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SUPER ENGINEERING

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Innovation and development of BeiDou Navigation Satellite System (BDS) project management mode

Keywords BDS, engineering management, systems engineering

1 Introduction

The BeiDou Navigation Satellite System (hereinafter referred to as BDS) has been independently developed and operated by China with an eye on the needs of the country's national security as well as economic and social development. As a temporal-spatial infrastructure of national significance, the BDS provides all-time, all-weather and high-accuracy positioning, navigation and timing services to global users.

The BDS has been developed following a three-step strategy. By 2000, the construction of BDS-1 was completed to provide services to China and surrounding areas; by 2012, the construction of BDS-2 was completed to provide services to the Asia-Pacific region; and by 2020, the construction of BDS-3 was completed to provide services worldwide.

BDS-3 is mainly comprised of three segments: The space segment, the ground segment and the user segment. The space segment consists of 30 satellites, including 24 satellites in Medium Earth Orbit (MEO), 3 satellites in Geostationary Earth Orbit (GEO), and 3 satellites in Inclined Geosynchronous Orbit (IGSO). The ground segment consists of 47 ground stations, including master control stations, time synchronization/uplink stations, monitoring stations, as well as operation and management facilities of the inter-satellite link. The user segment consists of basic products such as chips, modules and antennae, as well as various kinds of terminals, application systems and services.

BDS owns the following five major characteristics: First, it adopts dynamic optimization and active evolution; second, it offers rich functions and diverse services; third, its technologies are innovative, independent and controllable; fourth, it is widely applied and generates significant benefits; and fifth, it adheres to the principle of openness, compatibility and global promotion (Yang, 2010; Yang et al., 2018; 2019; 2020; China Satellite Navigation Office, 2018; Guo et al., 2019; Ruan et al., 2019; Yuan et al., 2019; Cai et al., 2020; GNSS and LBS Association of China, 2020). BDS possesses multiple unique service capabilities, such as short message communication, international search and rescue, precise point positioning, etc. Its global positioning accuracy is better than 10 m, velocity measurement accuracy is better than 0.2 m/s, timing accuracy is better than 20 ns, and service availability is better than 99%, while the performance in the Asia-Pacific region is better. BDS serves as a global public product contributed by China to the world.

On July 31, 2020, BDS was completed and commissioned, marking a new era for the BDS to serve the world. The completion and commissioning of the BDS-3 is an important milestone in China's quest for a competitive edge in aerospace, and a significant contribution to the construction of global public service infrastructure. Such remarkable achievements benefit from a coordinated, high-quality and high-efficiency BDS engineering management system, and the exploration of an effective path for scientific management.

2 BDS engineering management

Three major tasks are undertaken in BDS engineering, including project development, applications and services, as well as international cooperation. The engineering management is faced with plenty of difficulties and challenges, such as wide range of fields involved, large scale of systems, big span of technologies, high requirements for indicators, tough schedule of development, tight coupling of elements, difficulties in quality control, high rate of risk, difficulties in stable operation, and high

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consequence of interruption. Thus, it needs to adopt new methods and new concepts of system engineering on the basis of traditional space system engineering mode (Qian, 1982; Wang, 2006; Hua, 2007; Ma, 2008; Guo, 2011; NASA, 2007; Luan et al., 2016), to implement innovative management on elements such as organization, technologies, development, quality and operation, etc., and to establish a set of engineering management system suitable for BDS characteristics (Sun and Yang, 2017), as shown in Fig. 1.

2.1 Organization and implementation system featured with "centralized, unified, high-efficient and coordinated"

2.1.1 Organization architecture featured with "centralized and unified management, and hierarchical responsibility"

The organization architecture consists of the China Satellite Navigation System Committee, Leading Administration, the China Satellite Navigation Office, implementation and executive institutions, and task-undertaking units. A system of chief designers, experts' group and advisory institutions, as well as technological supporting agencies are also set up, as shown in Fig. 2. Unitedly led by the China Satellite Navigation System Committee, and specifically organized by the China Satellite Navigation Office, all institutions take their hierarchical responsibilities, and build up a kind of mechanism featured with smooth operation, high-efficient coordination, and standard and orderly management. Such organization architecture effectively integrates multi-dimensional strengths from governmental, industrial, research and academic circles, realizes organic combination of management, engineering and technology chains, and ensures optimized allocation of resources and elements, as well as the smooth progress of tasks.

