Chapter 19
Research on Technical Development of BeiDou Navigation Satellite System

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Abstract The development characteristics of BeiDou satellite system have been analyzed based on the construction experiences of BeiDou Navigation Satellite regional System. The mission requirement, platform characteristics and payload technology of BeiDou Navigation Satellite have been researched in this paper. The project propositions which are required to reinforce have been suggested for next BeiDou Navigation satellite system.

Keywords BeiDou · Navigation satellite · Satellite · Bus satellite · Payload

19.1 Introduction

Satellite navigation systems can provide all time, all weather and high accuracy positioning, navigation and timing services to users on the earth surface or in the near-earth space. It is an important space infrastructure, which extends people's range of activities and promotes social development. BeiDou satellite navigation system can meet the demands of China's national security, economic development, technological advances and social progress, safeguard national interests and enhance the comprehensive national strength.

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According to the development concept of starting with regional services first and expanding to global services later, BeiDou satellite navigation system is steadily accelerating the construction based on a 'three-step' development strategy.

Phase I: BeiDou Navigation Satellite Demonstration System. In 1994, China started the construction of BeiDou navigation satellite demonstration System. In 2000, two BeiDou navigation experiment satellites were launched, and the BeiDou navigation satellite demonstration system was basically established, which made China the third nation in the world in possession of an independent navigation and position satellite system. The space constellation includes two geostationary orbit (GEO) satellites, positioned at longitude of 80° east and 140° east respectively above the equator. Ground control segment consists of the ground control center and a number of calibration stations. BeiDou Navigation Satellite Demonstration System can provide the service of positioning, timing and short message communications based on the radio determining of satellite service [1].

Phase II: BeiDou Navigation Satellite (regional) System. In 2004, China started construction of BeiDou Navigation Satellite System. In 2007, the first satellite, a round medium earth orbit satellite (COMPASS-M1) was launched. In 2012, BeiDou Navigation Satellite (regional) System has provided service of positioning, timing and short message communications based on the radio determining of satellite service and the radio navigation of satellite service for the users of China and part of Asia-Pacific region. Space hybrid constellation includes five GEO satellites, five IGSO satellites, and four MEO satellites.

Phase III: BeiDou Navigation Satellite System with global coverage will completely be established by 2020.

During the course of building the BeiDou Navigation Satellite Demonstration System and the regional system, the Chinese Academy of Space Technology accumulated a lot of experience and lessons in satellite system design, production, testing and on-orbit applications. Satellite system design,space atomic clocks, large FPGA resistance space environment design, uplink injection of anti-jamming design, as well as satellite platform supply security have formed a series of achievements and experience, especially in the construction process of the regional system.

By combing, analyzing and summarizing, we can provide technical support for the next 2020 comprehensive construction BeiDou satellite navigation system.

19.2 The Characteristics and Functions of BeiDou Regional Navigation Satellite System

The space segment of BeiDou navigation satellite regional system includes 5 GEO satellites, 5 IGSO satellites, and 4 MEO satellites. The 5 GEO satellites point in 58.75° east, 80° east, 110.5° east, 140° east, 160° east respectively above the equator. To the 5 IGSO satellites, three of them are distributed in three inclined

geosynchronous orbit, orbit altitude of which is 36,000 km approximately, orbit inclination being 55°, sub-satellite track keeping coincide, intersection of longitude being 118°E, and phase position difference being 120°. The remaining two IGSO satellites also point in inclined geosynchronous orbit, the longitude of ascending node being 95°. The 4 MEO satellites distribute in two different orbits on average, orbit altitude of which is 21,500 km approximately, orbit inclination being 55°.

The three types of satellites were designed uniformly under the demand of batch production, intensive launching, and rapid make up constellation. The IGSO satellites and MEO satellites use DFH-3 satellite platform. GEO satellites use DFH-3A new satellite platform.

