Development of Integrated and Intelligent Geodetic and Photogrammetry Satellites with Corresponding Key Technologies

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Abstract: Aerospace surveying and mapping has become the main method of global earth observation. It can be divided into the geodetic observation satellites and the topographic surveying satellites according to the disciplines. In this paper, the geodetic satellites and photographic satellites are introduced respectively. Then, the existing problems in Chinese earth observation satellites are analyzed, and the comprehensive satellite with integrated payloads, the intensive microsatellite constellation and the intelligent observation satellite are proposed as three different development ideas for the future earth observation satellites. The possibility of the three ideas is discussed in detail, as well as the related key technologies.

Key words: aerospace surveying and mapping; gravity satellite; magnetic satellite; optical mapping satellite; microwave mapping satellite; microsatellite networking; intelligent satellite observation

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1 Introduction

Aerospace earth observation is the only way to realize global overall surveying and mapping of land and the sea. According to the disciplines, aerospace surveying and mapping can be divided into the geodetic observation satellites and the topographic surveying satellites; According to working modes, it can be divided into the return type satellite and the transmission type satellite[1]; And according to payloads and functions, it can also be divided into the single function satellite and the integrated function satellite[2].

Geodetic observation satellites can be divided into the positioning satellite, the gravity sensing satellite, the sea altimetry satellite and the geomagnetic surveying satellite. Existing global positioning satellite systems are Global Positioning System (GPS) of the United States, GLOBAL NAVIGATION SATELLITE SYSTEM (GLONASS) of Russia, Beidou Navigation Satellite System (BDS) of China, Galileo of European Union[3].

There have been many gravity satellite programs. Germany launched the Challenging Mini satellite Payload (CHAMP) in 2000, to recover a gravity model of 70 degrees using the high-low orbit tracking technology[4]. EU and U.S. cooperated the Gravity Recovery And Climate Experiment (GRACE) project adopting low-low orbit satellites tracking mode in 2002, to recover a gravity model of 120 degree and measure the variety of gravity with time [5-6]. After that, EU launched the satellite Gravity field and steady-state Ocean Circulation Explorer (GOCE) in 2008, to monitor the volcano and seismicity, and exploring the ocean currents, sea levels, and changes in the Arctic and Antarctic ice sheets. Though measuring the gravity gradient, the satellite can produce global gravity model with a spatial resolution of 200~80 km and geoid of 1 cm [7-9]. In May

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2018, NASA and GFZ German Research Centre launched GRACE Follow-On (GRACE-FO) satellites. Besides the existing payloads on GRACE (such as Ka-band range finder, accelerometer, on-board GPS receiver, and attitude indicator), GRACE-FO added the attitude measurement device to have more accurate attitude determination and inter-satellite alignment, as well as a laser interferometric ranging system with accuracy of 10 nm[10]. However, due to the accelerometer failure and frequency mixing errors of atmosphere and ocean, the gravity inversion accuracy and spatial resolution of GRACE-FO are equivalent to that of GRACE, while the accuracy of the higher-order part of the gravity field has slightly improved[11-12].

There have been more than 10 sea altimetry satellite projects around the world, and most of them were from EU and U.S., including Skylab, Geos-3, Seasat, GFO, Jason-1 of America, ERS-1, ERS-2, Envisat, Cryosat-2, Sentinel-3 of Europe, as well as Topex/Poseidon and Jason-2 collaborated by America, France, etc[13]. With the improvements on satellite orbit determination accuracy, altimeter accuracy, and data processing methods, satellite altimetry technology has advanced a lot and the accuracy reaches centimeter level. China launched HY-2 in 2011, the first satellite for sea altimetry carrying four kinds of microwave remote sensors, namely the radar altimetry, the microwave scatterometer, the microwave radiometer and the calibration radiometer with a comprehensive height measurement accuracy of 5~8 cm [14].

