

Intelligent remote sensing satellite system

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Abstract: This paper analyzes the disadvantages of the current remote sensing satellite systems, and describes the concept of the latest generation “intelligent remote sensing satellite system” and its main characteristics which mainly includes: (1) the adaptive remote sensor system; (2) the onboard real-time data processing system; and also introduces the key scientific issues and the key technologies involved. This paper presents the design of an intelligent hyperspectral satellite payload system with adaptive imaging and application mode optimization capacity, which consists of three parts: (1) a fore-field pre-judgment sensor for regional background information acquisition; (2) a main sensor for detailed surface observations; (3) an onboard real-time data processing and analysis subsystem. It also introduces the working principles and processes of intelligent hyperspectral satellite, and calls for the research on some frontier scientific theories and key technologies related to the intelligent remote sensing satellite system in an early stage to realize the leap-forward development in the field of remote sensing satellite in China.

Key words: intelligent remote sensing satellite, hyperspectral remote sensing, adaptive observation, real-time processing, Field Programmable Gate Arrays (FPGA)

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1 INTRODUCTION

In the 21st century, space remote sensing technologies are playing an increasingly important role in the development of national economy, defense and sustainable development of human society. Satellite remote sensing and its application technologies are developing rapidly, with some new earth observation satellites coming forth worldwide, and the concept of application orientated and space-earth integration is fully reflected in designing and manufacturing of remote sensing satellite system. High spectral resolution, high spatial resolution and high temporal resolution is the development trend of modern remote sensing technology, and some small remote sensing satellites with very strong data acquisition capacity for specific application purposes have been developed, which marks that we will usher in the era of earth observation data “explosion”. Under such situation, we really need to seriously think about the future development trend of remote sensing satellite to address some pressing problems in the following three aspects:

Firstly, the remote sensing satellite has an increasingly stronger data acquisition capacity, and the growing data amount brings great pressure on satellite data downlink transmission and post-processing. The imaging performances of remote sensing satellites such as spatial resolution, spectral resolution and swath width, *etc.* have been continuously improved, which also makes the amount of satellite data increase at a geometric rate. NASA’s data center receives data more than 3.5TB per day (Ramapriyan *et al.*, 2004), while only a small part are accessed

by users. Taking the domestic situation as an example, the Miyun Satellite Ground Station of Center for Earth Observation and Digital Earth (CEODE), Chinese Academy of Sciences (CAS), received a total of 369100 satellite images in 2008, but only 13600 images were purchased by users, accounting only for 3.7% of the total amounts. There is a huge gap between the amount of data received and the amount of data in actual use, and the efficiency of data use is low. The huge amount of raw data brings a huge pressure on downlink transmission and ground processing equipments. However, we are in urgent need of data with higher precision that meets quantitative professional application requirements.

Secondly, the relationship between environmental backgrounds and ground targets to be detected on the Earth’s surface are varied and complicated, and the remote sensing characteristics of the same type of ground targets on the Earth’s surface are also changed with the seasons. However the specifications of a satellite sensor after it is launched are basically unchangeable, including the foreign satellites (Landsat/TM, SPOT, MODIS and HYPERION EO-1, *etc.*) and the domestic counterparts satellite (CBERS, HJ-1A and HJ-1B, *etc.*) These satellites have fixed observation and imaging modes during their in-orbit operation, and the settings of their sensors such as imaging spectral bands, spatial resolution, spectral resolution, radiometric resolution and spectral response, *etc.* are pre-designed and unchangeable. The data acquisition requirements are different in the fields such as land resource survey, natural disaster monitoring, bioenvironmental protection and military reconnaissance, but the exist-

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ing remote sensing satellites are mostly unable to timely optimize and adjust payload imaging parameters according to different observation targets and missions, different environments in observation areas and different actual requirements and research purposes.

Thirdly, the automation level of data processing and the time effectiveness of information extraction are low. The traditional process of "satellite data acquisition-ground station receiving and processing - data distribution-professional application" can not meet the time-effective flexible requirements of disaster emergency response monitoring and military applications, in which data should be rapidly converted to information and distributed on a real-time or quasi real-time manner to end users of different levels. Presently, the data acquisition capacity of remote sensing satellite has been steadily improved, with spatial resolution ranging from the km-level to dozens of meters and even to sub-meter level (such as Quickbird, Geosyde) and spectral resolution ranging from 100 nanometers to nano level (such as HYPERION, CHRIS, ARTEMIS). In contrast to the increasingly enhanced satellite data acquisition capacity, the automation level of data processing is still low. There is too much human intervention in the process from data acquisition to information extraction and application, and some remote sensing application tasks such as information extraction are mainly carried out by manual visual interpretation, so it is difficult to ensure the time effectiveness of information services. In fact, the demand for satellite products has shifted from images to various specific information. Common users are not concerned about the details of complicated image processing technologies, and real-time processing and downlink transmission of information products will become one of the core concepts of satellite design in future (Tomar & Verma, 2007).

In summary, The traditional satellite remote sensing technologies can not meet requirements for fast, precise, flexible remote sensing data acquisition and information production, so we should establish an intelligent remote sensing satellite system with imaging mode optimization and fast information extraction and distribution. An overall consideration should be given to design of remote sensing satellite systems and development of ground information processing technologies, which is a major development trend of earth observation satellite technology with characteristics of high spectral resolution, high spatial resolution and high radiometric resolution.

This paper analyzes the current development status and characteristics of intelligent remote sensing satellites in section 2. Section 3 and section 4 presents new generation "intelligent remote sensing satellite system", detailed in the key technologies and system design.

2 CURRENT DEVELOPMENT OF INTELLIGENT REMOTE SENSING SATELLITE SYSTEM

Since the end of the last century, foreign and domestic scholars have carried out researches at different levels on issues related to intelligent remote sensing satellites. Hyperspectral remote sensing is today's forefront of the development of international earth observation technology (Tong, 2003). Due to the characteristics of mass data acquisition and the urgent demand for fast quantitative information extraction, intelligent hyperspectral remote sensing sat-

ellite has been a major trend of satellite development. The office of Naval Research (ONR) and the Naval Research Laboratory (NRL) have carried the Hyperspectral Remote Sensing Technology Program (HRST). The Optical Real-time Adaptive Spectral Identification System (ORASIS) was developed in this program to carry out real-time satellite data processing and compression, greatly being reduced the space-time redundancy in hyperspectral data (Wilson & Davis, 1998). This system was originally planned to be used in the U.S. Naval Earth Map Observer (NEMO) to demonstrate the feasibility of hyperspectral remote sensing for coastal zone and littoral environment surveys (Davis, 2000a). The report submitted to NASA also describes the outlook on future development of intelligent remote sensing satellite system, and holds that the system, which consists of comprehensive Earth observation, onboard data processors and data communication systems, can provide time-effective global spatial information services to various kinds of users (Zhou, 2001). The report clearly states that future intelligent remote sensing satellites should be based on the demand-driven concept, but does not discuss in detail on the implementation of these technologies. In addition, NASA has also carried out space-based scientific experiments, which flexibly combine various kinds of remote sensors, navigation and positioning equipments and ground research activities to form an automatically operating sensor network. This network can manage all sensors according to the needs of users or the priorities of emergencies. It is a good case that combining MODIS and HYPERION, respectively with high temporal resolution and with hyperspectral resolution characteristics, to carry out high-efficient intelligent earth observations (Chien, *et al.*, 2005). Academician Li Deren (2005) hold that intelligent earth observation satellite system should have multi-layer satellite network architecture, and perform together in the form of constellation to provide real-time earth observation data to various kinds of users worldwide and meet the application requirements in various fields.

Foreign remote sensing powers have attached great importance to the research and development of onboard real-time processing systems, and have developed some satellites with smart features, such as NEMO developed by U.S. Navy, BIRD developed by German Space Agency (DLR), COCONUDS system developed by the European Union and PROBA satellite developed by European Space Agency (ESA), *etc.* Compared with traditional earth observation satellites, these systems generally have the following characteristics:

(1) Function specialization

The intelligent satellite does not primarily aims at data acquisition, but instead it is designed for some special applications according to specific needs. The onboard hyperspectral imager and the 5 m resolution panchromatic imaging camera in the U.S. Navy's NEMO satellite are mainly used for fast analysis of coastal environment, extraction of surface reflectance, ocean surface remote sensing reflectance, water turbidity, chlorophyll, CDOM, suspended solids sediments, water depth and bottom reflectance, *etc.* (Descour & Shen, 1999). The FOCUS platform on the international space station (ISS) is used for automatic fire detection. FOCUS incorporates Fore-view Field camera, spatially highly resolving imaging sensors and Fourier transform infrared spectrometer to perform functions such as potential hot spot detection, sun glint or cloud filtering, warm surface removal and hotspot clustering, *etc.* The BIRD satellite of the German Aerospace Center is also mainly used

for detection and evaluation of thermal anomalies such as forest fire, volcano eruption, oilfield fire and coal mine fire, *etc.* (Winfried, 2001). In addition, the automatic flood monitoring will also be one of designed functions of future intelligent satellites (Yuhaniz, *et al.*, 2007).

