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Explore the Development History and Technical Analysis of Remote Sensing Spacecraft

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Abstract:

Modern remote sensing technology is an important means of non-contact Earth observation and has become a core technology for human beings to carry out scientific research on the Earth system and to obtain space information in multiple fields. As the key realization platform of remote sensing technology, remote sensing spacecraft play an irreplaceable role in global resource management and environmental monitoring. This paper summarizes the basic development history and technical analysis of remote sensing spacecraft and describes the shortcomings of today's technology as well as the challenges it faces at the political, economic and ethical levels. In order to better cope with these multiple challenges, this paper puts forward several prospects and suggestions for the future development of sensor technology and international cooperation. Through this paper, we hope to provide theoretical support for the coordination of technological breakthroughs, global collaboration and privacy balance, and help remote sensing technology to serve the goal of sustainable development.

Keywords: Remote sensing spacecraft; Development; Future perspectives

1. Introduction

Remote sensing is a non-contact technology for the detection of objects over long distances, with wide-area observation coverage, high timeliness, dynamic monitoring and multiple data fusion and analysis[1-3]. In the context of the rapid development of urbanization and scientific and technological innovation, this technology has gradually become an important tool for obtaining information about cities and the Earth's environment and an indispensable and important component in various fields. Remote sensing spacecraft as the core platform for earth observation, after more than half a century of development, its technology has evolved from optical imaging to all-weather observation, and then to the stage of intelligent remote sensing, the formation of multi-sensors such as multi-spectral, microwave and LIDAR synergistic observation system [4,5]. The current technology has broken through the weather

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limitations, realized efficient and intelligent data integration and analysis, and become a key technology to support economic and social development and environmental protection [6].

Therefore, remote sensing spacecraft technology has also become one of the important symbols of a country's level of scientific and technological development and comprehensive strength and has traditionally been emphasized by the world's major scientific and technological and economic powers. As one of the key scientific and technological development directions, many latest research results have also emerged recently. For example, in January 2024, Maxar Technologies of the United States and NASA jointly released an upgraded version of the WorldView Legion satellite, equipped with a new EagleEye-5 optical sensor, panchromatic resolution increased to 0.25 meters, the first integrated quantum dot-enhanced focal plane arrays, which significantly improves the quality of the imaging under low-light conditions. In February 2024, the 14th Institute of Electrotechnical Sciences of China will publicize the prototype of the "Sky Patrol-2" terahertz radar satellite, which operates in the frequency band of 0.3-1 THz, with a resolution of centimeter-level (5 cm), and with a 300% improvement in its ability to penetrate smoke and dust, suitable for the detection of internal structures of buildings.

However, despite the remarkable progress in remote sensing spacecraft technology, it still faces many problems and challenges. For example, at the technical level, problems such as insufficient continuity of observation data, high complexity of interpretation of SAR and other techniques, and low intelligence still exist [7]. And at the policy level, some regional bills have influenced the global collaboration [8].

In order to understand the development of remote sensing spacecraft technology more comprehensively, this paper aims to explore the development history of remote sensing spacecraft and make a comparative analysis of the technology, firstly, analyze the technology evolution and make a comparison of the current situation, then specifically analyze the current challenges, and finally, make suggestions and prospects for the future development direction.

2.2 Comparison of technology development history and current status

The development of remote sensing spacecraft can be roughly divided into three stages, which are the foundation stage of optical remote sensing, the stage of all-weather observation brought about by the development of SAR technology, and the stage of intelligence and ultra-high resolution nowadays [9]. Table 1 shows the representative spacecraft achievements of the three phases and lists their technical characteristics and significance.

In the first phase (1960-1980), representative satellites such as TIROS-1 and Landsat-1. Among them, the MSS sensor of Landsat-1 (1972) realized multispectral remote sensing for the first time, and the United States dominated the remote sensing spacecraft technology at that time, but it still relied on visible light at that time, and the rate of missing data caused by the meteorological factors, such as cloud cover, reached over 60%. The data missing rate was more than 60% due to meteorological factors such as cloud cover.