The topographic surveying satellite can be divided into the optical surveying satellite and the radar surveying satellite. Optical photogrammetry technology is relatively mature with rich research achievements and product categories. The development of international aerospace photogrammetry satellite has been introduced in many papers [2, 15], and here we mainly review the topographic surveying satellite launched by China. At present, TH-1[16-19], ZY-3[20-23], GF-7 and GF-14 are some of the on-orbit optical surveying and mapping satellites launched by China [24-25]. TH-1 and ZY-3 are mainly used for the production of 1 : 50 000 scale surveying and mapping products, while the GF-7 and GF-14 satellites are mainly used for 1 : 10 000 scale of mapping products. Therefore, compared with ZY-3 and TH-1, GF-7 and GF-14 have significant improvements on both image resolution and mapping accuracy.

The Interferometry Synthetic Aperture Radar (InSAR) surveying satellites have also been developed in China. In 2019, the first group of InSAR surveying and mapping satellites named TH-2, was launched to implement topographic surveying of 1 : 50 000 scale[26]; And in 2021, the second set of InSAR satellites was launched. The ground resolution of InSAR satellite is 3 m, and the absolute and relative positioning accuracy in horizontal and vertical components are better than 5 m and 2 m, respectively[27].

Factually, in China, a large number of commercial or experimental earth observation satellites have been launched, and plenty research results have been achieved [28]. However, the observation efficiency of Chinese space-based surveying and mapping satellites is not high enough, neither the economy efficiency of related products[2]. The existing problems can be concluded as follows: ① With similar functions, performances and products, the earth observing satellites launched by different organizations cannot compensate each other; ② Satellites with single function are usually designed, in which geodetic satellites do not measure topography, and topographic surveying satellites do not sensing the earth's gravity or magnetic field, furthermore, terrestrial surveying satellites do not work on the sea and vice versa; ③ The integration of the payloads is poor (For example: the optical observation and microwave satellites are usually separately developed, resulting in the low observation efficiency.); ④ Due to the heavy burden on data transmission, a lot of observation data cannot be transmitted to the ground, leading to the waste of a large amount of on-board observing time and data. In addition, a large amount of invalid information is transmitted to the data processing center on ground, which results in a backlog of observation data unable to perform expected efficiency.

In order to improve the satellite surveying and data processing efficiency, an alternative way is to develop an integrated observation satellite with multiple observation payloads, or densely networked microsatellites with particular observation payload. Furthermore, the intelligent earth observation satellites may be developed. However, we need to solve lots of critical techniques, whichever type of satellites is chosen. This paper focuses on the main development trends of the aerospace surveying and mapping satellite and attempts to sort out the corresponding key technologies.

2 The Development of Integrated Earth Observation Satellites with Corresponding Key Technologies

The transmission type satellite is the absolute main stream of earth observation type. Compared with the return type satellite, transmission type of earth observation satellites has longer on-orbit time and better observation coverage. Once an observation quality problem is found, it can be solved through software on-board reprogramming and reobserving. However, most existing transmission type satellites for surveying and mapping in China have obvious disadvantages, such as single function, incomplete surveying elements, relatively high observation costs, and relatively low observation efficiency.

Firstly, the terrestrial observation satellites do not work when flying over the sea which covers 71% of the earth's surface. Different satellites with different functions according to different principles (such as radar, optics and laser) are rarely integrated in earth observing. Furthermore, the data transmission is also the bottleneck resulting in the incapable transmission of measured data. In addition, it is difficult to realize the complementarity or integrity of various observations for the earth observation satellite with single function, increasing the difficulty in data fusion.

Factually, there have been a lot of integrated earth observation satellite projects, which integrate the reconnaissance and photogrammetric functions in the same satellite. This type of satellites can not only completely share the payloads, but also basically have the same sensing content. The differences between them are that the photogrammetric satellite focuses on the high position accuracy of the images, while the reconnaissance satellite focuses on the dynamic changes of key targets; And the photogrammetric satellite focuses on geometric relationship among images, while the reconnaissance satellite focuses more on the image resolution. In addition, the existing gravity satellites are also payloads integrated with multi-functions. For example, CHAMP measures the medium wave and long wave characteristics of the global gravity field and its variation with time, oberving the magnetic field of the earth and its space-time changes, and uses atmospheric/ionospheric occultation to detect meteorological elements. Similar to CHAMP, GRACE can not only measure the global gravity field, but also monitor the global environment variation (sea level and circulation variation, glacier melting trends, surface water and groundwater changes, etc.). GOCE, namely the abbreviation of Gravity field and steady-state Ocean Circulation Explorer, also belongs to the category of function integrated satellites.