(2) Changeable imaging modes

The onboard Compact High Resolution Imaging Spectrometer (CHRIS) carried by PROBA small satellite launched by ESA can acquire hyperspectral images from 5 different viewing angles (-55° , -36° , 0° , 36° , 55°) during a time period of 2.5 minutes, and can choose one of among the 5 five imaging modes with different spatial and spectral resolutions according to different observation targets such as water body, vegetation and land, *etc.* and different application demands (Barbara & Ruddick, 2004). It can provide 62 spectral bands with 34 m spatial resolution in the VNIR spectral range of 411—997 nm, or it can be reconfigured to provide 18 spectral bands (fully programmable) in the VNIR range (411—1019 nm) with 17 m spatial resolution aimed at water quality monitoring applications.

(3) Onboard real-time data processing

The onboard real-time data processing is the most striking feature of intelligent satellite, and after processing, the data amount of information products will be reduced significantly, which will reduce the pressure on downward transmission of products and allow users to receive remote sensing information directly. The U.S. NEMO satellite employs the optical real-time adaptive spectral identification system (ORASIS) for hyperspectral data processing, and the processing algorithm is based on convex set analysis and orthogonal projection technique to unmix a particular scene and generate 10 to 20 endmembers to perform automatic data analysis, feature extraction and data compression (Davis, 1997). The onboard data processing capabilities of the BIRD satellite include radiometric correction, geometric correction and thematic information production of disaster warning and monitoring, *etc.* (Winfried, 2001). The new generation Pleiades satellite developed by France employs the reconfigurable Field Programmable Gate Arrays (FPGA) as an onboard Module Video Processor (MVP) to realize data acquisition, pixel alignment, thermal control, power control and other functions, and it uses high-performance wavelet image compression algorithm with compression ratio up to 7 : 1 (Arnaud, *et al.*, 2006).

(4) Real-time data downlink

Coordinated Constellation of User Defined Satellites (COCONUDS) developed by European Union, which consists of 10 polar orbiting micro-satellites, is used for environmental monitoring. It directly transmits data without store data onboard (Verduijn, *et al.*, 2001). The data acquired by the French Pleiades satellite are compressed and then downlink at a rate up to 4.5 Gbit/s (Arnaud, *et al.*, 2006).

In addition to the intelligent satellites with real-time onboard processing performance, some commercial satellites that have been successfully launched or will be launched in future also have more smart features. For example, the WorldView-1 panchromatic satellite launched by DigitalGlobe in September 2007 provides 0.5 m-resolution and rapid response capability, and is able to carry out up to 24 times of continuous observations with different viewing angles for the same target according to actual needs. The WorldView-2, has more than eight spectral bands and one panchromatic band, and can flexibly realize the imaging mode of wide cover-

age (multiple scanning 65.6 km) and long strip (width 16.4 km) or three-dimensional observation (width 48 km) by relying on its strong control gyro (CMGs), greatly improving the data acquisition efficiency of high-resolution satellite. Spot 6 and Spot 7, which are scheduled to launch by SPOT Inc. in 2012 or later, have greater flexibility in satellite data acquisition and optimize data collection processes, combining long-term and short-term weather forecast to minimize acquisition of useless data in rainy and cloudy days (Campenon, 2009).

In general, with the rapid development of hardware technologies such as computer, communication and optical devices, *etc.* and in-depth research on onboard real-time processing algorithms, it is of great significance to carry out research and development of intelligent remote sensing satellite systems based on application demands. The intelligent satellite system will also help us to realize the change of the earth observation mode from “getting what we are provided” to “getting what we want”, and will improve the earth observation efficiency and data utilization efficiency.

3 INTELLIGENT HYPERSPECTRAL REMOTE SENSING SATELLITE SYSTEM AND ITS KEY TECHNOLOGIES

The hyperspectral remote sensing data contains rich spatial, radiometric and spectral information of surface features, and provides spectral curves reflecting ground objects' features, which greatly expand the application fields of remote sensing. It promote the development of remote sensing technology from “qualitative analysis” to “quantitative inversion” and create a broader space for introduction of new theories and methods. However, as the hyperspectral remote sensing data have the characteristics of huge mass and lots of spectral bands, we are faced with abovementioned three aspects of problems in “Introduction section” while seeking new remote sensing application fields.

With ground objects classification, target detection and emergency monitoring as major application purposes, we need to take an overall consideration in design of the remote sensing satellite system and development of ground information processing technology. Object classification and feature identification by hyperspectral images were performed after bands choosing or feature extraction, and the other bands will be completely unused. Amount of invalid data were stored during the mentioned data process. Moreover, the full spectral band settings to sensors without careful selection will lead to undesired spectral response range, spatial resolution and band SNR. Therefore, if we can start from the data source and provide spectral data with more specific physical meaning and characteristics according to different surface features, this will greatly improve the detection efficiency of a specific target and the inversion accuracy of surface parameters.

Two scientific problems should be first resolved in order to research and develop the new generation intelligent hyperspectral remote sensing satellite system.

Firstly, we should study the theory on optimization of remote sensing observation modes under the condition of mutually exclusion among different specifications of the hyperspectral remote sensor. High-precision and high-efficiency remote sensing needs strict requirements for sensor specifications, such as spectral resolution,

spatial resolution, radiometric resolution and time-phase resolution, *etc.*, but the above specifications are mutually exclusive and correlated. Therefore, based on research on spectral features of surface objects and information reversion models, we should further study the sensitivity of surface parameter inversion models to core specifications of remote sensor and the principles and methods of designing sensor specifications (signal to noise ratio, spatial resolution and spectral resolution, *etc.*), and establish mutual exclusion model of sensor specifications. We should also combine the surface parameter inversion model with the spectral imaging model to study and establish the best surface parameter observation modes under the condition of mutual exclusion of hyperspectral remote sensor specifications.

Secondly, we should study the adaptive observation theory under the support of prior knowledge and models. The low utilization efficiency of remote sensing data is largely attributed to the fact that remote sensors are basically acquire complex and diverse surface data in a fixed imaging mode, without taking into account the differences in remote sensing characteristics of specific surface environment and surface features. In addition, remote sensing process is influenced by different solar irradiation or different atmospheric conditions. So it is still difficult to remotely sensing surface type in a real-time, and real-time imaging mode optimization is still a great challenge. Therefore, we should study how to acquire real-time prior information of cloud and aerosol, such as optical thickness and radiometric dynamic range, *etc.* via multi-modes and different observation modes, carry out research on data expression and modeling methods of prior knowledge such as the surface type, the cloud / aerosol and the surface parameter model, *etc.*, and combine such prior knowledge with the adaptive imaging theory to implement real-time optimization of hyperspectral surface parameter observation modes.

The onboard real-time data processing involves fast parallel algorithms, data compression, data distribution and transmission, *etc.* On this basis, the specific data processing algorithms and application models can be implemented in onboard hardware to carry out onboard real-time data processing and emergency observation production and directly downlink data and information to users with different demands. With this system, information products can be generated onboard and directly distributed to different types of end users. It looks like GPS data received by most common users. And remote sensing information service like GPS will be realized by the development of intelligent remote sensing satellite system. It will greatly expand the application fields of remote sensing and improve the utilization efficiency of remote sensing data.

The key technologies involved in the intelligent remote sensing satellite system are as follows.

3.1 Remote sensor imaging mode optimization technologies

Presently, the satellite payload and sensor specification setting is mainly based on basic features of the observed targets. For example, a typical case of satellite payload specification designing for land resource monitoring satellites, Landsat / TM, designed 6 bands ranging from visible to shortwave infrared spectrum and a thermal infrared band, mainly aims to monitoring the land resources, such as vegetation, soil, water bodies, minerals, surface temperature and other aspects; the SPOT satellite, which imitates the payload design of Landsat, has ad-

ditional stereo mapping capability and a higher spatial resolution; the MODIS carried by the Terra & Aqua satellites is currently the most sophisticated sensor operating in orbit, and its spectral resolution, spatial resolution and radiation performance settings are based on the requirements of different the targets to be observed, with range of applications involving land, sea and atmosphere fields.