The satellite bus includes structure subsystem, thermal control subsystem, tracking-telemetry and command subsystem, electrical power subsystem, attitude and orbit control subsystem, propulsion subsystem, and data management subsystem. The satellite payload includes navigation subsystem and antenna subsystem. The navigation subsystem of GEO satellite are composed of RDSS, time synchronization and data repeating, uplink receiving and precision ranging, RNSS load. The navigation subsystem of IGSO and MEO satellite are composed of uplink receiving and precision ranging, RNSS load.

The basic mission and requirement of BeiDou satellite regional system as following.

1. Choosing mature satellite bus to meet the demand of effective load. The working life span of satellite is 8 years in orbit.
2. Keeping the functions of RDSS, time synchronization and data repeating of BeiDou Navigation Satellite Demonstration System, which is electromagnetic compatibility with newly added RNSS.
3. Using two-way satellite-ground time comparison technique, which can calculate accurate difference between satellite clock and ground station clock, to solve the problem that limited number of navigation satellite and ground observe and ground control station which are distributed in narrow territory.
4. Receiving the uplink receiving navigation message from ground control system, storing handling and generating downlink multichannel navigation signal. The satellite working state information is transmitted to ground operation control and user system.
5. Adapting three orbital hybrid constellation multi-satellite TT and C service, using new S band spread spectrum TT and C system and traditional mature USB TT and C system at the same time, to accomplish TT and C task independently, to ensure the reliability and safety of TT and C channel.

In the area of coverage, ensuring the G/T and EIRP values of receiving and transmitting signals, the broadcast navigation signal of satellite must be stable and continuous. Besides, scheduled interruption and unplanned interruption times and duration meet the project requirement.

19.3 The Technical Developments of BeiDou Regional Satellite Navigation System

According to the project general requirements, the conceptual design and prototype design for BeiDou regional navigation satellite system has been completed, and an experiment satellite was launched in April 14, 2007, which validated the RNSS load design, two-way satellite-ground time comparison technique, three-axis wheel control technique, yaw attitude control technique, on-board atomic clocks design. It marks China's entry into a new stage in independently development of navigation satellite system. At the same time, further measures were taken to solve the problem of anti-interference for satellite product and the complicated space environment. As a result, the technical state of satellite system, each subsystem and the product was determined, assuring the improvement of technical level and the quality of the project.

19.3.1 Satellite Bus

BeiDou regional navigation satellite system requires the satellite bus must inherit the mature technology, and the new technology also need to be applied at the same time.

Accord to the analyzing results of the missions and functions requirements of the satellite system, BeiDou regional navigation satellite system must adopt new technology based on DFH-3 satellite bus in electrical power capability, satellite attitude control requirements, thermal control requirements, self-management, TT and C. The key technology above mentioned must be breakthrough and experimental verification.

Characteristics and achievements of satellite bus are summarized as following.

1. The mixed solar array technology

The GEO satellites have RDSS and RNSS payload, which increased 900 W satellite power requirement compared with GEO satellite of BeiDou Navigation Satellite Demonstration System. Under the constraint of adopt the same DFH-3 the bus Solar Array structure and solar cell substrate, Si and GaAs/Ge mixed solar array technology were adopted firstly. The harmonizing problems of thermal characteristic, electrical characteristics and radiation characteristics were solved based on the technologies of circuit independent, sub-board layout, isolation diode and bypass diodes. The 2,500 W power requirement of GEO satellites was realized.

2. Wheel control in three axis and yaw control technology

In order to avoid or reduce the harmful effects to the system-level user positioning accuracy caused by thruster uninstalling the saturated momentum of

reaction wheel, GEO satellite control subsystem adopts the new program of wheel control in three axis. The adjustment of unloading reaction wheel momentum and station keeping are carried out at the same time especially.

The orbit inclination of IGSO and the MEO satellites are 55°. The incidence angle of the sun's rays changes with the right ascension of ascending node changing. Satellites cannot direct the sun and the Earth at the same time for DFH-3 satellite bus. Ascending node and inclination will directly affect the power output of the solar panels, according to the DFH-3 satellite bus design. Sunlight and the earth's shadow are larger than GEO satellite of the DFH-3 satellite platform, particularly the distribution of the length and number of changes to the earth's shadow. The design conditions of electrical power subsystem are different compared with the traditional DFH-3 satellite platform. In order to ensure the normal of solar array direct the sun with the accuracy better than 5°, The IGSO and the MEO orbit satellites adopted yaw control firstly.