In fact, most of the on-board payloads of space-to-earth observing satellites can be shared, such as the computer system, memory subsystem, orbit measurement system, the attitude measurement system, the antenna system, the power system and the data transmission system, etc. In addition, the laser ranging system and communication system can also be shared by different observation systems.

The earth observation satellites have less payloads, such as the optical camera on the photogrammetry satellite, microwave radiometer on the SAR and InSAR satellite, the synthetic aperture radar altimeter on the sea altimetry satellite and the accelerometer on the gravity satellite. Factually, most of the payloads on the earth observation satellites can be shared. If these and shared payloads are reasonably integrated, then the integrated earth observing satellites can be realized.

Step 1: To integrate all topographic surveying payloads, including the high-resolution optical payload, the microwave payload, the hyperspectral camera, the multispectral camera, and the laser ranging system, etc. And to form topographic surveying ability with all-weather, all-time, and all-airspace, and realize multiple functions with only one satellite. Step 2: Integrate geodetic and photogrammetry payloads to achieve all-element surveying with a single satellite pass. Step 3: Integrate hydrographic surveying payloads and terrestrial surveying payloads to achieve overall earth observing including land and the ocean. Step 4: Integrate meteorological, geodetic, and topographic surveying payloads to achieve overall surveying of multiple elements in geospatial environment.

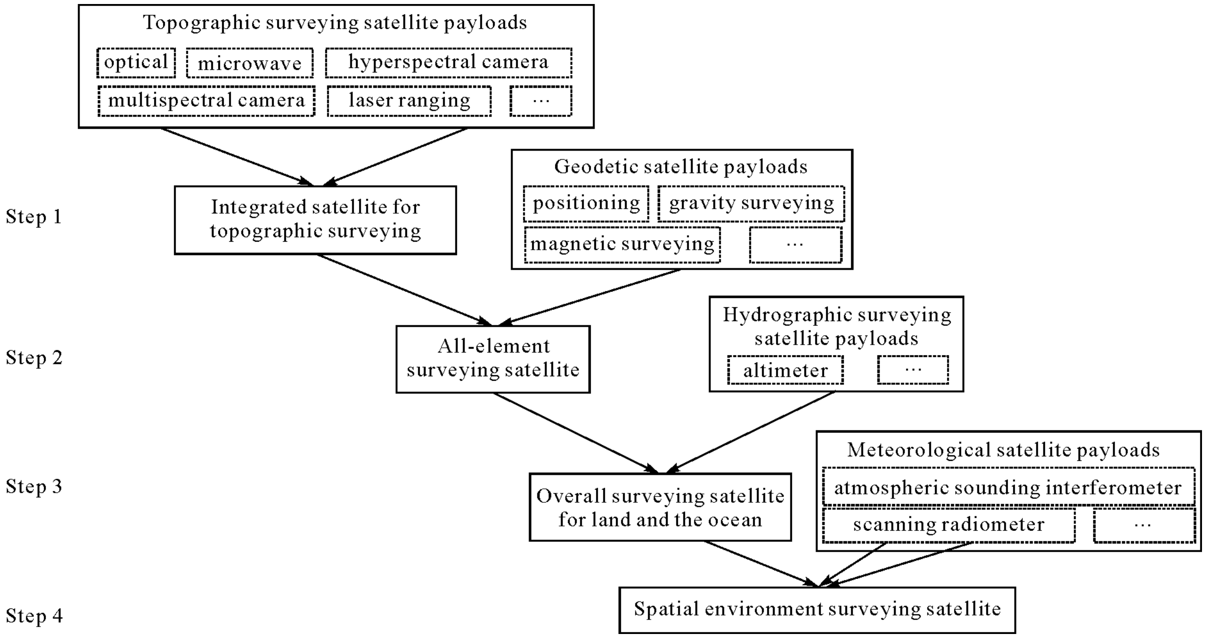

Fig.1 Development steps of the integrated surveying satellite

The integration of multiple payloads for earth observing satellites faces a series of technical difficulties.