With the development of hardware technology, the operation mode and parameter settings of sensor were continuously optimized. These parameter settings are still imprecise and inflexible, and the demonstration of sensor specification parameters such as spectral, spatial and radiometric performance, *etc.* is often based on a certain environment and imaging conditions, without fully considering the effectiveness of information extraction from image data under different environmental backgrounds, causing great difficulty in later data analysis and information extraction. For example, the ocean color bands (8-16) of MODIS sensor are often saturated and unusable in coastal areas with high suspended sediment concentration or inland water areas with high aerosol optical thickness (Zhang, 2009). Once the imaging mode of a sensor is determined, the corresponding payload's specification settings are unchangeable during satellite operation period. Therefore, for intelligent remote sensing system, we need first to study the technology for optimizing the imaging mode of sensor. Taking hyperspectral remote sensing satellites as an example, with its strongest optical information acquisition capacity, and we should study the best specification parameters of remote sensors under different environmental backgrounds and for different targets and should establish the remote sensing characteristics database for different targets to provide basis for dynamic adjustment of payload specifications.

To develop the technology for optimizing imaging mode of sensor, we should set out from the purposes of target monitoring and information extraction, use a variety of space-borne and air-borne remote sensing platforms and data acquisition methods such as ground survey and spectral sampling, *etc.*, and carry out comprehensive analysis of the best settings of sensor specifications for target monitoring purpose. We should take into consideration of the issue of optimal configuration of spectral, radiometric and spatial specifications according to change in season, region and environment. Finally, we establish the target characteristics database and the remote sensor specification parameter database under a variety of background environments, including parameters such as center wavelength position, spectral resolution, radiometric response, signal-noise ratio, detection sensitivity, spatial resolution and swath width, *etc.*

3.2 Technologies for adaptive adjustment of sensor specifications

There are mature technologies to carry out the satellite earth observation missions through ground control programming. For example, satellite such as Beijing-1 micro-satellite (BJ-1), Environment and disaster monitoring constellation (HJ-1) or SPOT satellite, can acquire data by using side-swing of satellite according to the observation program, but the spectral, radiometric or spatial specifications of these satellites can not be changed. The PROBA launched by ESA in 2001 was a typical case of ESA's satellite design adopting new onboard technologies and autonomy housekeeping advantages, and it can operate a large number of missions with very little human intervention. As an onboard intelligent sensor, CHRIS can adjust its imaging modes via pre-programming according to

different application purposes, such as monitoring land, vegetation, water and other aspects. The spectral bands rang from 18 to 62 and spatial resolution is adjustable from 17–34 m, and spectral positions are selectable (Mode2-Mode5) (Barnsley, *et al.*, 2004; Cutter, 2002).

Therefore, to realize adaptive specification parameter adjustment for remote sensors, we should give an overall consideration to application targets and performances of satellite payload, and realize adaptive and optimized acquisition of data for different environmental backgrounds and application demands via optimizing the detector specifications according to different mission requirements and targets. In future, intelligent remote sensing satellites will be endowed with such detection capabilities as adjustable / selectable spectral resolution, spatial resolution, radiometric resolution and center wavelength to improve the efficiency of data acquisition, data processing and information extraction.

3.3 Onboard real-time data processing and fast information generation technologies

Onboard real-time data processing technologies have developed with the signal processing hardware technologies, and some processing algorithms are increasingly mature. The Coastal Ocean Imaging Spectrometer (COIS) in NEMO satellite is used to characterize littoral region environment. It uses Optical Real-Time Adaptive Spectral Identification System (ORASIS) to accomplish spectral filtering and spatial filtering and finally generate battlefield environmental information and direct downlink (Wilson & Davis, 1999; Davis, *et al.*, 2000b). BIRD launched by German Space Agency (DLR) uses the infrared detector for hot spot detection and warning based on the thematic neural network classifiers. TacSat-3 satellite launched by the United States in 2009 carries an image spectrometer called ARTEMIS, which can carry out anomaly detection via onboard data processing, distinguishing man-made targets from natural backgrounds automatically. Many scholars proposed that FPGA (Field Programmable Gate Array) is used as a core component for real-time onboard processing. With an optimal design structure, FPGA can realize parallel data processing, greatly improving data processing efficiency. Comparing with general processors and DSP, FPGA dissipates less energy and has a data processing rate 10 times at least. (Choi, *et al.*, 2003; Guo, *et al.*, 2004; Wei, *et al.*, 2008). Du *et al.* proposed implementing the parallel Independent Component Analysis (pICA) algorithm on FPGA, and carried out tests on the computing platform embedded with Xilinx VIRTEX V1000E, which show that FPGA has great potential in performing complicated algorithms on large volume data sets of large data sets (Du & Qi, 2004). Miguel *et al.* proposed an FPGA-based implementation of hyperspectral image compression algorithm to greatly minimize the complexity of data processing and accomplish onboard data compression (Miguel, *et al.*, 2004). Morales *et al.* proposed an Image Space Reconstruction Algorithm (ISRA) implementing in FPGA, which is a complex and iterative algorithm, and the results show that FPGA has advantages in complex computation, but its time-consuming data access is still a main time-consuming factor of reducing processing performance (Morales, *et al.*, 2006). Surrey Satellite Technology Limited Ltd headquartered in Britain that has been committed to development of small satellites has also used FPGA to develop an onboard data processing chips (Vladimirova, 2004). Domestic scholars have also developed a variety of real-time processing techniques of high-

resolution data based on FPGA or FPGA + DSP (Wang, 2006; Fang, 2006; Xu, 2006; Jia, 2006; Yin, 2007). The current FPGA-based real-time onboard data processing algorithms mainly involves such aspects as data compression (Cook & Harsanyi, 2002; Davis, 2002), neural network (Loyola, 2002), dimension reduction (Du & Qi, 2004), endmember extraction (Valencia, *et al.*, 2005) and image space reconstruction (Morales, 2006), *etc.* FPGA has become a core onboard real-time data processing component and will play a big role in future hyperspectral remote sensing image processing and application projects. However, some current high performance real-time processing systems are still realized by “FPGA + DSP” combined structure to meet actual demands. Therefore, “FPGA + DSP” combined structure may be a transition scheme while fully digging the performance of FPGA.

However, these real-time processing algorithms are still lower-level data-preprocessing algorithms. It is still difficult to implement higher-level algorithms that are based on expert models and directly generate information desired by users. Therefore, the future intelligent remote-sensing satellites will combine data acquisition with applications, and implement application models or analysis models in satellite hardware to incorporate data processing and analysis process into the data acquisition system as a whole so as to directly extract thematic information onboard. For the natural disaster monitoring, intelligent remote sensing satellite can directly generate thematic information such as location of disaster and damage scope and level, *etc.*

3.4 Satellite maneuver control and multi-access information sending technologies

The programmable maneuver control capacity is an important feature of future intelligent satellite. As shown in the previous paragraphs of this paper, the existing ground programming technologies to realize observation missions and observation modes are relatively mature, but it is still unable to flexible downlink satellite data to users. However, an important concept of intelligent satellite is that different level users can directly receive satellite information products, similar to choosing TV channels flexibly, without complex data reception, analysis and re-distribution processes.

Therefore, the intelligent satellite system will enable ground staffs to closely interact with the satellite and its payloads. Except the adaptive observation capability of satellite, ground staffs can upload instructions of different image modes according to actual demands, and the satellite can generate different information and send them to different users on a real time or quasi real-time basis. The intelligent remote sensing satellite system can realize high-efficient seamless integration of data processors and remote sensors with flexibly adjusting imaging specification parameters, and users can conveniently acquire thematic information of interesting regions without complicated skills and special processing equipments.

End Users can be divided into different levels. Higher-level users can directly raise their customization requirements and even apply for uploading their data processing and application models, and lower-level users can only select production from standard product catalogue. The intelligent remote sensing satellite system greatly improves the effectiveness of information generation and information distribution. It will be a major innovation of existing earth observation technologies in terms of data acquisition capacity or information extraction efficiency.