2.1.2 Coordination mechanism featured with "multi-level and high-efficient"

To ensure high-efficient operation of the organization, a kind of multi-level and near-real-time coordination mechanism is established, including satellite navigation committee meeting, overall coordination meeting, administrative meeting of chief designers, thematic coordination meeting, etc. The satellite navigation committee meeting is organized by the China Satellite Navigation System Committee, to centrally coordinate, investigate and make decisions on significant issues, and to review annual work plans and other key matters. The overall coordination meeting is organized by the Chair of the China Satellite Navigation System Committee, to make decisions on major issues related to technologies and managements. The administrative meeting of chief designers is organized by the China Satellite Navigation Office, to coordinate and make decisions on key technical issues, and to advise on management issues. The special coordination meeting is organized by the leading body of the system engineering, to timely coordinate and make decisions on specific matters. Based on this coordination mechanism, thousands of issues can be solved timely and effectively, which provides strong support for the rapid progress of system.

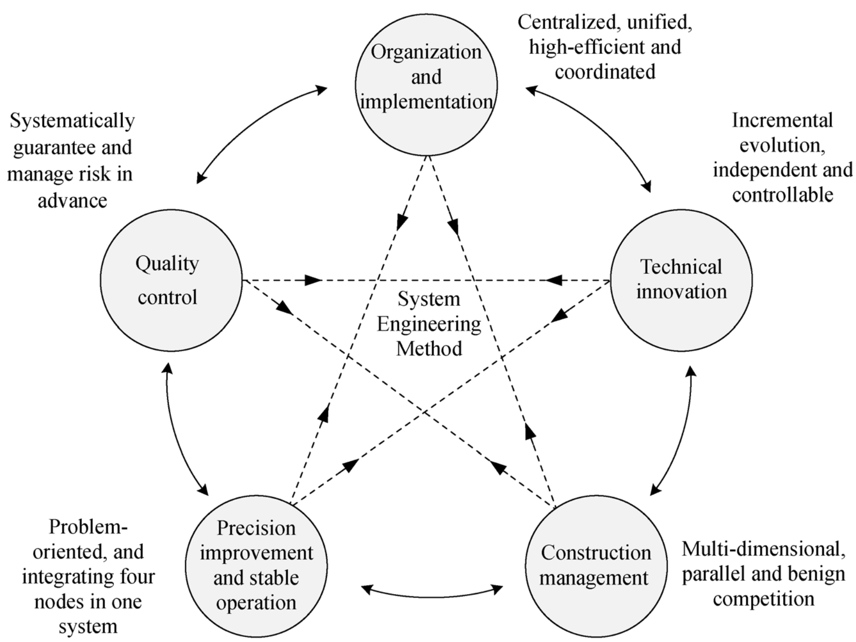

Fig. 1 BDS engineering management system.