(1) The volume and weight issue of the payloads. Multi-payload integration usually occupies more spaces and increases the weight of the satellite platform. Therefore, it is necessary to break through the design and manufacturing technologies of miniaturization, modularization, and even microminiaturization of payloads, for the high integration.

(2) Power consumption issue. Multi-payload integration involves power consumption issue inevitably. Thus, it is necessary to break through the low-power consumption design technology of integrated payloads based on miniaturization and microminiaturization design and manufacturing.

(3) Data transmission issue. The amount of observations increases enormously for the integrated observation satellite with multiple payloads and multiple observing elements. Therefore, it is necessary to increase the transmission bandwidth, or implement multi-channel transmission, multi-site reception, and even increase the overseas receiving stations, to ensure the complete receiving of multi-type observations. Otherwise, there will be a lot of observation data that cannot be transmitted to the ground, no matter how many observations are observed onboard.

(4) Compatibility issue. The prominent problem for satellites with intensive payloads is that the different types of payloads are prone to interfere each other. Therefore, the satellite with intensive payloads must make sure that no unacceptable interference is made to achieve the electronic compatibility of multiple payloads. This is the premise of integrated perception, transmission, and multi-source information sharing.

(5) The orbit optimization issue. The selection

of orbital altitudes and inclination angles should consider the observation sensitivity of each payload, as well as orbit periods and observing coverage. For the availability, the integration of satellite payloads at similar orbit altitude and inclination angle should be firstly implemented. For example, the satellite orbit altitude of 500 km could be a compromised selection for integrate payloads which can meet the requirement of most topographic surveying and gravity surveying mission. As it should be, an appropriate design of satellites at different orbit altitude and different inclination angle can supplement perception sensitivity and observation coverage.

(6) Data processing issue. The significant characters of earth observing satellites with intensive payloads are large amount and diverse types of measured data. Therefore, optimizing the data processing processes and strategies is one of the key technologies. Certainly, the measurement of satellite orbit and attitude could be processed as shared information, while the rest could be processed separately according to specialized subjects.

The main advantages of payloads integrated earth observing satellites are as follows.

(1) One satellite with multiple functions can improve satellite utilization efficiency. Rich space-to-earth observations can be acquired with a small number of satellites, which could save the recourses of satellites and rockets, and reduce the space junk and observation costs.

(2) One payload for multiple purposes. One payload serving multiple types of earth observing purposes can improve the usage efficiency of the payloads.

(3) Mutual complement of multiple elements observed in the same orbit. The multiple observing elements including geometric element, gravity field element, magnetic field element, and even hydrologic element, are conducive to the complementarity of multiple elements in the same orbit. Geometric observation requires gravity and magnetic field correction information, while the recovery of the gravity and magnetic field requires topographic correction information. Therefore, the integrated observing of multiple elements is beneficial for the improvement of geometric integrity of geodetic and topographic measurements, which is conducive to the data fusion. In addition, the integration and fusion of optics, microwave, hyperspectral, and multispectral observations can significantly improve the overall coverage of geometric elements and physical attributes.

(4) The complementary observing by high and low orbit satellites not only facilitates the complementarity of observation geometry, but also enables radio occultation atmosphere detection, which is conducive to the detection of environmental information.

It must be pointed out that there exist series of unsolved difficult issues for the integrated satellites with mutiple payloads, such as power consumption, cost, revisit period, and data transmission etc. With fewer satellites, the revisit period is longer; with more satellites, the costs are increased.