4 DESIGN OF INTELLIGENT HYPERSPECTRAL SATELLITE PAYLOADS

The intelligent hyperspectral satellite imaging system with imaging mode optimization and adaptive adjustment capacity consists of a fore-field pre-judgment camera and a main camera. The former is used for cloud or aerosol identification and estimation, coarsely estimation of surface coverage and background radiometric information in imaging zones and assisting the main camera to optimize imaging modes, and the later is used for surface observations with an optimal mode.

In order to save onboard resources and facilitate integration with existing ground systems, the adaptive observation system can work in two ways (Fig. 1): (1) under the premise that targets and observation missions are known, the user can set some imaging parameters according to their own needs, the ground system will establish the initial observation mode via analysis of imaging coupling models according to the existing surface coverage information and the basic characteristics of remote sensor, and send it to the satellite for programming and acquisition of data in intended areas; (2) before reaching intended areas for data acquisition, the satellite will estimate the cloud, aerosol and background radiation via the onboard fore-field pre-judgment system and real-time processors, and then optimize observation modes such as gain adjustment, *etc.* to realize adaptive observations. The operation of the adaptive observation mode mainly involves technologies in two aspects: establishment of a ground observation mode database for determining the initial observation mode, and real-time data processing and analysis by the onboard pre-judgment system for adaptive optimal mode selection.

We should carry out analysis of the coupling model between surface parameter imaging indices characteristics and sensor specifications, integrate basic surface information into sensor imaging modes, set adjustable specification parameters for sensors through imaging modes optimization, and finally establish an observation mode database. We should set initial observation mode via fast interpolating from observation mode database according to users' requirements. The observation modes include: ordinary common user mode and expert mode. When the ordinary common user

model is selected, the system will provide best data acquisition mode. As the onboard resources are limited, when a certain specification is highlighted, other imaging specifications will be adjusted accordingly to the observation mode. For example, when the swath width demands or other special demands are set, the system will automatically determine spatial resolution, central wavelength, spectral resolution, dynamic range, signal to noise ratio, quantitative levels and other specifications. But with fixed swath width and demands, common users can reselect spatial resolution, and now the other specifications will be adjusted accordingly to maintain the best observation scheme under restriction conditions. If certain specification does not meet the relevant requirement (for example, the signal to noise ratio is too low), the system will give a warning. In the expert mode, you can randomly set imaging specifications without any restriction condition. In addition, you can also update the observation mode database of the ground system or the onboard observation mode database via satellite-ground communication to realize adaptive adjustment of satellite sensor specifications and observation modes according to ground programming requirements.

The entire transmission process of the hyperspectral intelligent observation satellite is shown in Fig. 2, including data acquisition, onboard real-time processing and information product.

The multi-spectral images in intended imaging areas acquired by the onboard fore-field camera will be directly processed with FPGA-based information processing system hardware to accomplish the cloud identification and the background identification of imaging areas. Then the results will enter into the onboard control center, or users can upload prior knowledge or imaging requirements to the onboard control center, and the onboard control center will select the best imaging mode according to these information and mode database. At last, the instructions will be sent out to the hyper-spectral main camera to acquire images with the best mode. These images will be directly processed by the FPGA-based processing chips with corresponding data processing algorithm (flood monitoring, hot spot detection and target identification, *etc.*), the processed information products will contain much lower

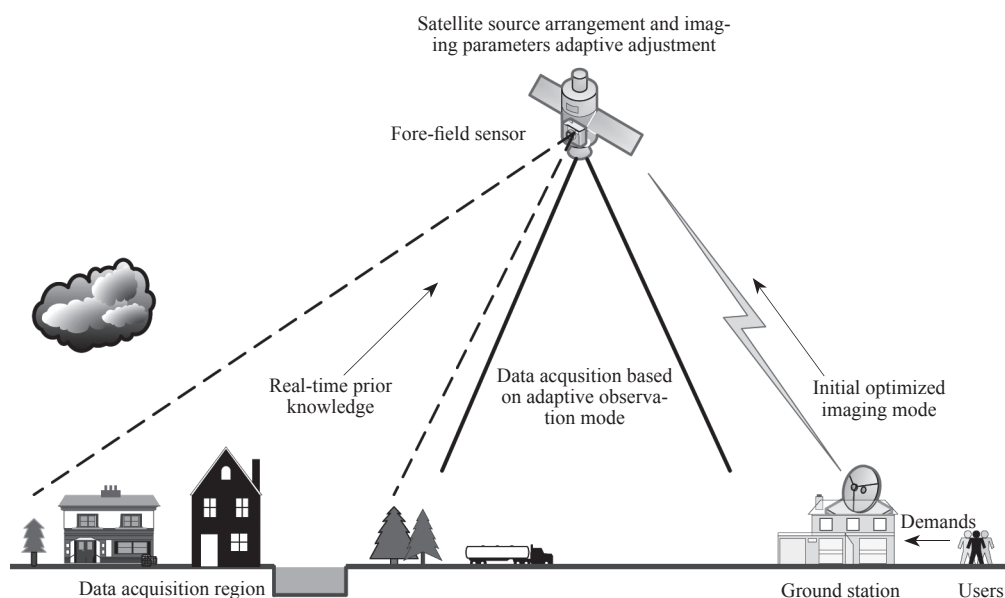


Fig. 1 Schematic diagram of adaptive observation mode

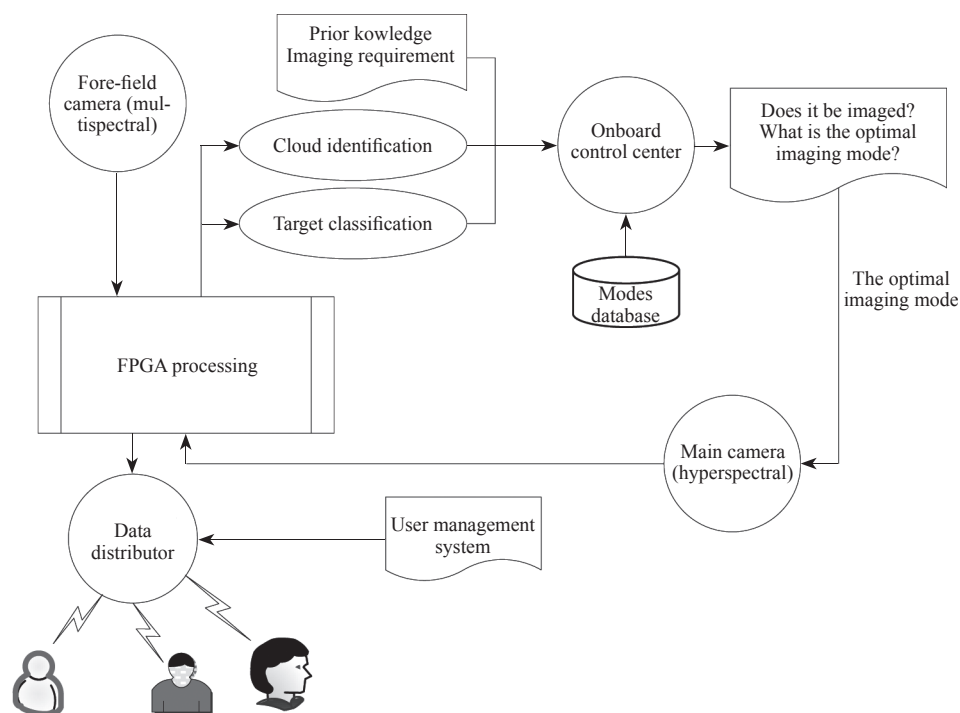


Fig. 2 The intelligent observation data processing process

amount of data, which will be finally stored onboard and downlink distributed according to different user levels and types.

The onboard real-time processing is critical to realize intelligent observation, so processors with best hardware processing efficiency and low power consumption should be selected. FPGA is consist of a large number of programmable logic units, and such hardware resources can be designed as different computing systems according to different application requirements. FPGA can implement parallel processing to improve data processing performance. FPGA has not only solved the problems of custom circuit, but also overcome the disadvantage of limited number of gate circuit of existing programmable devices, so it is a good choice in design of onboard system. Therefore, onboard real-time data processing should be implemented by FPGA, parallel process should be used in processing algorithms as much as possible. Algorithms such as geometric preprocessing, radiometric preprocessing and information extraction, *etc.* should be integrated to accomplish one-off generation of information process from raw data to information products.

