Research on key technologies of space-based surface anomaly instant detection system

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ABSTRACT

The existing space-based remote sensing has problems such as weak collaboration, slow response, and long links, which cannot meet the application requirements of real-time anomaly detection, recognition, and transmission. This article studies the characteristics of existing surface anomaly classification, establishes a demand matrix for anomaly remote sensing, establishes a new surface anomaly real-time detection system, and proposes a working mode for anomaly real-time recognition, Using the constellation system task and information flow design combined with the on-board intelligent processing unit, improve the anomaly recognition and service capability of the space-based system, design the mission flow and information flow of the constellation system, and finally analyze the communication link and timeliness of the system. The simulation analysis results show that the system can achieve minute level efficient anomaly recognition and early warning, effectively improving the service capability to users, this provides an overall idea and architectural reference for the construction of future space-based surface anomaly real-time detection systems.

Keywords: Space-based remote sensing, Surface anomalies, Instant detection, Constellation System

1. INTRODUCTION

In recent years, various sudden surface anomalies (such as natural disasters, environmental pollution, ecological damage, safety accidents, illegal development, etc.) caused by natural and human factors in China have occurred frequently, and have shown the characteristics of wide distribution, high occurrence frequency, fast evolution speed, large impact range, and heavy economic losses. They have caused serious losses to people's lives and property, and also had a huge impact on the production and life of the entire society. Especially with global climate change and rapid economic development, the connotation and extension of surface anomalies continue to deepen and expand. Various surface anomalies are intertwined and stacked with each other, making local surfaces more fragile and sensitive. The various risks that may arise further intensify, and the constraints on the healthy and sustainable development of China's economy and society become more apparent. Therefore, the occurrence of various surface anomalies Timely monitoring and early warning of the development process has become a top priority in ensuring social security and stability, high-quality economic development, and ecological civilization construction in China's new development stage[1].

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The surface anomaly situation awareness is mainly combined by manual patrol inspection, sensors for monitoring and early warning, micro motion monitoring technology, 3D Digital Photogrammetry technology, 3D laser scanning technology, active/passive remote sensing technology and other ways. It is mainly concentrated on the surface anomaly changes or disasters, inevitably wasting a lot of human and financial resources, and the current situation of frequent geological disasters is difficult to effectively solve[2]. Satellite remote sensing has the characteristics of large detection range, continuous space, rich information, and good dynamism, making it the most effective method for detecting large-scale surface anomalies[3-4]. However, due to the suddenness, diversity, randomness, concealment, and complexity of the surface anomalies we are concerned about, a large number of surface anomalies are often not detected in the actual detection process, especially if they are not detected and warned in the first place. The time efficiency and accuracy of satellite detection are far from meeting the needs of emergency rescue, accident handling, pollution control[5-6]. The need for real-time remote sensing services characterized by minute level response, such as supervision and law enforcement. The existing space-based remote sensing capabilities are also limited to data acquisition and preprocessing. From remote sensing features to the remote sensing knowledge information that users need, a series of lengthy links such as on-board data acquisition and preprocessing, satellite to ground data transmission, ground data processing, and data distribution need to reach users, making it difficult to meet the remote sensing needs of sudden anomalies[7]. Therefore, it is urgent to vigorously develop real-time and intelligent research and application of remote sensing detection of surface anomalies, By instantly discovering, identifying, and transmitting anomalies, traditional data remote sensing information can be transformed into new knowledge remote sensing information, enabling users to have "what they see is what they get" for abnormal remote sensing information, thus gaining the initiative in emergency response to surface anomaly events, effectively alleviating the investment of a large amount of human and material resources, and improving the coverage of surface anomaly monitoring, the timeliness, scientificity, and effectiveness of disaster rescue.

Based on the analysis of surface anomaly classification and remote sensing features, this article proposes the use of distributed constellation to solve the problems of detection coverage and response efficiency in surface anomaly detection. The working mode of the satellite cluster system is studied, and the characteristics of system coverage efficiency and information transmission timeliness are analyzed. Several key issues in establishing a real-time detection system for surface anomalies are summarized, and solutions and ideas are proposed, this provides a reference for future space-based detection of surface anomalies.