3. Spread Spectrum structure and TT and C Technology for multi-satellite TT and C service

The new S band spread spectrum TT and C system was utilized to solve TT and C mission and frequency interference problems of multi-satellite hybrid constellation. The key technologies of low threshold, high dynamic dispreading, rapid acquisition of spreading code and Fine tracking digital baseband processor have been solved. The new S band spread spectrum TT and C system have many merits, such as strong anti-interference ability, high positioning accuracy, and low-density signal power spectrum.

4. Energy self-management techniques

In order to control the IGSO and MEO orbit satellite in invisible orbit, the new data handling system are designed to control battery power and satellite cabin temperature automatically.

5. RNSS power enhancement technology

In order to fulfill the requirements of RNSS power enhancement and the capability of anti-jamming in wartime, the data composed of satellite ephemeris, satellite attitude and antenna beam pointing come from payload, attitude and orbit control, antenna and data handling subsystems are fused.

6. High-precision thermal environment control technology

Navigation satellite atomic clocks are sensitive to ambient temperature. Their operating range is $-5\ ^{\circ}\mathrm{C} \sim +10\ ^{\circ}\mathrm{C}$ in-orbit. The rate of temperature change ratio is $\pm 0.5\ ^{\circ}\mathrm{C}/24$ h. The thermal control subsystem designs the atomic clock independent temperature control small cabin. The high-precision closed-loop automatic temperature control algorithm is designed.

19.3.2 Satellite Payload

Navigation satellite payload is the main instrument for satellite's navigation function and service performance, its technical level and reliability directly influence the function and performance of the system.

For BeiDou regional satellite navigation system, two kinds of navigation and positioning system coexistence, RNSS and RDSS. RDSS payload inherits the function of BeiDou satellite navigation experiment system. RNSS payload is a whole new payload, including uplink receiving and precision ranging subsystem, time and frequency synthesis subsystem, navigation signal generation subsystem, signal amplification link.

Satellite payload characteristics and main achievements are summed as follows:

1. High precision and stability in-board atomic clock technology

The energy level transition frequency of rubidium atomic is very stable. In use of this feature, rubidium signal with low frequency drift is generated and locked in high stability crystal oscillator through the effective power incentive of microwave cavity, spectrum signal detection and filtering, control of magnetic field and temperature field. By this way the functions of the atomic clock is realized. The domestic on-board rubidium clock in BeiDou navigation satellites is developed through advance research, prototype development and identification products development. After three manufacturer respectively developed two identification products, products for space tasks was eventually generated. During the development of rubidium atomic clock, lots of engineering problem were solved, such as life assessment, burn-in test method, high precision measurement, temperature sensitivity characteristics, performance difference between vacuum and atmospheric environment, long term stability test method, which ensured the development of on-board atomic clocks products.

At the same time, small quantity production was realized through means such as design verification and process control. The on-board rubidium atomic clock products have good consistency and compatibility.

2. Precision management technology for satellite's time and frequency standards

In order to ensure the synchronization of time and frequency between uplink and downlink, the reference frequency synthesizer was designed. The reference frequency synthesizer ensure the correlation between multiple frequency signals, including satellite's time signal, frequency signal, baseband signal and the receiver clock signals. So it can provide reliable, stable and continuous satellite clock signal to navigation payload.

By precision adjustment and control, Satellite clock has good short-term and long-term frequency stability characteristics. The precision control and management on satellite time and frequency standards, such as frequency transfer accuracy, frequency adjustment resolution, frequency adjustment and signal spectrum monitoring between main and backup atomic clock, meets the demands of

engineering construction. In using the reference frequency synthesizer, the satellite equipment integration was improved, and the volume and weight of the satellite equipment was reduced.