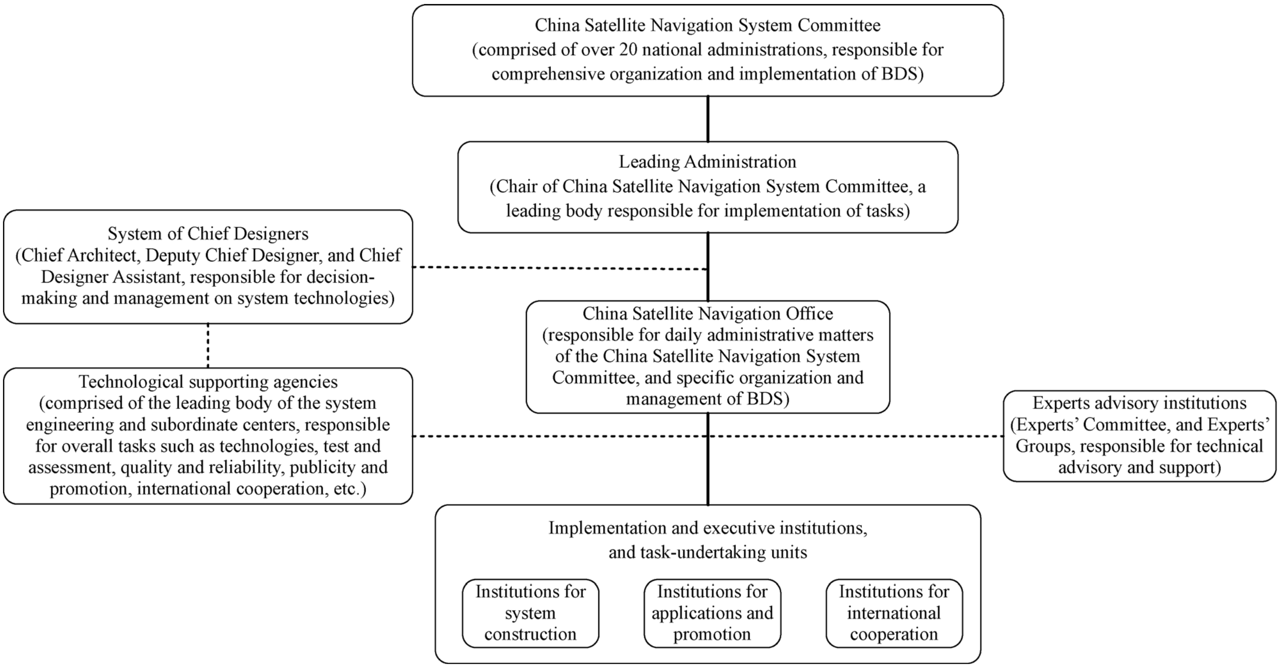

Fig. 2 Organization architecture of BDS.

2.1.3 Overall design unit featured with "small core and large periphery"

As proposed by Qian (1982), overall design unit plays an important role in system engineering, and serves as an essential technical leading body during the overall system research and manufacturing process. A navigation satellite system is one mega space system with active innovation as its main characteristic. Therefore, it is highly required to set up a strong overall design unit. The BDS engineering creates a cross-industry and cross-domain model to establish an overall design unit featured with "small core and large periphery", while at the small core are the China Satellite Navigation Office and the China Satellite Navigation Project Center affiliated to it, and at the large periphery are 5 experts' groups, 9 subordinate centers, and more than 10 specialized research institutes and academies, as shown in Fig. 3. This unit has played an important role in constructing BDS with a manner of collaboration, high-quality and high-efficiency.

2.2 Technical innovation system featured with "incremental evolution, independent and controllable"

2.2.1 Evolution path featured with "incremental evolution and gradual improvement"

During the construction and development of BDS-3, a new mode of "incremental evolution" has been explored and put into practice, which provides scientific methodology for BDS-3 to continuously iterate and evolve, and to consistently pursue better status. In the aspect of strategic planning, BDS has been developed in three steps from BDS-1, to BDS-2, and to BDS-3; its technical schemes develop from regionally active, to regionally passive, and to globally passive; and its capabilities are improved from being available, to chasing foreign systems, and to being comparable with others even going beyond. In the aspect of overall proposal, many versions of BDS-3 overall proposals have been raised and iterated since 2011. During its evolution, the development objectives are gradually identified, from advancing shoulder by shoulder, to surpassing foreign systems and being first-class world-wide. In the aspect of implementation of engineering, 30 BDS-3 satellites are divided into three batches. Based on the on-orbit performances of satellites in previous batch, along with upgrading of overall proposal, the technical status requirements are upgraded batch by batch, thus to continuously improve satellite performances. In the aspect of technical system, system service type increases from 2 types of BDS-2 to 7 types of BDS-3; satellite-ground network extends to the combination of satellite-ground and inter-satellite networks by inter-satellite links; and system operation develops from relying on ground control segment to autonomic control of space constellation.

2.2.2 Technical system featured with "top-level optimization and integration"

The technical system of a navigation satellite system determines its function and performance. The BDS has