2. ARCHITECTURE OF SPACE-BASED SURFACE INSTANT DETECTION SYSTEM

2.1 Classification and recognition of surface anomalies

There are many types of known surface anomalies, including acute and destructive disasters such as natural disasters and human accidents, as well as hundreds of chronic and large-scale events such as environmental pollution and ecological damage[8]. The remote sensing characteristics of these anomalies are summarized and summarized, and surface anomalies are divided into typical categories, including water environment anomalies, land environment anomalies, atmospheric environment anomalies, etc[9]. Establishing a threshold lookup table for surface anomaly remote sensing elements. The remote sensing elements of relevant ground features include but are not limited to radiation features, spectral features, geometric features, texture features, scattering features, etc. Each ground feature can be quantitatively described through the above remote sensing elements. According to the correlation degree of various anomalies and corresponding features, it is divided into strong anomalies (single element recognition) and weak anomalies (multi element recognition), as shown in Table 1.

Table 1. Margins and print area specifications.

Surface anomaly categories	**Surface anomaly subclass**	**Related abnormal features**	**Is it strongly abnormal**
Water environmental anomalies	Oil spilling	Scattering, spectroscopy	No
	Algae floating plants	Spectroscopy	Yes
	Blowdown causes an increase in water temperature	Temperature	Yes
	……	……	……

Terrestrial environmental anomalies	Damage to bridges, railways	Geometry, Spectrum	No
	Building damage	Geometry, Spectrum	No
	Vegetation diseases and pests	Texture, Spectrum	No
	……	……	……
Atmospheric environmental anomalies	Air pollution	Spectrum	Yes
	Building fire	Temperature, Geometry	No
	……	……	……

By using image background target threshold segmentation and edge detection to preliminarily determine suspected surface anomaly areas, an index response model is used to establish a remote sensing element threshold lookup table corresponding to remote sensing response characteristics[10]. Based on prior remote sensing information, the threshold range corresponding to the normal remote sensing feature index of ground features is determined. After the remote sensing element threshold exceeds the normal range, it can be determined that an anomaly has occurred, the surface anomaly is roughly identified through the threshold range of the multi feature index, and further refined identification is carried out in combination with geometric and structural features to identify the specific type and severity level of the anomaly. The satellite system will transform the responsive remote sensing information into more advanced Semantic information, which will reach users through multiple communication links.

2.2 Architecture of surface anomaly detection system

The constellation for real-time detection of surface anomalies uses a distributed satellite system architecture, where multiple satellites are distributed to form virtual satellites through inter satellite tasks and information interconnection. The ground remote sensing information processing center is retained to configure the remote sensing cloud computing layer, achieving continuous iterative updates of anomaly remote sensing thresholds and exponential feature models; At the same time, on the basis of traditional distributed satellite information and information interconnection and collaborative control, space based edge computing is used to realize inter satellite collaborative hierarchical anomaly recognition[11], and emergency ground anomaly information is quickly transmitted to users. In the real-time detection system, satellites are used as the endpoints of system information acquisition, and distributed constellation are used as the basic functional units of anomaly recognition, Establish a distributed satellite cluster fog computing layer, utilizing the advantages of fog computing to solve the problems of high transmission delay of remote sensing information and untimely acquisition of abnormal information; The traditional ground station downlink and uplink functions are retained on the information transmission link, while adding a space-based communication system that utilizes relay satellites and Beidou short messages to achieve the transmission of abnormal information slicing and emergency abnormal semantic short messages, shortening the transmission path of emergency abnormal information, as shown in Figure 1.