3. Two-way satellite-ground time comparison technique

For BeiDou satellite navigation system, range between satellite and ground station was ranged through microwave channel respectively by satellite and ground station at the same time. In this way clock bias between satellite clock and ground station clock standard is calculated and the two-way satellite-ground time comparison and synchronization are realized. High precision timing synchronization is achieved by establishing high precision ranging link and two-way satellite-ground time comparison and synchronization. Some key technology are broken through such as the long code tracking capture, multichannel receiving, on-orbit zero range monitoring and calibration.

4. Time–frequency anti-jamming technology

High density and intensity electromagnetic interference is a serious problem in the construction of BeiDou regional satellite navigation system. This problem have to solve. It directly affects the communication between the satellite and ground, including ground station and all kinds of terminal, result in reducing the system performance. The uplink data receiving directly decide whether the navigation satellite payload can work normally, therefore the anti-jamming and security design for uplink channel is particularly important. This problem was solved by precision fast acquisition and tracking algorithm, and low signal amplification technology with wide linear range and low time delay effect. The technical requirements that bit error rate is better than 10^{-8} and the ranging accuracy is better than 1 ns are satisfied.

5. Navigation signal design technology for anti complicated space environment

On-orbit satellite will inevitably be influenced by space charged particle radiation from the radiation belt of the earth, cosmic rays, solar cosmic ray, etc. Due to satellite's internal components, such as DSP, CPU, SRAM and FPGA, contains a large number of triggers and memory, there is a risk of SEU events in the effects of space environment. In order to minimize the risk and provide continuous, stable, reliable navigation signal for the user, BeiDou navigation satellite's SEU protection strategy was designed in three aspects, which is device selection, circuit design and instrument design. The satellite's surface charging and cabin deep dielectric charging protection are also designed. Through means such as hardware protection design, software fault tolerance, three modular redundancy, timing refresh and replacing FPGA with ASIC, the design and verification for the space borne products against environment are realized.

6. Continuation and stability technology for multi-channel high power signal

BeiDou navigation satellite payload include uplink receiving and precision ranging subsystem, time and frequency synthesis subsystem, navigation signal

generation subsystem and signal amplifying link. It has many signals with different frequency. In order to ensure the ground users can receive the signal from satellites more effectively, satellites are designed with high power amplifiers to ensure the signal transmitted has enough power.

In order to ensure the satellite's internal instruments working normally, EMC analysis and verification of system level is required. In accordance with the requirements of new design, many key problems were solved, such as electromagnetic isolation between RNSS and RDSS payload, intermediation suppression between uplink received signal and downlink transmitting signal, multipaction and power resistance, passive intermediation suppression for microwave high power devices, enhancing product protection and determine the product working state etc.

19.4 The Development Experience of BeiDou Navigation Satellite

BeiDou satellite navigation regional system reserved BeiDou satellite navigation experimental system of active positioning and short message communication service. It has begun to provide the continuously positioning, navigation, timing and message communication and other services in China and some areas around. BeiDou satellite navigation resolves the problem of having the RNSS positioning system in China, which is an integral part of China's economic and social development of spatial information services.

The main experiences of the BeiDou navigation satellite system as followed:

1. Combination of inheritance and innovation, and strengthen the ground test validation

According the requirements and characteristics of the BeiDou navigation satellite, CAST completed the structure model, the thermal control model, electrical model. However, we must adopt mature product inherited DFH-3 satellite platform technology. The key technical in concept phase must solve to ensure little risk in the preliminary design phase [2].

The BeiDou satellite reliability for special project has been arranged, which carry out the weaknesses of SADA, power controller, battery pack, earth sensor, and the reference frequency synthesizer etc., including the analysis, improvement and validation work.

2. To ensure the reliability and quality of the product batch approved

Based on self-research, innovation and development, the key technologies are solved, such as the space borne rubidium clock, precision ranging, two-way time range, the inhibition of the multipation and passive intermediation, large scale ASIC chip alternative FPGA devices, yaw control, rubidium, cabin small precision temperature control;

3. RNSS, and RDSS two positioning navigation system coexist, provide multi-function services

Besides high-precision, and reliable positioning, navigation and timing services, BeiDou Navigation Satellite System can provide the service of short message communications, integrity and difference service also. A differential service and integrity services, compared with the GPS system, the advantage of the BeiDou satellite navigation system is service area within diversification and the interaction between the users. It will continue to play a special role in the command and dispatch, disaster relief, and environmental data monitoring.