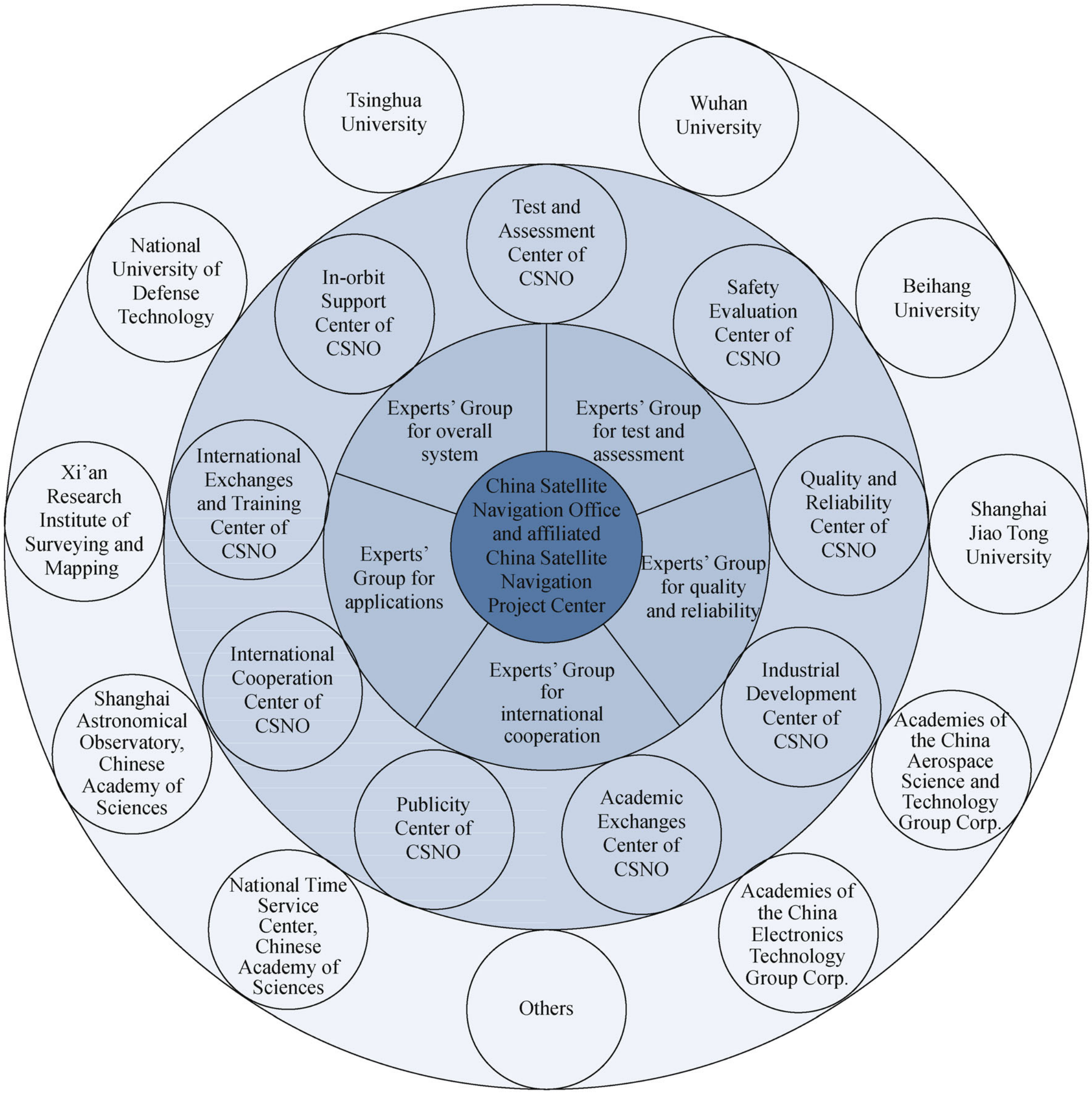

Fig. 3 Overall design unit of BDS engineering featured with "small core and large periphery".

optimized its technical system from the top level, making breakthroughs in core technologies such as multi-service integration, inter-satellite links, heterogeneous hybrid constellation, on-board atomic clocks, and downlink navigation signals, laying a foundation for comprehensive improvement in service functions and performance. A new system has been established, which integrates multiple services, such as navigation and positioning, global short message communication, satellite-based augmentation, international search and rescue, precise point positioning, etc., and greatly enriches service functions. The inter-satellite links of the whole constellation are established to realize information transmission between the satellites. The satellite orbit measurement accuracy reaches centimeter level, and global high-precision navigation is achieved without relying on overseas ground stations, which also provides important support for autonomous navigation. The world's first global heterogeneous hybrid constellation has been innovatively designed, including satellites located at GEO, IGSO and MEO, which expanded the service functions of navigation satellite systems. The main and backup satellite clock systems, which combine onboard hydrogen clock and onboard rubidium clock with independent intellectual property rights, have been developed to ensure high-precision ranging and timing. A downlink navigation signal modulation mode with independent intellectual property rights is designed to improve the anti-multi-path and anti-jamming capability of BDS-3 signals (Guo et al., 2019; Yang et al., 2019; 2020; Cai et al., 2020; Ruan et al., 2020) .