5 CONCLUSION

The development of remote sensing satellite started late in China, and there is a gap between China and developed countries in innovation capacity in the aspects of satellite system design and payload specification settings. This gap shows not only in technologies but also in design idea and management system, which should be changed and innovated. The development and design of satellites and sensors should be consistent with the development of ground application in order to establish a mutual technology system. And application-oriented concepts behave in the whole process of remote sensing system design, manufacture and acceptance. In order to develop intelligent remote sensing system, firstly, we should tightly combine data processing

algorithms, application models and data simulations according to different application fields, application objects and emergency demands, which is a fundamental work. Secondly, we study corresponding technologies such as adaptive imaging mode transformation and onboard real-time data processing. Thirdly, we can also fully utilize airborne remote sensing platforms while research the satellite intelligent remote sensing systems. As we know, most of remote sensing satellite systems with innovation features have gone through airborne tests and validations. So, both of the adaptive observation technologies and real-time data processing technologies can be validated by airborne remote sensing tests.

Nowadays, some new concepts and new technologies are developing rapidly in current space remote sensing fields. Also, China has made great progress in satellite remote sensing after nearly two decades' development, which has also played an important role in various fields of national economic and social development. The continuous enhancement of national economy provides solid foundation for the development of China's remote sensing satellites. Therefore, we should carry out systematic planning of intelligent remote sensing system to promote the development of satellite remote sensing to achieve a great leap forward, and launch scientific and technological development programs as soon as possible to promote the development of frontier technologies such as space-earth integration, intelligent observation and intelligent data processing, *etc.* We should work hard on the frontier of scientific and technological innovation and development, only then will we further promote the development of satellite remote sensing to achieve a great leap forward and become one of the world's powerful countries from great countries in the field of satellite remote sensing.

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智能遥感卫星系统

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摘要: 分析了当前遥感卫星系统存在的一些不足, 论述了新一代“智能遥感卫星系统”的概念及其主要特点, 对其自适应遥感成像和星上数据实时处理两个核心部分进行重点介绍, 并对其涉及的关键科学问题和关键技术进行阐述。设计了一套具有自适应成像和应用模式优化能力的智能高光谱卫星有效载荷系统。该系统由用于区域背景信息获取的前视预判传感器、用于地表详细观测的主传感器以及星上数据实时处理和分析3部分组成。对智能高光谱卫星的工作原理和流程进行介绍, 并呼吁中国尽快围绕智能遥感卫星系统开展一些前沿性的科学理论和关键技术研究, 以实现中国在卫星遥感领域的跨越式发展。

关键词: 智能遥感卫星, 高光谱遥感自适应观测, 实时处理, 现场可编程门阵列

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1 引言

进入21世纪, 航天遥感技术在国民经济建设、人类社会可持续发展和国防建设中的作用越来越重要, 卫星遥感及其应用技术的发展日新月异, 国际上一些新型对地观测卫星不断涌现, 以应用为导向、天地一体化的理念在遥感卫星系统的设计和制造中得到越来越充分的体现。卫星遥感在努力追求更高空间分辨率、光谱分辨率和时间分辨率的同时, 一些数据获取能力很强、应用更具针对性的遥感小卫星也迅猛发展, 这些都标志着人类即将迎来遥感数据“爆炸”的时代。在这种形势下, 确实需要认真思索卫星遥感未来的发展方向, 以解决目前已经开始逐渐显现出的一些紧迫问题, 主要体现在以下3个方面:

第一, 遥感卫星数据获取能力越来越强、数据量越来越大, 给卫星下行数传和后处理带来巨大压力。遥感卫星空间分辨率、光谱分辨率和扫描幅宽等成像性能的不断提高, 也使得卫星数据量以几何级数递增。例如, 美国NASA每天要接收超过3.5 tb的观测数

据(Ramapriyan 等, 2004), 而真正最终使用的仅是其中很小的一部分。再以中国的情况为例, 中国科学院对地观测中心的密云遥感卫星接收站2008年共接收各类遥感卫星数据36.91万景, 但只有1.36万景被用户订购, 订购量仅占接收量的3.7%。数据获取量和实际使用量之间存在巨大反差, 数据使用效率比较低。而且, 这些庞大的原始数据也给卫星数据的下传和地面处理设备带来巨大负荷。但另一方面我们非常缺乏精度更高、更符合定量化专业应用要求的数据。

第二, 地面环境背景与观测目标复杂多样, 即使同类型地物的遥感特性也随季节不同而变换。但卫星载荷研制发射后其指标就基本一成不变, 如Landsat/TM、SPOT、MODIS、EO-1等卫星, 以及中国的CBERS、HJ-1A、HJ-1B等卫星在轨运行期间具有固定的观测与成像模式, 传感器成像谱段、空间分辨率、光谱分辨率、辐射分辨率和光谱响应等设置都是预先设计并固定不变的。国土资源调查、自然灾害监测、生态环境保护 and 军事侦察等对卫星数据需求各不相同, 现有主要遥感卫星无法根据观

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测对象、观测任务和观测区域环境的不同,依据需求和研究目标的不同对载荷参数指标做出适时优化和具针对性的调整。

第三,数据处理自动化程度低,信息提取的时效性较差。传统的“卫星数据获取—地面站接收处理—数据分发—专业应用”的模式无法满足未来高机动性、高应急性灾害应急监测和某些军事应用的时效性要求,需要将数据快速转换为信息并实时或准实时地发送到不同层次最终用户手里。目前,遥感卫星数据获取能力不断增强,空间分辨率从公里级到几十米甚至亚米级(如Quickbird, Geoeye);光谱分辨率从上百纳米提高到纳米级(如HYPERION, CHRIS, ARTEMIS)。相对不断增强的卫星数据获取能力,数据自动化处理水平还相对较低:从数据获取到信息提取再到应用产品过程中人工干预较多,一些信息提取等遥感应用工作还主要以人工目视解译为主,信息服务难以保障时效性。实际上,人们对于卫星产品的需求已经从图像本身转向越来越多样化的专题信息,普通用户并不关注图像处理复杂的技术和细节,卫星实时处理并下传专业应用产品已成为未来卫星设计的核心理念之一(Tomar和Verma, 2007)。

综上所述,传统的卫星遥感技术已经难以适应快速、准确、灵活的遥感数据获取和信息产品生产需求,需要构建具有工作成像模式优化、信息快速生产和发送能力的智能遥感卫星系统。将遥感卫星系统设计和地面信息处理技术发展统筹考虑,这是当前面向高空间、高光谱、高辐射分辨率地球观测卫星技术发展的一个重要前沿方向。

本文首先分析智能遥感卫星系统的发展现状和特点,然后提出新一代“智能遥感卫星系统”,对其关键技术、系统设计等方面进行详细阐述。

2 智能遥感卫星系统发展现状

从20世纪末开始,国内外学者就智能遥感卫星问题展开了不同层次的讨论。高光谱遥感是当今遥感技术发展的前沿(童庆禧, 2003),由于高光谱卫星的海量数据获取特点,适宜于自动处理的优点,以及快速信息提取的迫切需求,高光谱遥感卫星的智能化一直是智能遥感卫星系统发展的主流。在美国有关实验室的高光谱遥感技术计划(Hyperspectral Remote Sensing Technology Program, HRST)中,采

用实时自适应光谱识别系统(Optical Real-time Adaptive Spectral Identification System, ORASIS)进行星上数据实时处理和压缩,大大降低了高光谱数据的时空冗余度(Wilson和Davis, 1998),这一系统原计划装载到美国NEMO卫星上,用于技术论证高光谱遥感对海岸带和浅海环境调查的可行性(Davis, 2000a)。在美国NASA的有关报告中也对未来智能遥感卫星系统发展进行了展望,认为该系统由多种成像模式的传感器、星上数据处理和强大的数据通信系统组成,能够为多种用户提供高时效性的全球空间信息服务(Zhou G, 2001)。该报告明确指出了未来智能遥感卫星以用户需求为驱动的理念,但该报告对这些技术的实现没有展开详细论述。另外, NASA也开展了相关的航空科学试验,将多种传感器、导航定位设备和地面科研活动有机结合形成自动运行的传感器网络,按照用户需求或者突发事件的优先级综合利用多种卫星传感器,如结合高时间频率MODIS数据和高光谱HYPERION数据进行智能化对地观测(Chien S等, 2005)等。李德仁院士和沈欣(2005)认为智能对地观测卫星系统应采用多层卫星网络结构,按照星座形式组成传感器网络协同工作,为全球各类用户实时提供对地观测数据和满足各个领域应用需求的信息。