4. Compatible design, product interchange

The three orbiting satellite requirements in accordance with the "one-design, group batch manufacture, serial testing, intensive launching, rapid make up constellation" to carry out stand-alone product design, to ensure that most of the three types of satellite products have interchangeability; does not with interchangeable products, mechanical, electrical, thermal interface also give full consideration to compatibility. Rapid make up constellation of BeiDou satellite launch process giving top priority to the work carried out for the product quality problems is of great significance and has played a special role.

5. The coordinated integrated 3D design for satellite configuration and layout

BeiDou satellite has a coordinated integrated 3D design digital system, which has the development process and configuration and layout for satellite structure with thermal control cooling surface of thermal control subsystems, cable networks of power distribution subsystems, pipeline layout of propulsion subsystem. Using AVIDM system, integrated data interface for Unit, product layout, mechanical interface, thermal interface to improve the overall configuration and layout design. It also promotes the piping design correctness and efficiency.

6. Establish a test data comparing system.

BeiDou satellite products have batch manufacture features. We establish the test data comparing system based on the test data of different batch satellite and different phase of the same satellite. It is convenient for us to obtain the varying trends and fluctuating scopes of key technical index. So, we can carry out risk reviewing based on such critical data characteristics.

19.5 The Suggestions for BeiDou Next Navigation Satellite

The satellite navigation system is an space-based time and space infrastructure which based on the service range, accuracy, availability, continuity and integrity. In order to improve the performance of the next generation system in the process of construction BeiDou satellite navigation system, some work need to be

systematically summarized and analyzed. The works include the characteristics and results of the BeiDou satellite navigation system, the working status of satellites in orbit. The project propositions and suggestions are required to be reinforced, the works are as follows.

1. To strengthen the system top-level design analysis, to improve the system reliability

In order to ensure the continuity and stability of whole satellite navigation systems, some efforts need to be strengthened which including of the constellation configuration design and analysis, satellite and ground station integrated collaborative design, the constellation of running state satellite backup strategy and the strategy of mending their nets research, etc.

Availability, affordability and accuracy are the three key features of the satellite navigation system, in order to achieve the availability of the system, the first requirement is that the number of satellites in orbit.

Effects-based studies have shown that a constellation of 30 MEO satellites plus three backup satellites distribution will increase the availability of users for PNT in the space environment effects [3].

2. Long life, miniaturization and high reliability of space borne products

In order to improve the reliability and security of the satellite platform, reduce weight, size and power consumption of satellite products, the long life of the space borne product and miniaturization and high-reliability design work needed to be reinforced.

Through the component selection, the circuit redundancy design, system-level backup and fine coordination and management, as well as a large number of ground reliability and life testing, the working life of the satellite can be enhanced from 8 years to 12 years.

3. To strengthen the state management and selection of components

BeiDou navigation satellite system products must formulate batch production target in the design phase, identify and complete experimental verification of its products, process assessment and establish of process control file, etc. Through the analysis of the product's characteristics, the selection of components and raw materials, attention to the quantitative design for key characteristics parameters, we can obtain the best system qualify.

4. Reduction interrupt operation within plan

According to the actual situation of the our ground operation system (For limited by the area and the number of injection station, the monitoring stations, the track measurement and prediction accuracy still need to be further improved), interrupting operation of the position keeping and orbit control the need to be further reduced for satellites.

5. Strengthen crosslink and autonomous navigation technology research

The GPS system crosslink positioning changes with the system targets. Transmission of information from the support nuclear explosion detection, to support autonomous navigation of inter-satellite ranging and information transmission, to the full support of the space integrated information network communications.