3 Development of the Densely Networked Microsatellite with Its Key Technologies

Integrated payloads for the global geo-information observation satellites have high observing efficiency. However, due to the multiple integrated payloads, we have to solve the series problems, such as the great satellite weight, high power consumption, mutual interference between payloads, high data transmission pressure, and high costs on satellite networking and so on. In addition, we have to face the problems of long global revisit period, difficulty in global observing coverage, etc.

With the support of global basic geographic information, a low-cost and densely networked microsatellite observing system can be constructed to achieve the convenience and high efficiency in the earth observing with miniaturized satellites, modularized on-board payloads, and resilient satellite networking. A series of key technologies are involved in the densely networked microsatellite earth observing.

(1) Modularized design of satellite payloads. Most of the existing earth observing satellite payloads are bundled together, which occupy more space on the satellites, have relatively higher power consump-

tion, and is hard to realize the isolating and dissipating of the heat of each payload. The modularized design of the satellite payloads needs not only systematic design techniques, but also high-precision component processing techniques.

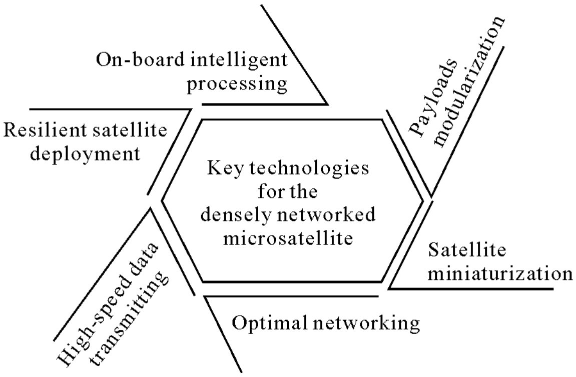

Fig.2 Key technologies for the densely networked microsatellite

(2) Miniaturized design of satellites. Satellite miniaturization is difficult to achieve without the premise of miniaturization and modularization of the payloads. The miniaturization of satellites involves microelectronics technology, micro-processing technology, and even the integrated manufacture of satellite and payloads.

(3) The optimal networking technology for satellites. With the foundation provided by satellite miniaturization technology, the realization of satellite optimal networking in large scale should be solved, which include the geometric configuration, optimal networking design, and reasonable allocation and distribution of satellites with different types of payloads. It is important that the networking of satellites with different inclination angles aiming to ensure the comprehensive perception in high and low latitude areas should be taken into account as well.

(4) Data transmission and reception technologies. Due to the large number of satellites and abundant observations, relay satellites should be used to solve the difficulty in the massive data transmitting, if rapid inter-satellite data transmission and globally distributed ground receiving stations are unavailable.

(5) Resilient satellite deployment technology. The most significant advantage of densely networked microsatellites is the short revisit period, which is particularly beneficial for disaster monitoring and environment monitoring. However, the key area of disaster monitoring needs intensive observations. So, it is necessary to address the resilient orbit maneuver and rapid networking technologies. Moreover, it is also necessary to address the key technology for autonomous control of a large constellation.

(6) On-board processing technology. In order to solve the transmission problem of massive observations existing in the large constellation, it is necessary to realize on-board intelligent judgment and identification of observability, as well as on-board rapid processing technology, striving to achieve the goal of no invalid storing or transmitting. Therefore, the validity identification of on-board data is one of the key issues in densely networked microsatellites for earth observing.

4 Intelligent Earth Observing Satellite Project

As is known that, the dilemma of ground systems lagging behind the satellite observation supply (the supply side is more than the data reception and processing side) exists both in single and integrated earth observing satellites, as well as the densely networked microsatellites. Firstly, it is difficult to make overall planning of ground systems. Currently, almost each type of satellite has its own ground receiving and processing systems. The more satellites are launched, the more ground systems are constructed. In addition, the construction of ground systems has always been unable to meet the actual needs of data processing, resulting in the serious data backlog and low efficiency in data processing and application. Secondly, in order to decrease the amount of data, satellites do not observe at full capacity, even so, regional observing data can hardly be downloaded due to the low transmission efficiency. Meanwhile, the transmission of necessary observations, repeated observations and invalid observations with no difference, leads to a large number of invalid transmission, making it impossible to transmit some useful data. In addition, towards the integrated earth observing satellite, the data collection volume will be larger and larger and the data transmission will be more difficult. Finally, the efficient observation processing is difficult, leading to a large number of repeat observations may be repeatedly processed with no difference, namely which results in invalid processing indeed. The relatively low efficiency in data processing results in the difficulties in real-time support of required data and urgently needed data.