一些航天遥感大国近年来十分注重星上数据实时处理技术发展,已经开始研制开发一些具有某些智能特征的卫星,如美国海军的NEMO卫星、德国宇航局的BIRD小卫星、欧洲的COCONUDS系统、欧空局的PROBA卫星等。相对于传统对地观测卫星,这些卫星系统普遍具有如下特点:

(1) 功能专用

智能卫星不以数据获取量为主要目的,而是针对某些专业应用、根据特殊需求而设计。美国NEMO卫星搭载的超光谱成像仪和5 m分辨率的全色相机,主要用于海岸带环境快速分析,提取地表反射率、海面遥感反射率、水体混浊度、叶绿素、CDOM、悬浮物、水深、水底反射率等(Wilson和Davis, 1999);国际空间站上FOCUS平台用于自动火点探测, FOCUS综合利用前视相机、高空间分辨率相机和Fourier红外成像光谱仪实现潜在火点探测、太阳耀斑或云去除、暖地表去除、热点聚类等功能;德国宇航局的BIRD卫星主要用于森林大火、火山爆发、油田和煤矿着火等热异常探测与评估(Winfried, 2001)。另外,洪涝灾害自动化监测也是未来智能卫星设计的方向之一

(Yuhaniz 等, 2007)。

(2) 成像模式可变

欧空局发射的PROBA小卫星搭载的紧凑型高分辨率成像光谱仪 (Compact High Resolution Imaging Spectrometer, CHRIS)可在2.5分钟之内获取5个角度的高光谱图像(-55°、-36°、0°、36°、55°),并能根据水体、植被和陆地等不同观测目标和应用需求,实现5种不同空间和光谱分辨率成像模式的转换(Barbara和Ruddick, 2004)。它可以在411—997 nm波段获取62个波段、34 m空间分辨率图像,也可以针对水质遥感的需要,将成像模式转变为在411—1019 nm波段获取18个波段、17 m空间分辨率的高光谱图像。

(3) 星上数据实时处理

星上数据实时处理是智能卫星最突出的特点之一,处理后的信息产品数据量大大减少,在减小数据传输压力的同时也使得遥感信息能够直接被终端用户接收。美国NEMO卫星的高光谱数据处理采用自适应光谱识别系统ORASIS,其数据处理采用凸面集分析和正交投影变换技术,对特定场景分解生成10—20个端元,实现自动数据分析、特征提取和数据压缩(Davis, 1997)。BIRD卫星在轨数据处理能力包括辐射校正、几何校正以及灾害预警和监测专题信息生产等(Winfried, 2001)。法国研制的下一代Pleiades卫星采用了可重构的现场可编程门阵列(Field Programmable Gate Arrays, FPGA)作为模块化的星上图像处理器(Module Video Processor, MVP),实现数据采集、像元对齐、热控、电控等功能,实时处理采用高性能小波图像压缩算法,压缩比高达7:1(Arnaud 等, 2006)。

(4) 数据实时下传

欧洲COCONUDS(Co-ordinated Constellation of User Defined Satellites)星座由10个极轨卫星组成,用于环境监测,星上不存储数据,实现数据实时下传(Verduijn 等, 2001);法国的Pleiades卫星数据经过压缩后以高达4.5 Gbit/s的速度下传(Arnaud 等, 2006)。

除上述具有星上实时处理性能的智能遥感卫星外,目前已经成功发射或者未来规划中的某些商业卫星也具有更多智能化特点。例如, Digital Globe公司在2007年9月发射了具有0.5 m分辨率的WorldView-1 全色影像卫星,具备极佳的快速响应能力,可根据需求对同一目标进行多达24次的连续多角度观测。随后发射的WorldView-2具备8个多光谱波段和1个全色波段,依靠其强大的姿态控制陀螺(CMGs)可根据

需求灵活实现宽覆盖(多次来回扫描65.6 km)、长条带(16.4 km)或立体观测(幅宽48 km)成像方式,极大提高高分辨率卫星数据采集效率。SPOT公司计划于2012年以后发射的SPOT 6和SPOT 7卫星在数据获取方面也具有更大的灵活性,结合长期和短期的天气预报,减少阴雨天气情况无效数据的获取,优化了数据采集过程(Campenon, 2009)。

总体来看,随着计算机、通信、光学器件等硬件技术的飞速发展和星上数据实时处理算法的深入研究,以应用需求为牵引进行智能遥感卫星系统研制具有重要意义,可以实现从现有遥感卫星“给什么要什么”的模式向“要什么给什么”的模式转变,提高遥感成像效率和数据利用效率。

3 智能高光谱遥感卫星系统及其关键技术

高光谱遥感数据包含地物丰富的空间、辐射和光谱信息,特别是提供反映地物特性的光谱曲线,从而极大扩展了遥感的应用,推进了遥感技术从“定性分析”到“定量反演”的发展,而且为新理论新方法的引进创造了更加广阔的发展空间。但是,高光谱遥感数据因其自身数据量大、波段多等特点,在开辟遥感应用新道路的同时,也带来诸如引言所论述的3个方面问题,而且这些问题显得尤为突出。

以地物分类、目标探测和应急监测为应用重点,需要将遥感卫星系统设计和地面信息处理技术发展统筹考虑。对高光谱图像进行地物分类与识别应用时,常常是先进行波段选择或者特征提取,对于其他波段则完全不采用,这种做法导致部分应用中大量无效数据的存储。而且,毫无选择的全波段设置会导致非理想化的光谱响应范围、空间分辨率和波段信噪比。因此,如果能从数据源出发,根据不同地物的波谱特性有针对性地提供具有更为明确物理意义和特征的谱段数据将能极大提高特定目标探测效能和地表参数反演精度。

研发新一代智能高光谱遥感卫星系统首先要解决两个方面的科学问题。

一个方面是高光谱传感器指标互斥条件下的地物遥感最佳观测指标优化理论。地物的高精度、高效率遥感对成像传感器的光谱分辨率、空间分辨率、辐射分辨率、时相分辨率等有很高要求,但传感器的上述

性能指标互斥且相关联。因此需要在地物波谱特性和信息反演模型研究基础上,研究地表参数反演模型对遥感器核心指标的敏感性。研究遥感器的指标(信噪比、空间分辨率、光谱分辨率等)取舍原则和方法,建立遥感器指标互斥模型,将地表参数反演模型与光谱成像模型相结合,研究并建立高光谱遥感器指标互斥条件下的地表参数最佳观测指标。

另一个方面是先验知识与模型支持下的遥感自适应观测理论。遥感数据利用效率低的一个重要原因是目前遥感器基本是用同一固定模式获取复杂多样的地表数据,没有考虑到特定地表环境及地物遥感特性的差异。同时,遥感数据受到光照、大气条件等干扰,遥感器实时探测地表类型还存在较大困难,观测模式的实时优化还存在巨大挑战。因此,需要研究如何利用多模式和可变模式探测云、气溶胶光学厚度以及辐射动态范围等实时先验信息,研究地表类型、云/气溶胶和地表参数模型等先验知识的数据表达与建模方法,并与自适应观测理论相结合,以实现地表参数高光谱观测模式的实时优化。

另外,星上数据实时处理涉及快速并行算法、数据压缩、数据分发和传输等核心技术问题。在算法研究基础上,将特定数据处理与应用模型进行硬件固化,实现星上数据实时处理和应急应用产品生产,并可针对不同用户需求进行数据和信息的直接下传服务。借助于星上数据实时处理系统,信息产品可以在轨生产并直接分发给不同类型的终端用户,就像现在的GPS数据能够被广大普通百姓接收一样。遥感信息服务的GPS化也将通过智能遥感卫星系统的发展得以实现,这必将大大扩展遥感应用的范围,提高遥感数据的使用效率。

智能高光谱遥感卫星系统涉及的主要关键技术如下:

3.1 遥感器工作模式优化技术

目前,卫星遥感器参数设置主要是根据观测目标基本特征,如:Landsat/TM系列卫星主要用于探测陆地资源,分别设置了从可见光到短波红外的6个波段和1个热红外波段,能够用于植被、土壤、水体、矿产、地表温度等多方面的监测,是陆地资源卫星载荷指标设计的经典案例;另外,SPOT卫星在仿照Landsat卫星载荷设计的同时,还增加了立体测图能力,并提高了空间分辨率;还有Terra & Aqua卫星上装载