BeiDou's satellite navigation constellation design, especially for management strategies in a variety of track between the link failure mode, comprehensive and in-depth analysis need to be developed on the rate of data transfer, the number of crosslink, measurement cycles, inter-satellite link frequency and autonomous navigation time and so forth. System simulation and experimental verification need to be carried out, simulation and verification work of crosslink signal system and autonomous navigation algorithm must be deep studied.

6. To improve the integrity monitoring capabilities of satellite navigation signals

As the integrity is a key performance of the satellite navigation services, design of reasonable integrity of signal system need to be further developed. The navigation signal integrity monitoring capabilities is a basic requirement, including of the system working condition, the receiving of uplink navigation message and the generation of downlink navigation signal, the health status of the satellite platform, satellite attitude and etc. Base on the autonomous integrity monitoring and diagnosis, alarming and correction of the imperfect state in time.

7. Enhance the onboard atomic clock performance

The stability of atomic clock of navigation satellite is the key factors to determine the performance of real-time user location. The stability of the atomic clock is the basis for establishing a high-precision time reference and time comparison technology with two–way ranging of satellite and ground. The performance of BeiDou system satellite-borne atomic clocks has not yet reached an excellent level of GPS BLOCK IIF satellite clock [4].

While the construction of the next generation BeiDou satellite system, the onboard atomic clock performance need to be matched with system construction, the day stability performance must be further improved, the manufacturing process and the debugger needs to be fitted the group batch production requirements. Particularly, atomic frequency discriminator signal enhancement, the light frequency shift, loop noise and temperature sensitivity suppression technology are further studied, while also further resolve the long life and reliability of space borne atomic clocks. At the same time of enhancing the onboard atomic clock performance, ground testing and assessment of methods of space borne atomic clocks need to be improved further.

8. To improve the delay stability of navigation signal

To broadcasting continuous, stable and reliable navigation signals is the basic task of the navigation satellite, the quality of the navigation signal determines the

merits of the navigation satellite. Building BeiDou next-generation system, the stability of the navigation satellite signal delay need to be improved, in order to facilitate operation and control systems and users, the navigation signal path delay value should to be strictly control to achieve the consistency of the delay of multiple frequency navigation signals for each work state.

9. Strengthen the new navigation signal system design to achieve the interoperability of GNSS systems compatible.

GPS, GALILEO, GLONASS and BeiDou systems coexist. The four systems are to provide free services to users worldwide. In order to be not interfering with each other, the compatibility must be considered to realize the joint PNT services to provide continuous, stable and reliable services for civilian and commercial users. GPS system occupied the global PNT market have a strong attraction to users, the survive possibility of the next generation BeiDou system must be compatible with the GPS system but not rely entirely on the GPS system. To this end, the design of the navigation signal system need to be further improved, including the parameters of the signal frequency, signal modulation mode, encoding format of information, the spectral characteristics, the output signal power, etc. BeiDou satellite navigation systems have to maintain continuous and stable service, but also fully compatible and interoperable with other GNSS systems.

19.6 Conclusions

BeiDou regional satellite navigation system has been established in 2012, and the satellites are working in good condition. It began to provide navigation service, including RNSS services, RDSS services and short message communications services for PRC and Asia–Pacific region.

During the navigation satellite development, CAST realized the coordination of the succession of innovation in satellite system design, adhered to the unity of the user requirements and technology, broke through several key technologies, and made a series of achievements. Moreover, a lot of valuable experience was also accumulated.

It is necessary for us to summary the BeiDou satellite development achievements. There is still need for intensive study for some subjects and items in next stage. To solve the key technical from above mentioned suggestions, establish and improve projects methods, will be beneficial to complete the construction of the BeiDou global satellite navigation system.

References

1. Navigation Satellite System(V1.0) China Satellite Navigation Office (2012) Report on the development of BeiDou(COMPASS)
2. Fuxiang X (2002) Satellite Engineering, China aeronautics press, China
3. Parkinson J (2010) ITT Exelis Completes GNSS Navigation Panel Milestone for GPS 3 Program. Satell Today, 5 Oct 2012
4. Jiao W, Wen L, Xiaorui H (translation) (2012) The preliminary review of BeiDou navigation satellite regional system, GPS Solution Online First