To improve the efficiency of integrated and densely networked earth observing satellites, it is necessary to address the efficiency issues of satellite data collection, transmission, and processing. Therefore, the intelligent earth observing satellite has become an inevitable development trend.

Firstly, satellites should have intelligent perception function[3], which means that no observing in the areas without demands or valid observing condition (e.g., the optical satellite does not need to work in the areas covered by clouds or heavy rain). Satellite payloads should also be automatically combined based on observability, to greatly reduce the ineffective observation and save power consumption.

Secondly, the satellites should preload photogrammetry images with high geometry precision, and have the ability to intelligently identify, intelligently store and intelligently transmit newly acquired images. Then, the differences between new images and the basic images can be automatically and rapidly identified once the new images are achieved. If no difference or change are found, the storing and transmitting can be ignored. Only the perceived variations of terrain feature (including important target motion) are stored and transmitted. In this way, the amount of data storage and data transmission requirements can be significantly reduced.

Furthermore, the intelligent processing on-board should be achieved, on the basis of intelligent observing. It means that the intelligent processing and updating of on-board observations (updating ground objects, target images, and coordinates) could be achieved with existing basic control data and on the basis of intelligent identification.

In addition, satellites should have intelligent collision prevention functions, including self-alarming, self-maneuvering, and self-avoiding of non-cooperative objects. The launch vehicles should be automatically tracked the rocket debris as well. Even the landing point of the rocket should be controlled to reduce the uncertainty.

In order to have capabilities of intelligent sensor integration, intelligent perception, intelligent storage, intelligent transmission, and intelligent on-board processing, as well as intelligent requirements like the intelligent safety management of satellites and rockets, a series of key technical issues must be addressed.

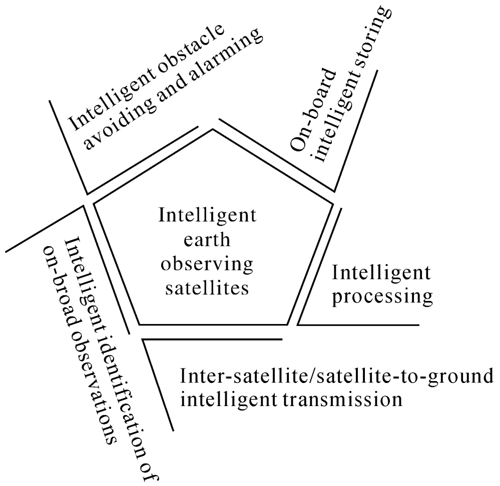

Fig.3 Key technologies of intelligent aerospace surveying satellite

(1) Intelligent identification technology for on-board observations. In order to achieve the effectiveness of intelligent identification with on-board sensors, satellites should preload high-precision and high-resolution basic photogrammetry products for comparison and identification. Therefore, the ground system should implement global large-scale (such as 1 : 10 000) high-precision, and high-resolution integrated adjustment of basic image data; construct basic and unified image products that can serve as reference image and reference geodetic datum; obtain high-precision coordinates of feature points, topographic elements, and geophysical field elements. The key technologies need to be solved include the functional model, stochastic model, and parameter estimation criteria for combined adjustment of multi-

source images[26]. Robust estimation with systematic error composation terms can be applied to control the effects of outlying measurements and the systematic errors, to improve the accuracy and resolution of global basic photogrammetry products after adjustment. The preprocessed adjusted image products on ground are the foundation for the intelligent data processing onboard.

(2) Intelligent storage technology for on-board observations. The data center of satellite-to-earth observation contains a large number of invalid and repeated observations, which requires on-board computers to have the intelligent learning ability to store useful data and delete invalid data. So, it is necessary to establish knowledge graph for learning and identifying effective observations.