2.2.3 System featured with "innovative breakthrough, independent and controllable" for tackling key problems

In terms of independent innovation of key technologies, more than 160 key technologies have been systematically arranged, to tackle technical difficulties and to solve core and key problems in engineering construction. To ensure success, the technical leading body acts the role of Party A, and is responsible for the coordination and management of all projects; specialized domestic institutions act the role of Party B, and are responsible for specific research and solving problems; and related subsystems of the engineering act the role of Party C, and are responsible for supervision. Simultaneously, a twin digital system of ground and on-orbit test is established, to fully verify the results of key technological breakthroughs, and to continuously iterate and improve them to ensure the rapid and comprehensive transformation of these achievements.

In terms of localization of devices and components, and ensuring independent and controllable, an independent development route is set in advance, reflected as "guided by engineering model, verified and promoted by applications, implementation per phase manner, and driven by large-scale". Three layers of management system are established as "decision-making, consultation and implementation". A special coordination body is set up to be responsible for the overall decision-making, and planning tasks such as development, applications and others as a whole. Experts' advisory institutions are responsible for the formulation of standards and norms, basic technical research, and coordination of technical issues. Each subsystem of the engineering is responsible for the development, verification and applications of components. During the development process, it constantly puts forward suggestions on product optimization and improvement to effectively promote the development and maturity of products. Since the implementation of above measures, the key components have been 100% made in China.

2.2.4 Status control and management mode featured with "integrating six nodes in one closed-loop in the whole process"

According to the characteristics of BDS, a status control and management mode is established by integrating six nodes of "design, test, evaluation, integration, operation, and coordination". In such a process, status is generated from "design", verified by "test", grasped through "evaluation", confirmed by "integration", and optimized along with "operation". In view of the technological problems in this process, general problems are solved directly after coordination, and complex problems are solved after analysis, research, verification and coordination. This mode realizes the closed-loop control and management of the technical status of the BDS, as shown in Fig. 4.