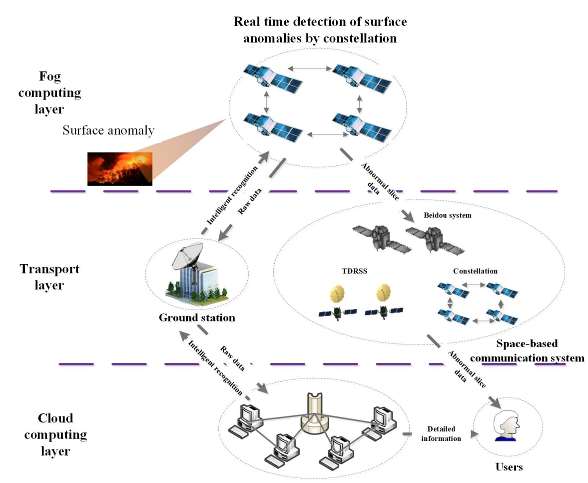

Figure 1. Architecture of real-time detection constellation system for surface anomalies

3. RESEARCH ON THE WORKING MODE OF THE REAL-TIME DETECTION SYSTEM FOR SPACE-BASED SURFACE ANOMALIES

The task of remote sensing of surface anomalies has the characteristics of uncertain observation areas and complex observation elements[12]. It requires satellites to observe the Earth for a long time[13], traverse the surface environment, independently discover and identify anomalies, and transmit anomaly information.

The working mode adopts the satellite cluster integration mode, and the working mode of census and detailed survey is adopted for multiple satellites in each small satellite cluster. The task planning model is closely integrated with the on orbit intelligent processing algorithm based on the remote sensing response feature threshold. The remote sensing task of surface anomaly needs to decompose the anomaly remote sensing task according to whether it is a strong feature according to the anomaly type obtained by the census satellite, and the subsequent detailed survey satellites further identify the anomaly to form Semantic information, it can be directly distributed to users, as shown in Figure 2.

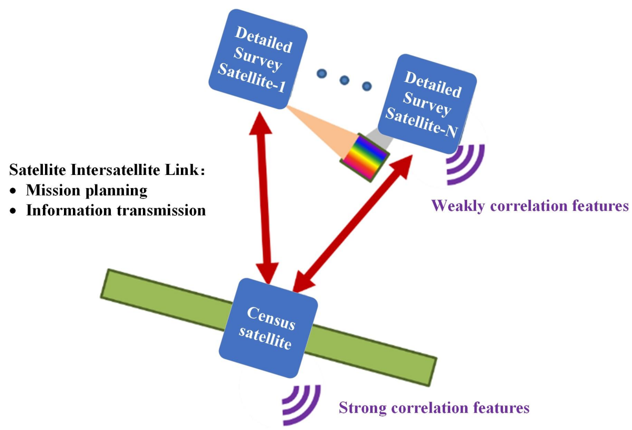

Figure 2. Schematic diagram of working mode

Based on the above work characteristics, a distributed constellation composed of census satellites and several detailed survey satellites is the basic unit of the real-time detection constellation for surface anomalies. The distributed constellation is composed of different types of satellites, and its connotation is a multi-modal satellite formation with both multi-functional and time difference remote sensing capabilities. Multiple satellites within and between the constellation collaborate to complete observation tasks.

The connection is established through inter satellite communication links within the satellite distributed constellation, and the system operates within the constellation through the following process.

1. Preliminary identification of anomalies and task planning

Preliminary anomaly identification refers to the process of discovering suspected anomalies during routine ground imaging tasks by reconnaissance satellites in distributed constellation. The onboard threshold lookup table is used to clarify the tasks step by step, and such remote sensing data is preliminarily evaluated. Based on the preliminary anomaly assessment results, task planning is carried out, and complex tasks such as reconfirmation and collaborative identification are interpreted to generate detection meta tasks within the cluster.

2. Distribution and execution of detection tasks

The remote sensing data obtained from the survey satellites in the distributed satellite cluster is processed and read by intelligent data processing. After identifying the abnormal state, detailed investigation tasks are distributed. The detailed investigation satellites within the satellite cluster accept task requests, and the satellites independently perform observation and identification tasks. The intelligent processing unit on the satellite is used to identify the types and severity of anomalies in detail.

3. Abnormal information transmission

Abnormal information transmission is the final step in task planning within a constellation. The abnormal information obtained from the distributed constellation fog computing layer is transmitted to the ground station or user through communication nodes based on different categories of information (raw data, information slicing, and short message semantic knowledge information).