的MODIS传感器是目前在轨运行的任务最为多样的遥感器,光谱分辨率、空间分辨率和辐射性能参数根据不同目标监测需求进行设置,应用范围涉及陆地、海洋和大气等。

随着硬件技术发展,传感器工作模式和参数设置不断得到优化。尽管如此,这些参数设置仍然不够精细和灵活,载荷的光谱、空间、辐射性能参数论证基于一定环境和成像条件,尚未完全考虑不同环境背景条件下成像数据对于信息提取的有效性,为后期数据分析和信息提取带来一定困难。如MODIS设置的海洋水色8—16波段,在高悬浮泥沙沿海或者气溶胶光学厚度较大的内陆水体区域往往饱和而无法使用(张浩,2009)。一旦传感器工作模式确定后,相应的载荷指标在卫星运行期间无法改变。因此,智能遥感系统首先需要研究遥感器工作模式优化技术,以光学信息获取能力最强的高光谱遥感卫星为例,研究不同背景环境、不同目标的最佳遥感器载荷参数,建立目标遥感特性数据库,为载荷指标动态调整提供科学依据。

实现遥感器工作模式优化,需要从监测和信息提取目的出发,在多种星载、机载遥感平台和地面调查、光谱采样等数据获取手段支持下,考虑季节、地域和环境变化带来的光谱、辐射及空间指标的优化配制问题,综合分析实现监测目的所需设置的最佳遥感器载荷参数,最终建立多种背景环境下目标特性数据库和遥感器载荷参数数据库,包括:中心波长、光谱分辨率、辐射响应、信噪比、探测灵敏度、空间分辨率、调制传递函数和扫描幅宽等。

3.2 遥感器参数自适应调节技术

通过地面控制编程实现卫星观测任务的技术已日趋成熟,如北京1号卫星(BJ-1)、环境与减灾卫星(HJ-1)、SPOT卫星,可根据观测计划实现卫星侧摆获取数据,但这些卫星不能更改传感器光谱、辐射、空间指标。欧空局2001年发射的PROBA卫星源于欧空局对新的星上技术和星上自治优点的示范构思,它实现了在极少地面人为干预的情况下运行大量的任务操作函数。该卫星搭载的智能型CHRIS传感器,可根据应用目的通过预先编程方式调整不同成像模式。分别实现不同的陆地、植被和水体等方面应用监测,光谱波段数从18—62、空间分辨率从17—34 m可调,而且光谱波段可实现有选择的设置(Barnsley等,2004;Cutter,2002)。

因此, 在实现传感器参数自适应调节时需要综合考虑应用目标和卫星载荷的性能, 依据任务需求和目标对象不同, 通过优化配置探测系统指标参数实现面向不同环境背景和应用需求的数据自适应和最优化获取。未来智能遥感卫星必将具有光谱分辨率、空间分辨率、中心波长、辐射分辨率、辐射增益可调/可选的探测能力, 提高数据获取、处理和信息提取效率。

3.3 星上数据实时处理与信息快速生成技术

星上数据实时处理技术随着信号处理硬件技术发展而发展, 目前某些处理算法日趋成熟。NEMO卫星搭载的海岸带海洋成像光谱仪(Coastal Ocean Imaging Spectrometer, COIS)用于探测海岸带与浅海环境, 利用实时自适应光谱识别系统完成光谱维和空间维滤波, 实现有关情报信息的直接下传(Wilson和Davis, 1999; Davis等, 2000b)。德国空间中心(DLR)针对BIRD搭载的红外探测器基于专题神经网络分类器实现火灾的准实时快速灾害监测和预警。美国2009年发射的TacSat-3卫星搭载了ARTEMIS高光谱仪, 该卫星系统可通过星上数据光谱处理进行异常探测, 将不同地物目标从自然背景中自动区分出来。很多学者提出, 采用FPGA(Field Programmable Gate Array)作为星上实时处理的核心组件, 因为FPGA良好的设计结构, 能够实现数据并行处理, 极大提高数据处理效率, 比通用处理器和DSP系统节省能耗, 处理速度至少可提高10倍以上(Choi等, 2003; Guo等, 2004; 韦宏卫等, 2008)。Du和Qi(2004)提出采用FPGA实现了并行独立成分分析算法(parallel Independent Component Analysis, pICA), 并在以Xilinx VIRTEX V1000E为核心的运算平台上进行试验, 显示出FPGA实现大数据集复杂运算的巨大潜力。Miguel等(2004)提出了一种基于FPGA实现的高光谱图像压缩算法, 最大程度上减少数据处理复杂度, 完成星上数据压缩。Morales等(2006)提出采用FPGA实现较为复杂、包含迭代过程的图像空间重建算法(Image Space Reconstruction Algorithm, ISRA), 结果表明FPGA在实现复杂计算方面具有较大优势, 但数据存取耗时仍然是降低处理性能的主要因素。一直致力于小卫星研制的英国萨瑞公司也采用FPGA来实现星上数据处理芯片(Vladimirova, 2004)。国内学者利用FPGA

方式或者FPGA结合DSP方式研究了各种高分辨率数据实时处理技术(王海涛, 2006; 房鹤, 2006; 徐欣锋, 2006; 贾友华, 2006; 尹乐, 2007), 目前基于FPGA的星上实时处理算法主要涉及数据压缩(Cook和Harsanyi, 2002; Davis, 2002)、神经网络(Loyola, 2002)、降维(Du和Qi, 2004)、端元提取(Valencia等, 2005)、图像空间重建(Morales等, 2006)等方面。FPGA已经成为星上数据实时处理核心实现组件, 将在未来海量高光谱遥感图像处理与应用工程中发挥越来越大的作用。但是, 目前某些高性能实时处理系统仍然需要通过FPGA和DSP的组合结构来满足实际需求。所以, 在充分挖掘FPGA自身性能的同时, 考虑其和DSP组合结构也是一种过渡解决方案。

然而, 这些实时处理算法仍然主要集中在数据预处理相关的低端算法, 实现基于专业模型直接生成用户可用的信息产品的高端算法仍存在较大困难。因此, 未来智能遥感卫星将卫星数据的获取和应用结合在一起, 将应用分析模块固化到卫星上, 使得数据处理和分析与有效载荷数据获取系统连为一体, 数据获取后可在星上直接处理提取专题信息。在自然灾害应急监测中, 智能遥感卫星能够直接生成受灾位置、受灾范围、受灾程度的专题信息。

3.4 卫星机动控制与信息多路发送技术

可编程的机动控制能力是未来智能卫星的重要特点之一。目前, 在地面编程实现观测任务和观测模式方面技术已经比较成熟, 但卫星数据仍然无法机动灵活地直接传送给用户, 而智能遥感卫星的一个重要理念就是不同层次用户可以直接接收不同层次的信息产品, 类似选择电视频道一样自由灵活, 无需复杂的数据接收、分析和再次分发过程。

因此, 智能卫星系统将实现地面人员和卫星及其载荷状态的密切互动, 除了卫星本身的自适应观测能力外, 地面人员可以根据不同需要上传不同观测模式指令, 卫星可实时或准实时将专题信息分发给不同需求用户。智能遥感卫星系统实现了参数灵活可调的传感器与数据处理器的高效无缝集成, 用户无需复杂的专业技能和携带专门的处理设备, 就可以通过终端设备, 方便地获得所关心区域的专题信息。

用户可分为不同级别, 高级别用户可以对成像模式设置直接提出定制要求, 甚至申请上传数据处理和

应用模型。低级别用户只能对标准产品目录提出选择要求。智能遥感卫星系统大大提高了信息产品生成和分发的时效性。无论从数据获取能力还是从信息提取效率方面,都是对现有对地观测系统的一次重大创新。

4 智能高光谱卫星有效载荷系统设计

具有工作模式优化和自适应调节的智能高光谱卫星成像系统包括前视预判相机和主相机,前者用于云、气溶胶的识别和估算,以及成像区域地表覆盖与背景辐射信息的初步估算,辅助于主相机的成像模式优化选择;后者用于以最优模式对地表进行光谱成像观测。

为了节省星上资源和便于与现有地面系统集成,自适应观测系统可以按照两种方式工作(图1):一种是在已知目标和观测任务前提下,用户可以根据需求设置部分成像参数,地面系统将依据已有的地表覆盖信息和传感器基本特性,通过成像耦合模型分析,制定初始观测模式,并发送至卫星用于预定区域数据的编程获取;另一种是卫星在到达预定区域进行数据获取前,通过星上前视预判系统和实时处理器进行区域云、气溶胶和地面背景辐射的估算,然后卫星将包括增益调整在内的观测模式优化,实现自适应观测。自适应观测模式运行主要涉及两方面的技术:一方面是地面观测模式库建设,用于确定初始观测模式,另一