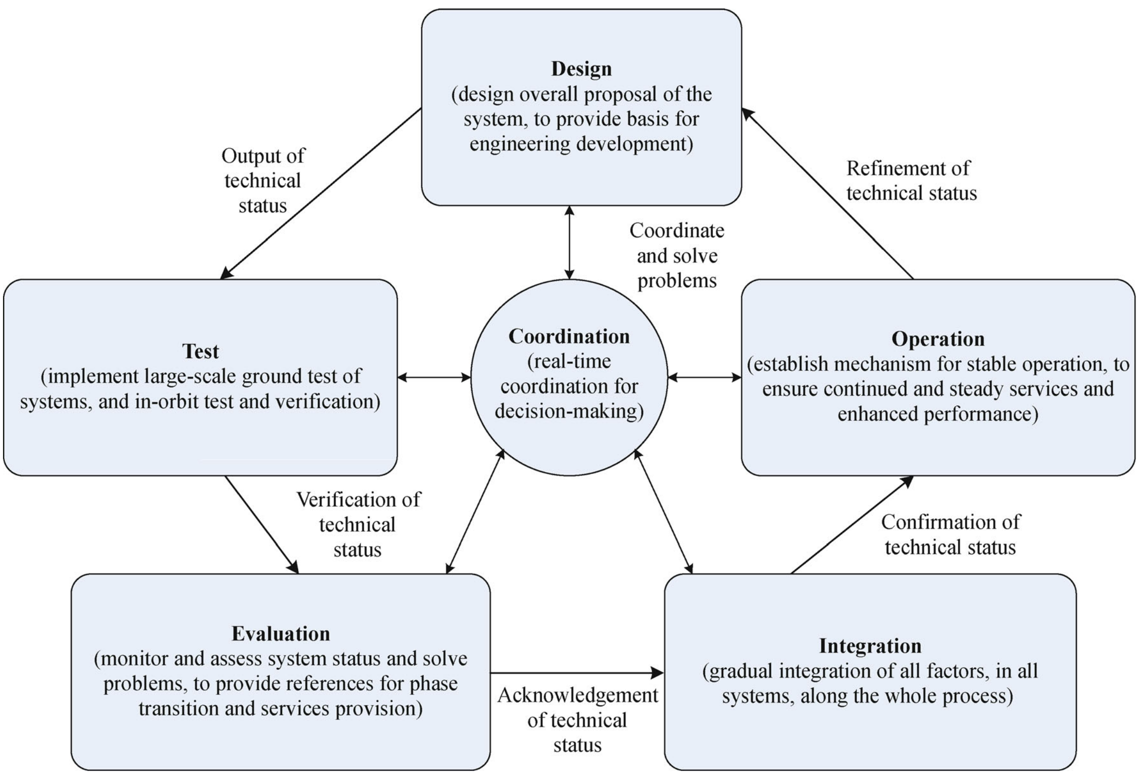

Fig. 4 Status control and management mode by integrating six nodes in one closed-loop.

2.3 Construction management system featured with "parallel progression and competitive selection"

The construction and management mode of "parallel progression and competitive selection" has been established. The work processes are optimized, including overall design, key technology research, test and verification, development and networking, operation and services, etc., which are also highly paralleled and rapidly iterated. At the same time, the competitive mechanism is introduced to mobilize the country's superior resources for brain-pooling. In two and a half years, 30 satellites were launched by 18 carrier rockets, and the construction of BDS-3 was completed six months ahead of schedule, which represents the "Chinese speed".

A new mode is created to manufacture aerospace products in group batch. On the basis of the traditional scientific research and production management mode of single satellite and single carrier rocket, a new group batch production mode of "centralized design, unified status, comprehensive production, acceptance per batch manner, streamlined operation, and iterative backup" for aerospace products has been established, and the satellites and carrier rockets have been delivered according to high-density plan.

The development process is comprehensively optimized. The satellite launch site adopts remote test mode, optimizes the on-site test process for carrier rocket, and conducts test and evaluation of various services in parallel. Thus, the time for satellite-ground link and inter-satellite link is shortened by 50%, and the test and evaluation time is shortened from 90 days to 28 days.

Test and verification support the progression of the whole system. A twin digital test and evaluation system is built, by "integrating the satellite and ground segment, combining the virtuality and reality, and ensuring accuracy and reliability". The on-orbit test, satellite-ground link, on-orbit experiment, and performance evaluation are carried out as a whole. An iterative evolution mode is set up including "development, assessment, improvement, and revalidation", which can continuously optimize system status and performance. Thus, the system is commissioned as soon as it is built, while the services are available right away.

The competitive selection mechanism is introduced to gather wisdom to tackle key problems. As for the construction of research and development team, a benign competition pattern is established, covering multi-level and multi-designation, from the whole system to the subsystem, and then each individual unit. In accordance with the principle of "guarantee development of the same type and heterogeneous system, and guarantee the schedule by real-time supplementary", multiple institutions are designated, including two lead bodies for satellites, two lead bodies for payloads, as well as institutions for two types of satellite buses and a number of key individual units. As for practical measures, development tasks for 30 satellites are assigned in batches proportionally, according to the method of comprehensive evaluation and competitive bidding. A full play to the competitive pressure is given, while positivity of all parties is also maximized.

2.4 Quality control system of "systematically guarantee and manage risk in advance"

2.4.1 Quality and reliability guarantee based on the "four systems"

Traditional quality management mode of space engineering is mainly targeted at the spacecraft, and paying attention to quality control in the whole process and delicacy management of quality. Quality management of BDS engineering adheres to the concepts of "full coverage, focusing on prevention, controlling sources, and persistent management", throughout the framework from overall system to each system of engineering, and then subsystem and individual unit. Besides, evaluation and supervision by the third party, and fundamental guarantee are adopted. A quality management mode is established, including four systems, namely "reliability design, test and verification, evaluation and supervision, and fundamental guarantee", as shown in Fig. 5.

Reliability design system mainly focuses on the design and decomposition of reliability indicators at different levels, and establishes an indicator system on quality characteristics such as availability, continuity and integrity.

Test and verification system carries out all kinds of simulations, tests and experiments, to verify whether indicator requirements are met at different levels from bottom to top. At bottom levels, test and verification are carried out at the levels of individual unit, subsystem, and system, to ensure full coverage of test, completeness and effectiveness of the system. At the top overall system level, a set of ground test and verification system is established to test and evaluate the overall scheme and the results of key indicators.