Into the second phase (1980-2010), representative satellites such as ESA ERS-1, and Germany TerraSAR-X, with the breakthroughs in synthetic aperture radar (SAR) technology, sensor performance has been significantly improved, the resolution has reached the order of ten meters, the number of hyperspectral bands increased by about 50 times, Europe began to occupy a leading position in the field of SAR, China has also begun to achieve a certain degree of development.

Nowadays, in the intelligent and ultra-high resolution stage (2010 to present), the development is becoming more and more polarized, China (Gaofen-7), the U.S. (WorldView-4 commercial optical satellites) and the EU (Sentinel series) have made progress in their fields, but the routes are relatively different, the U.S. is inclined to be commercialized, focusing on high-resolution and real-time data, while China's research and development is led by the state and put more emphasis on the full spectrum of coverage and emergency response capabilities, while the EU is led by the state and put more emphasis on the full spectrum of coverage and emergency response capabilities. China's state-led R&D emphasizes full-spectrum coverage and emergency response capability, while the EU is more concerned with environmental protection, focusing on climate change and environmental monitoring.

Table 1.Example analysis of representative satellites in three phases[2,3,4,9,10,11,12,13,14,15,16,17]

Stages	Time scale	Representative satellites	Resolution (meters)	Technological characteristic	Remark
Stage1	1960-1980	TIROS-1	8,000	Visible light meteorological observations	First meteorological satellite
		Landsat-1	80	Multi-spectral scanning	Civilian Earth observation begins
		Meteor-2	1,000	sun-synchronous orbit satellite	Large-scale meteorological monitoring
		SJ-2	1,000	China's first remote sensing test	Technology validation phase
Stage2	1981-2010	ERS-1	30 (SAR)	First operational SAR satellite	Breakthrough in all-weather observation
		JERS-1	18 (SAR)	L-band multi-sensor fusion	Forest Resources Survey
		TerraSAR-X	0.25 (SAR)	X-band commercial high resolution	Sub-meter SAR benchmark
		ZY-3	2.1	China's Stereoscopic Mapping Breakthrough	1:50,000 topographic mapping
Stage3	2011-2023	WorldView-3	0.31	Short-wave infrared + AI target recognition	World's highest commercial optical resolution
		Jilin-1 Gaofen	0.75 (vedio)	Dynamic target tracking	Frame rate 25fps, 92% ship recognition
		ICEYE-X2	0.25 (SAR)	Micro-SAR satellite constellation	Low-cost, high-frequency monitoring
		Gaofen-7	0.65	Laser altimetry + stereo imaging	Sub-meter stereo mapping

3 Analysis of representative satellites by phase

Remote sensing spacecraft at this stage are mainly multi-spectral scanners with a resolution of only a kilometer to a hundred meters, which are mainly used for surface coverage classification and basic meteorological monitoring, but play a pioneering role in technology and lay the foundation for subsequent research directions. Table 2 lists the representative satellites at this stage and analyzes their technology and significance.

Table 2 . Analysis of representative satellites in phase I with the technology process[2,3,4,9]

Year	Satellites	Technological breakthrough	Impact and significance
1960	TIROS-1	First meteorological satellite with visible light imaging and resolution of about 8 kilometers	Pioneering meteorological satellites and verifying the feasibility of remote sensing technology
1972	Landsat-1(ERTS-1)	Multi-spectral scanner (MSS), 4 bands (green, red, near-infrared), 80 m resolution	The first civilian Earth observation satellite, opening the era of multi-spectral remote sensing
1975	Meteor-2	Visible and infrared sensors with 1-2 km resolution	The first operational meteorological satellite in the USSR, facilitating meteorological monitoring in Eastern Europe
1978	Landsat-3	MSS sensor upgraded with new thermal infrared band (10.4-12.6μm) and 80m resolution	First realization of surface temperature inversion to support agricultural drought monitoring

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Year	Satellites	Technological breakthrough	Impact and significance
1980	SJ-2	Equipped with a simple optical camera with a resolution of approximately 1 km (experimental)	China's first attempt at an autonomous remote sensing satellite, accumulating technical experience for subsequent development

At this stage, SAR technology was mature, and there was a breakthrough in microwave and hyperspectral sensors, with a resolution of 10 meters. At this time, cloudy and night observation (such as ERS-1) has been realized, but the data processing relies on manual labor and the degree of intelligence is low. Table 3 shows the representative satellites of the second stage and analyzes the technology and significance.