The remote sensing constellation for surface anomalies is composed of several distributed constellation. After construction, the entire constellation system has a huge scale, and matching between different populations within and between clusters is already a relatively complex problem. How to achieve the optimal adaptive matching under specific constraints (such as the number of satellites, observation time, etc.) is a more complex planning problem. Based on the characteristics of surface anomaly observation tasks, a hierarchical satellite cluster task planning method is proposed. The entire anomaly identification and task planning process is shown in Figure 3.

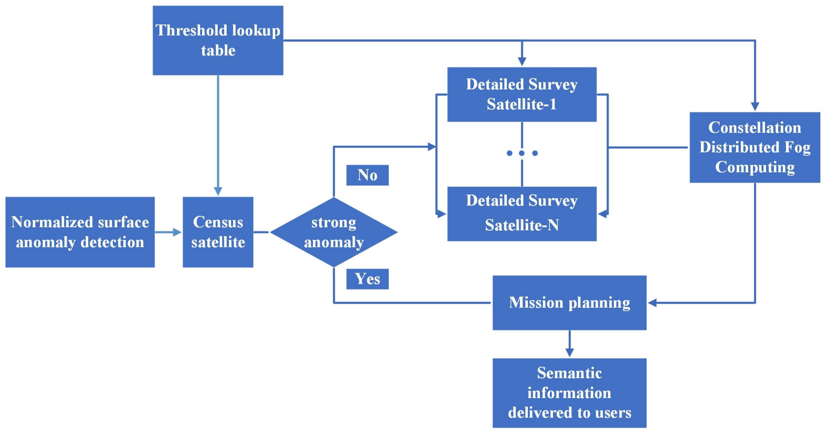

Figure 3. Abnormal identification and task planning workflow

4. RESEARCH ON THE WORKING MODE OF THE REAL-TIME DETECTION SYSTEM FOR SPACE-BASED SURFACE ANOMALIES

4.1 System information transmission link

In order to solve the problem of long transmission links and delayed response in existing satellite systems, the surface anomaly real-time detection system has established a self-circulating communication link, ensuring the real-time or near real-time communication ability of self-communication within the distributed satellite cluster, which can achieve information circulation within the constellation. The survey satellite also serves as a communication node satellite, and information can be transmitted within and between the constellation, Any information within a distributed constellation can be transmitted to the ground station and can serve as a communication node for other distributed constellation, achieving the communication ability of the constellation system to "see a single satellite to the ground, and transmit constellation information as needed", fundamentally solving the problem of weak information transmission ability. As shown in Figure 4, the schematic diagram shows the information transmitted back to the domestic ground station through the inter satellite link after the real-time detection constellation of surface anomalies discovers anomalies.

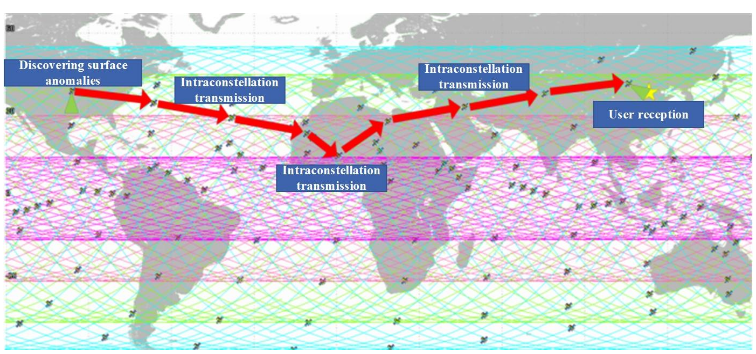

Figure 4. Schematic diagram of overseas real-time relay mode

The constellation that meets the real-time transmission of information mentioned above can be considered as a "inter visibility" type constellation with real-time monitoring and communication capabilities. To meet the "inter visibility" capability of the constellation, the geometric relationship of the satellites is analyzed, as shown in Figure 5.