Evaluation and supervision system mainly relies on the third party to carry out quality supervision and evaluation on the whole system and whole process of development activities, such as reliability design, test and verification of the engineering. At the top overall system level, an International GNSS Monitoring and Assessment System (iGMAS) is established to monitor and assess the service performance of the BDS. At the bottom levels, a set of product supervision and acceptance system is established, implementing maturity evaluation of key individual units, devices and components.

As for fundamental guarantee system, special project for reliability improvement is implemented to increase system reliability. The National Technical Committee on BDS of

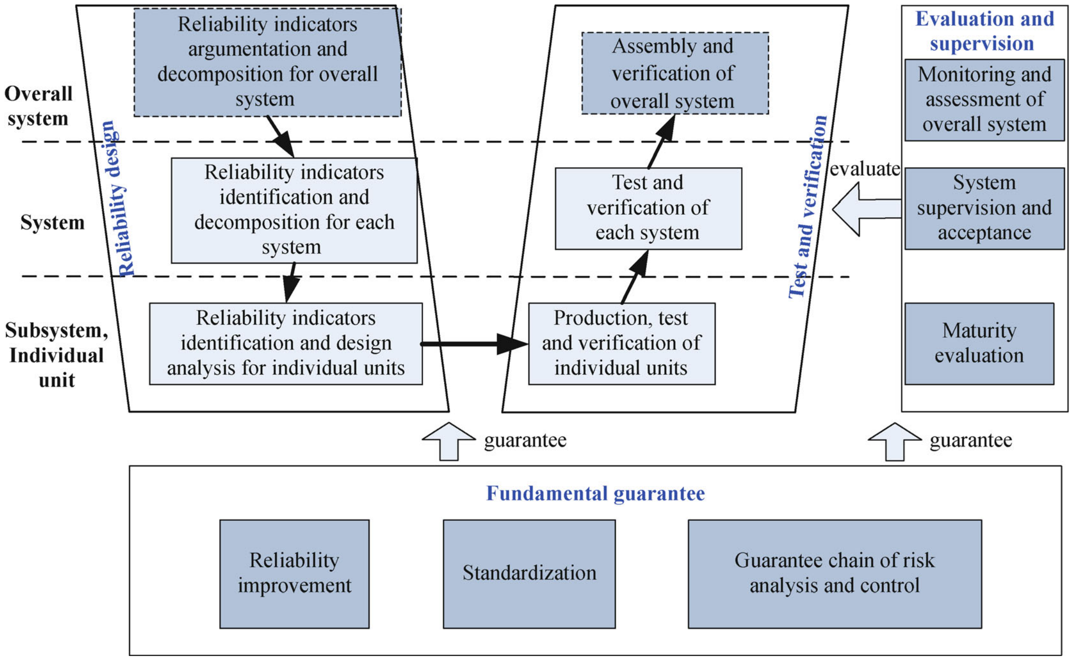

Fig. 5 Quality management mode based on the "four systems".

Standardization Administration of China is set up, and a BDS standard system is established, to promote the healthy development of the satellite navigation industry.

Quality management mode based on the "four systems" has achieved the goals of "zero defect" in the phase of products development, "zero fault" in the phase of satellites launch and networking, and "zero interruption" in the phase of operation and services, and guaranteed the 100% success in the launch of 18 carrier rockets and networking of 30 satellites.

2.4.2 Risk analysis, prevention and control mechanism based on the "control and guarantee chain"

Targeted at multiple types of risks related to schedule, research and manufacturing, launch, stable operation and other aspects, a set of risk control and guarantee chain is created, by integrating multi-source data for risk cognition and analysis, combining quantitative and qualitative analysis for dynamic evaluation, and grade-to-grade transmission and taking precautions for early warning and control. A closed-loop as "identification, assessment, prevention and control" for risk control is formed. The traditional mode of "managing quality in advance" is successfully transformed into "managing risk in advance".

Integrating multi-source data for risk cognition and analysis means using multi-source data of different levels, including overall system, system and individual unit product; at different time domain, including preliminary prototype, flight model phase and test phase; and at different space domain, including ground and in-orbit. Mass intersection analysis method and risk matrix evaluation method are jointly adopted to identify and analyze risks from multiple dimensions, all-round and throughout the whole process.