方面是星上预判系统获取数据的实时处理与分析,用于自适应优化模式选择。

研究地表参数成像指标和传感器指标耦合模型,集成地表基础信息,通过优化组合设定可用于传感器指标调整的参数,建立观测模式数据库。通过传感器观测模式查找表,依据用户需求快速内插计算,完成初始观测模式的设定。观测模式包括普通用户模式和专家模式两种。普通用户模式运行时,系统提供最优的数据获取模式。由于卫星星上资源有限,当侧重于某一指标时,其余指标会依据模型做相应调整,如设定幅宽和专业需求,系统会自动确定空间分辨率、中心波长、光谱分辨率、动态范围、信噪比和量化级数等,但普通用户在固定幅宽和需求的条件下,可以再选择空间分辨率,这时其他指标参数再做相应调整,保持约束条件限制下的最优观测方案。如果某项指标不满足需求,如信噪比过低,系统会给予警告。专家模式可以随意设置观测模式,不受条件约束,此外,专家也可以通过星-地通信更新地面系统或星上的观测模式数据库,依据地面编程要求实现卫星指标参数和观测模式自适应观测。

根据本文设计的智能高光谱遥感卫星,整个数据获取—星上实时处理—产品信息下传的过程(图2)。

卫星首先由前视相机获取预成像区域的多光谱图像,直接交与由FPGA构成的信息处理系统硬件进行处理,完成云识别和成像区域背景判别,结果进入星上控制系统,也可以由用户上传先验知识或者成像需

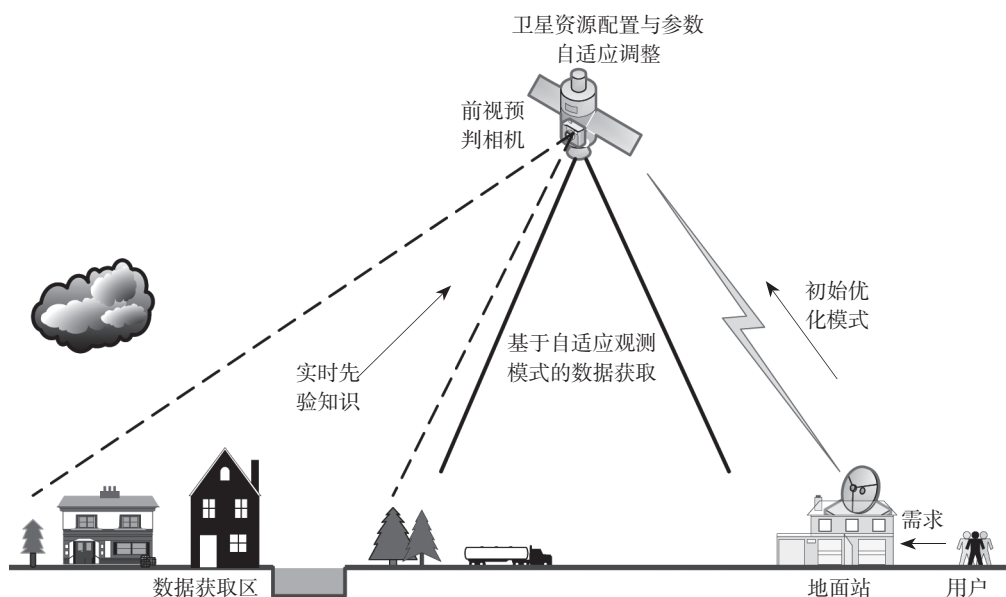


图1 自适应观测模式示意图

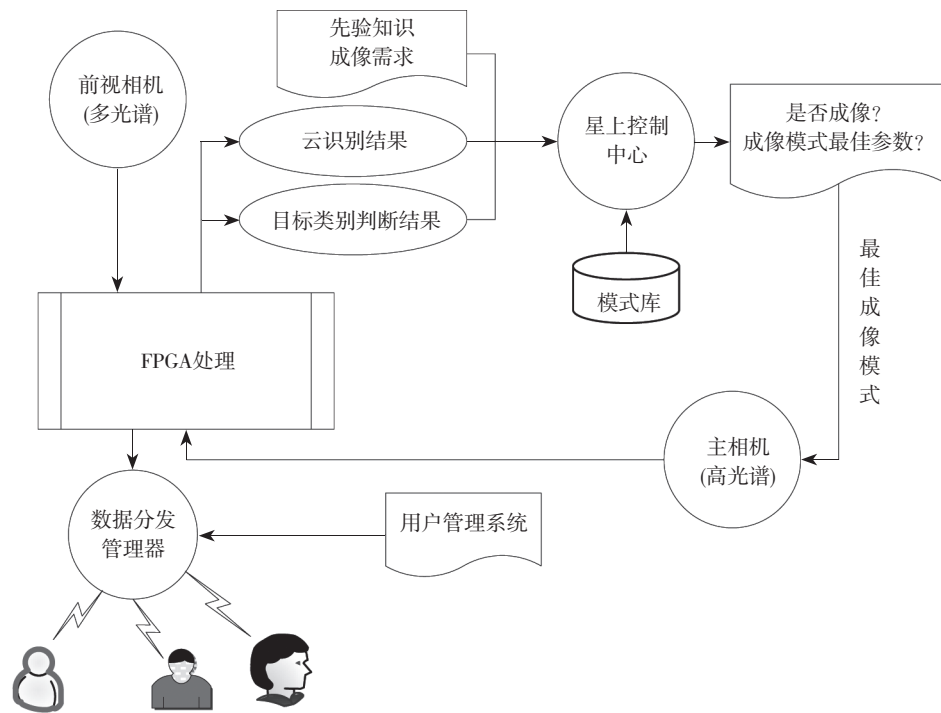


图2 智能观测数据处理过程

求到星上控制系统，星上控制系统根据这些信息，在模式库支持下进行最佳成像模式选择，并发出指令到高光谱主相机按照最佳模式获取图像。这些图像直接进入由固化相应处理算法(洪水监测、火点监测、目标识别等)的FPGA构成的处理芯片，处理后的专题产品信息大大降低数据量，然后利用用户管理系统，按照用户级别和类别不同，对各类信息产品分别进行星上存储和下发。

星上实时处理是实现智能观测的重要组成部分，在硬件处理效率、功耗方面必须选择最优器件。FPGA是由大量的可编程逻辑单元组成的，这些硬件资源可以根据不同的应用需求设计成不同的计算系统，并且能够实现并行处理来提高系统处理性能。FPGA既解决了定制电路的不足，又克服了原有可编程器件门电路数有限的缺点，是星上系统设计中优选方案之一。因此，星上实时数据处理由FPGA进行实现，处理算法尽量采用并行过程，将几何预处理、辐射预处理和信息提取等后端算法进行集成，一次性完成从原始数据到信息产品的生产。

5 结 论

中国卫星遥感事业起步较晚，在卫星系统设计

和载荷指标设置方面的创新能力一直不足，与西方先进国家仍有一定差距。这种差距不仅仅体现在技术方面，在思想观念和管理体制方面也存在差距，有必要同时进行这些方面的变革和创新。卫星及传感器研发要与地面应用一体化统筹考虑，共建一个相互融合的技术系统，以应用为导向要体现在遥感卫星系统设计、制造到验收的全过程。因此，对于发展智能遥感卫星系统来说，一方面要针对不同的应用类型、不同应用对象、不同应急要求，将数据处理算法和应用模型与遥感数据模拟紧密结合，建立遥感模式库，这是一个基础性的工作。在此基础上，研究相应的自适应成像模式变换以及星上实时处理等技术。另一方面，在开展星载智能遥感成像研究的同时，要充分利用航空遥感实验平台。国际上一些具有创新意义的卫星遥感系统大部分都经历了航空遥感实验和验证阶段。无论是自适应观测技术还是实时数据处理技术均可以通过航空遥感实验进行技术可行性论证。

当前国际空间遥感领域新观念、新技术飞速发展。中国卫星遥感技术经过20多年的发展也已经取得长足进步，在国民经济建设和社会发展的各个领域发挥着重要作用。国家经济实力的不断增强也为中国遥感卫星事业的发展奠定了坚实的物质基础。因此，在发展智能遥感卫星系统方面需要系统规划，尽早开展

一些涉及天地一体化总体技术、智能观测与智能数据处理技术的前沿性科技攻关, 促进中国卫星遥感跨越式发展。

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