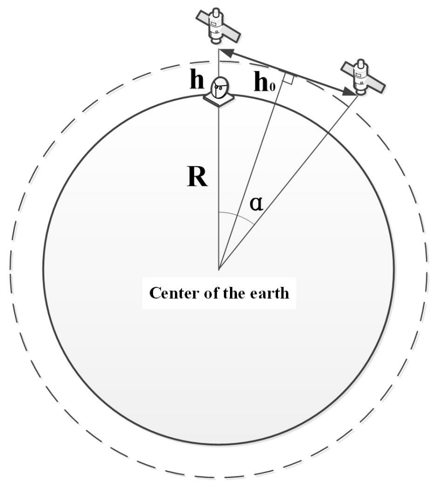

Figure 5. Constellation Geometry Relationship Satisfying "Intervisibility" Ability

Obtain the relationship between satellite orbit height and geocentric angle based on geometric relationships.

$$\cos\left(\frac{\alpha}{2}\right)=\frac{R+h_0}{R+h} \tag{1}$$

$$L=R\alpha \tag{2}$$

Wherein, α refers to the geocentric angle between satellites, R refers to the Earth radius, h_0 refers to the altitude of the low layer surface atmosphere affecting the intersatellite laser communication transmission, h refers to the satellite orbit altitude, and L refers to the satellite spacing. Then the relationship between the orbital height of the "intervisibility" satellite constellation and the satellite spacing is shown in Figure 6.

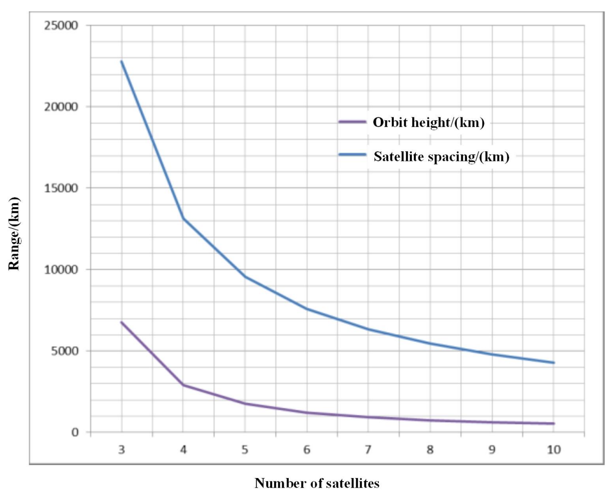

Figure 6. The Relationship between Orbital Altitude and Satellite Spacing of Constellation Satellites Satisfying Intervisibility Conditions

According to the calculation results, as the number of satellites increases, the corresponding orbital altitude and inter satellite distance decrease, and the difficulty of launch and communication efficiency increase. However, the construction cost also increases. Therefore, in the design phase, it is necessary to balance the single satellite design and the overall layout of the constellation.

4.2 Transmission duration analysis

The surface anomaly real-time detection system has communication capability within and between distributed constellation, and the whole system has self-circulation and external circulation communication capabilities, as shown in Figure 7, which is the information flow diagram of the surface anomaly real-time detection constellation.

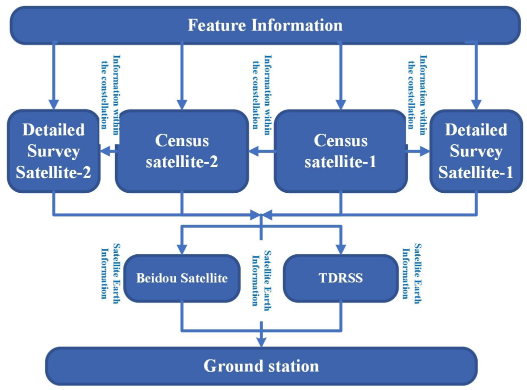

Figure 7. Information flow of communication, navigation and remote sensing constellation

From the discovery of surface anomalies to the arrival of abnormal information in the hands of users, the following process is required:

1. Abnormal detection time

The time of anomaly discovery in remote sensing of surface anomalies is determined by the coverage of the satellite system. If the average number of anomalies per day in the world is N, and the coverage of satellite constellation is P days. The earliest abnormal event detected by the satellite is t1=0s.

2. Abnormal recognition time (coarse)

Based on the calculation capability of existing onboard intelligent processing modules, t2=30s.