Combining quantitative and qualitative analysis for dynamic evaluation means adopting the combination of qualitative analysis and quantitative calculation method, to comprehensively evaluate the identified risks. The probability, affected objects and damage degree of risks are determined, classified and graded. According to the changing status of the risk elements, control and guarantee measures are carried out, to continuously evaluate risks and dynamically adjust the level of risks.

Grade-to-grade transmission and taking precautions for early warning and control means transferring risks from top to bottom, and taking prevention, control and guarantee measures in accordance with respective classes and grades. The early warning information of risk is released in time, the implementation of control and guarantee measures is paid close attention to, and the risk prevention and control situation is specially reviewed in key nodes, such as product acceptance, phase transfer and ex-factory review.

2.5 Precision improvement and stable operation system featured with "problem-oriented and integrating four nodes in one system"

To ensure the continuous and stable services of the system, a system for precision improvement and stable operation is established, which adopts multi-means throughout the whole process, by integrating four nodes of "operation and maintenance, monitoring and assessment, precision and stability improvement, and smooth transition", as shown in Fig. 6. The system is problem-oriented, to implement problem-solving measures through "operation and maintenance", to detect and pre-judge problems through "monitoring and assessment", to study and solve problems through "improving precision and stability", to stabilize system services and enhance performance through "smooth transition", and eventually to realize long-term and closed-loop control on the precision and stability.

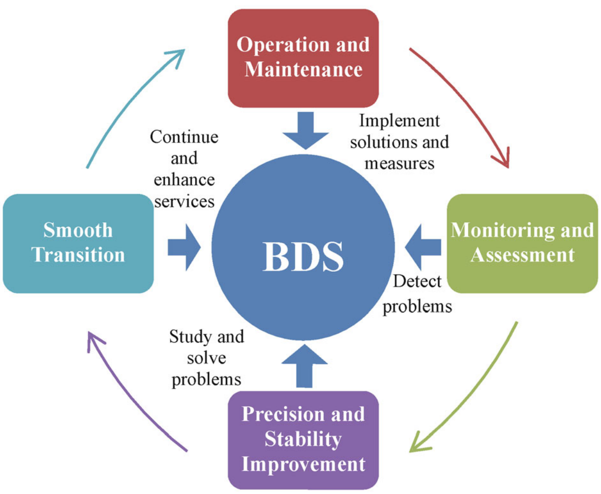

Fig. 6 BDS precision improvement and stable operation system.

As for operation and maintenance, a "multi-party joint-guarantee" mechanism is created, to guarantee the overall system through joint efforts of operation and control system, measurement and control system, inter-satellite link system, and satellite system. A system is built to integrate data within three circles, while in the inner circle is the system service data, in the middle circle is product development status data, and in the outer ring is external monitoring and assessment data. Intelligent operation is implemented based on big data, cloud computing, and artificial intelligence technologies, to evaluate the system real-time online, to rapidly diagnose and address fault, to support decision-making, and to improve scientific and intelligent operation and management.

As for monitoring and assessment, a globally distributed iGMAS network is established, to conduct regular monitoring and assessment of system service performance and operation status, and to timely identify problems and weak links in the system.

As for precision and stability improvement, in view of the problems found by monitoring and assessment, measures are taken to analyze the deep causes, to research and propose solutions, and to carry out key technical breakthroughs and engineering improvements.

As for smooth transition, the space, ground, user and signal segments of the BDS-2 are transferred to the BDS-3 in an orderly and smooth manner, to ensure that hundreds of millions of users will not be affected during the transition.

Since the BDS-2 started to provide services at the end of 2012, the BDS has been operating continuously and steadily for eight years without interruption, and its positioning accuracy has been improved from 10 m to better than 5 m, providing high quality services to the world.

3 Conclusions

The BDS is a successful practice of complex space system engineering, and enriches the connotation of space management system. On the basis of the traditional space engineering management mode in China, the BDS project has realized innovation and development according to the characteristics of the BDS, and formed the BDS engineering management mode with Chinese characteristics. Owing to scientific management and management science, the BDS has been constructed with high quality, high speed and high efficiency. The innovative management mode explored and established during the construction of the BDS, has been fully verified in the BDS engineering, which can provide reference for engineering management in aerospace and other fields. A more ubiquitous, integrated and intelligent national comprehensive positioning, navigation and timing (PNT) system based on the BDS will be built in the future. The BDS engineering management mode will also be continuously innovated and developed, to promote the development of BDS to a higher level, with higher quality.

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