of the transceiver, and τ_a is the delay introduced by analog devices such as RF channels and RF cables. τ_d and τ_a are two certain value that can be measured at a certain clock frequency and a certain temperature, hence the transmission delay accuracy of the RF signal is mainly determined by the accuracy of 25 ms. Notice that the accuracy of 25 ms is determined by 10 MHz and 1PPS, so the average value of the transmission delay of the RF signal is $\tau \pm 2ns$.

6 Implementation of the Test Platform

The GNSS remote docking test platform builds a multi-level flexible and controllable simulation test platform that approximately represents the real state of the GNSS. It can carry out simulation design and test verification that integrates all elements and the whole system. The test platform mainly has the following capabilities.

1) The test platform represents the overall technical status of the GNSS, and its composition and scale match the GNSS. It forms a system-wide test and verification environment for the entire system and configuration, which can cover the entire system's complete interfaces and business relationships (information flow, control flow, time flow).
2) The test platform has a flexible and controllable system architecture, and the hardware and software can be flexibly controlled and configured; it also takes into account

the mutually complementary verification methods of hardware verification and software simulation, and can be expanded and upgraded in time according to changes in needs and technology.

3) The test platform has the ability to connect the satellites to be tested in the satellite plant to the system, and can carry out the ground integration test of satellite navigation equipment. It can verify the correctness and matching of the signal flow, information flow, and time flow of the entire satellite navigation system. It can assess the accuracy of all commands and telemetry information, and focuses on verifying the operation process and service performance of system-level services such as inter-satellite links and autonomous navigation.

- Delay stability of remote interconnection fiber transmission.
- Time synchronization accuracy of remote interconnection fiber transmission.

Based on this platform, some tests were carried out, We verified the following performance: the correctness of the interface protocol between the satellite, ground control section and application verification; the matching, coordination and service performance of the integrated operation process of the satellite-satellite-ground; system basic intact function and process; onboard autonomous integrity monitoring functions and processes; Short message function and process; satellite-based enhanced information calculation, betting, broadcasting and user receiving functions and process; autonomous navigation function and process accuracy. And in the process of docking test, we found related problems such as autonomous navigation and basic integrity of the two networks. This platform improves the coverage of ground-level system-level test verification projects, reduces the pressure of satellite on-orbit networking testing, reduces the change of satellite on-orbit technical status, and accelerates the progress of satellite network access to provide service.

6.1 Performance of the Integrated Operation Process of the Satellite-Satellite-Ground

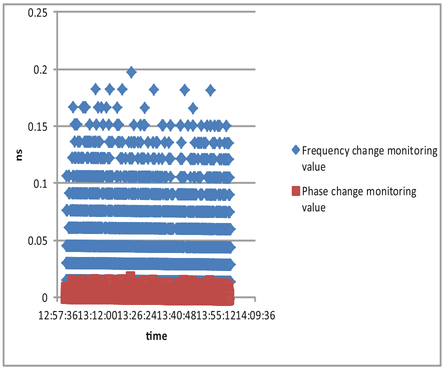
Mainly verify the correctness of operation control and measurement and control business information transmission on each network node and link of the whole system. The correctness of the integrated information flow function and process (Table 1).

6.2 System Integrity

Mainly verify the continuity test of various satellite monitoring data. The correctness of the processing function and process of the satellite's autonomous integrity is tested and verified. The continuity of intact monitoring data such as satellite carrier phase, signal power, satellite clock frequency/phase jump, on-board correlation value, etc. is verified. Realized the test of the basic integrity alarm process, and verified the alarm time and other indicators, which effectively supported the confirmation of the status of the satellite technical process (Fig. 6).

Table 1. Test results

Navigation message type	Expected injection state	Actual injection result	Expected comparison result	Actual comparison results	Compliance
Ephemeris parameters/ Star clock and group delay parameters/ Ionospheric model parameters/ Basic navigation information	Successful injection	Successful injection	Match correctly	Match correctly	Conform



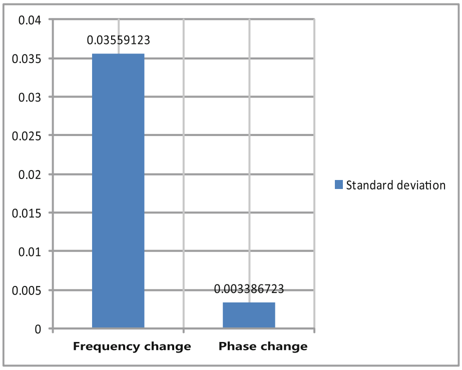


Fig. 6. System integrity results

7 Conclusion

The GNSS remote docking test platform builds a full-system, full-state, full-scale satellite navigation test verification system. It can provide four working modes: software, hardware, software-hardware collaboration, and virtual-real combination, and it integrates design verification, engineering docking, Equivalent operation and simulation test are all in one. At the same time, through the remote transmission technology of radio frequency signals, the satellites to be tested distributed in different locations and the ground simulation system are interconnected. A comprehensive docking test for parallel access of multiple real systems is carried out, which can effectively verify the correctness of the system-level service signal flow, information flow, and time flow for satellite navigation system inter-satellite links and autonomous navigation. This platform can fully expose the problem before the satellite is launched, and modify it in time to avoid the repeated technical status of the satellite in orbit and avoid improving the quality of the project construction. The construction quality of the project can be improved, the construction risk can be reduced, and the connection cost can be saved. This platform facilitates the implementation of satellite high-density networking launches.

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