3. Task planning and intra cluster transmission time 1

Multi satellite task planning requires the establishment of a communication link from a survey satellite to a detailed survey satellite for each data transmission. Taking the 1-satellite 500 task for 1 second as a reference, a total of 3 satellites are set up in the constellation. Each data transmission requires the establishment of a communication link from a wide satellite to a high-resolution satellite, with a maximum path of 2000km. The transmission time is equivalent to the sum of the task planning time and transmission time, t3=3.005s.

4. Abnormal recognition time (precise)

Same as the anomaly recognition time in 2.

5. Task planning and intra cluster transmission time 2

Calculate time in the same way as in 3, t5=t3=3.005s.

6. Link transmission time between constellation

The transmission of links between constellation is established through satellite surveys, so the total time required for inter cluster communication (calculated based on the maximum number of hop links and a distance of 22500km) is assumed to be t6=0.059s.

7. Ground to ground data transmission time

a) Loop transmission within the system

After the system is fully established, it can ensure real-time communication with census satellites as communication nodes.

b) External loop transmission of the system - estimation of relay link duration

Launch time: The satellite up preparation and servo adjustment time of the data transmission system is set to 120 seconds. After in orbit testing, the transparent forwarding queue time of information at the relay satellite center station is generally about 1-2 seconds, and the limit of multi satellite queuing forwarding is about 10 seconds.

Path transmission time: Each data transmission requires the establishment of a ground station GEO satellite communication link, with a path transmission time of 0.5 seconds.

c) External loop transmission of the system - estimation of the duration of Beidou short messages

Transmission waiting time: Send information every 15 seconds, and the short message antenna generally takes 0.2~0.3 seconds to transmit short messages each time.

Path transmission time: Two communication links between ground stations and GEO satellites need to be established for each path, with a path transmission time of 0.5 seconds.

d) External Loop Transmission of the System - Estimation of Satellite Network Duration

Transmission waiting time of satellite network system: The satellite network system is a low orbit communication network, referring to Starlink that has been partially put into operation abroad, with a transmission waiting time delay of about 50ms.

Jump time: The waiting time for a single node in the satellite network system to forward is 0.4ms.

Table 2. Information Transmission delay

	Delay evaluation (/s)	**Estimation of the shortest Transmission delay to ground (/s)**	**Minimum Total Delay Estimation (/s)**
Constellation system	66.069	0	66.069
TDRSS Link		122	188.069
Beidou short message		16.2	82.269
Satellite network		0.0545	66.0604

The real-time detection system for surface anomalies, from discovering anomalies to transmitting abnormal information to users, can achieve the fastest information transmission of 66.069s by completely using the constellation system itself as a communication and remote fusion system for data transmission, as shown in Table 2. When the system coverage density is sufficient, the real-time detection system for surface anomalies has the ability to detect and transmit surface anomalies in real time. At the same time, by using existing relay systems, Beidou short message systems, and future satellite network systems, it can better complete the task of real-time detection of surface anomalies.

5. CONCLUSION

The construction of a satellite system for real-time detection of surface anomalies involves theoretical reconstruction and methodological reconstruction of the entire process of acquiring, processing, transmitting, and applying remote sensing data of surface anomalies. A theoretical and methodological system for real-time detection of surface anomalies is created, characterized by inter satellite interconnection, inter satellite feedback, on satellite processing, and direct transmission through satellite chains, To provide a scientific basis for the system to solve the international problem of "invisible, unclear, fast, and distant" in remote sensing detection of surface anomalies, and to lay a theoretical foundation for the implementation of real-time remote sensing detection products and services for surface anomalies up to user mobile terminals. There are still some key technologies that need to be urgently addressed in the construction of constellation systems, such as the determination of real-time detection feature thresholds and comprehensive indices for full spectrum remote sensing of surface anomalies, intelligent recognition technology for on satellite surface anomalies based on comprehensive thresholds, nonlinear response detection technology for pixel level super large dynamic range of surface anomalies in complex scenes, and a series of software and hardware technologies such as constellation intelligent task planning response mechanism driven by diversified abnormal events, Ultimately, establish a space-based system that can detect, diagnose, and warn in orbit in real-time.

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