(3) Inter-satellite intelligent data transmission. For either inter-satellite observations or satellite-to-ground observations, it's appropriate to expand the edges of observing areas with new variations, to provide enough reference information for the data matching from different satellites, and the registration of satellite observations and existing ground data. The data sensitive to time should be transmitted to the ground processing center (such as gravity observation, ocean altimetry data, and environmental perception data), in order to deduce the physical variations in various spheres of the Earth.

(4) On-board and ground-based intelligent data processing technology. On-board intelligent data processing must emphasize the principle of simplicity, which means that only changing observations need to be processed; ground data processing centers focus on eliminating the contradictions in the data observed by various satellites and sensors, as well as the contradiction in new and existing data, to ensure the consistency between the updated partial observations and the overall basic data. If high-precision ground control information is involved, it should be fully utilized to implement intelligent adjustment and updating with partial data to ensure the global basic earth observing products newest and reliable.

(5) The intelligent obstacle avoiding and alarming of satellites. Two fish-eye cameras with hemispherical observing ability might be installed in front of and behind, or left and right of the satellite to identify non-cooperative targets. Once a non-cooperative target is found approaching, the satellite should start automatic alarming and maneuvering procedures. For the automatic tracking and landing control of rocket debris, a Beidou terminal with position tracking function and a control system should be installed on the rocket to reasonably control the landing position of the rocket debris.

It should be noted that on the basis of intelligent perception, intelligent transmission, and intelligent on-board processing, the re-adjustment of global observation data must be initiated. Once sufficient surveying and mapping data with higher accuracy, higher resolution, and better timeliness is obtained, the contradictions can be adjusted, the reliability and currency of the basic products can be achieved. In addition, the gravity field models and sea surface height models require regular overall data processing to accurately extract time-varying information of physical fields and further update the Earth's gravity field model and seabed topographic model.

The main advantages of future intelligent earth observing satellites are as follows.

(1) The ineffective observations and payload power consumptions can be significantly reduced, through on-board intelligent perception.

(2) The data transmission burden on satellite-to-ground can be significantly reduced, the pressure on ground receiving systems and its constructions will be reduced as well, if the intelligent data processing and identification are realized.

(3) The ground processing system can intelligently implement partial updating, which can significantly reduce the pressure of large-scale data processing on the ground, based on the relatively fewer downloaded data.

(4) The currency and freshness of global surveying and mapping products can be ensured, and almost real-time global observing support capabilities can be achieved, by partial updating of global basic surveying and mapping data with high-precision.

(5) The safety of satellites and the controllability of rocket landing points can be enhanced, by the in-

telligent Beidou position tracking of the satellites and rockets.

5 Conclusion

What makes aerospace-to-earth surveying satellites significantly different from other dynamic monitoring satellites is the foundational nature of its data products. The variations in global surveying and mapping products are usually not significant, therefore, the focus of surveying and mapping satellites should turn to the monitoring and updating of partial variations on the basis of global precise products.

The geodetic and photogrammetry satellites with single function achieve engineering goals well. However, it has lower systematic observation efficiency. Therefore, a large number of observation satellites are often needed to meet the users' requirements.

Integrated surveying and mapping satellites can significantly improve observing efficiency with integration of multiple payloads, strengthen the complementarity of various observations, and improve the data fusion efficiency. However, the pressure on data processing and data transmission is also enormous due to the significant increase on data amount.

The densely networked microsatellite observing system with short revisit period, low cost, and relatively fewer payloads per satellite, can perform quicker dynamic variation monitoring, which is suitable for disaster monitoring, environmental monitoring, and moving target monitoring.

Intelligent earth observing satellites not only emphasize the intelligent integration of satellite payloads, but also intelligent identification, intelligent perception, and intelligent transmission on-board. This type of satellite is expected to significantly improve the observing efficiency and data processing efficiency, as well as the freshness of the data and guarantee the ability of surveying and mapping products.

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