Table 3. Analysis of representative satellites in phase II with the technological process[10,11,12,13]

Year	Satellites	Technological breakthrough	Impact and significance
1991	ERS-1	Equipped with C-band synthetic aperture radar (SAR) with a resolution of 30 meters, enabling all-weather observation for the first time	Breaking through optical remote sensing weather limitations to promote ocean and polar monitoring
1992	JERS-1	L-band SAR synergized with optical sensors with 18 m resolution (SAR)	First validation of multi-sensor fusion potential to support forest resource surveys
2000	EO-1(Hyperion)	Hyperspectral sensor, 220-band (0.4-2.5 μm), 30-m resolution	Opening the era of hyperspectral remote sensing to support mineral exploration and inversion of vegetation biochemical parameters
2007	TerraSAR-X	X-band SAR with a resolution of 0.25 m (spot beam mode) and a revisit period of 11 days	Commercial high-resolution SAR satellite representative for urban mapping and disaster response
2010	ZY-3	Three-line array stereo mapping camera with 2.1 m resolution (panchromatic)	China's first three-dimensional mapping satellite, realizing 1:50,000 scale topographic mapping

At this stage, a variety of sensors have been developed and matured, usually equipped with a variety of sensors working together, and with certain AI-driven on-board processing capabilities, real-time dynamic monitoring can be realized, and the resolution has reached the sub-meter level. Table 4 below shows some representative satellites in the third stage and analyzes their technological breakthroughs and significance.

Table 4. Analysis of representative satellites in phase III with the technological process[14,15,16,17]

Year	Satellites	Technological breakthrough	Intelligent Embodiment	Impact and significance
2013	WorldView-3	Multi-spectral + shortwave infrared, resolution 0.31 m (panchromatic), 8-band shortwave infrared	Equipped with AI chip to realize automatic target recognition (ATR), supporting automatic labeling of military facilities and minerals.	Commercial satellites with the highest global resolution to support mineral exploration and military reconnaissance
2014	Sentinel-1A	C-band SAR with 5-metre resolution and 6-day revisit period (dual-star network)	Deep learning-based automatic deformation detection algorithm (PS-InSAR) for real-time monitoring of surface settlement	Free and open data policies to promote global environmental monitoring

Year	Satellites	Technological breakthrough	Intelligent Embodiment	Impact and significance
2016	GaoFen-4	Geostationary optical satellite, 50-meter resolution, 20-minute revisit	On-board real-time fire detection algorithm, combined with BeiDou short message to realize disaster warning automatic trigger	The world's first geostationary orbit high-resolution remote sensing satellite, focusing on real-time disaster monitoring
2020	Gaofen-3	Video remote sensing, resolution 0.75 m, frame rate 25 fps	Dynamic target tracking AI model (YOLOv5 improved version) with 92% ship recognition accuracy	Realization of dynamic target tracking (e.g., ships, vehicles), promoting the evolution of remote sensing from static to dynamic
2022	PlanetScope	150+ small satellites with 3-meter resolution and daily global coverage	Cloud-based AI automated change detection (e.g., deforestation, farmland expansion) with daily processing capacity of 2 million square kilometers	Low-cost, high-frequency monitoring to support agriculture and climate change research

4 Challenges and prospects

4.1 Challenges

Although remote sensing spacecraft have come a long way, they still face deficiencies and challenges in areas such as technology, policy and ethics:

From the technical level, current remote sensing spacecraft face several specific problems. First, there is a problem of poor continuity of the data it acquires, especially in complex areas such as tropical rainforests, where the effective data acquisition rate of optical satellites is generally lower than 40% [18,19]. Second, the data interpretation relies on manual labor with insufficient automation, which leads to a high error rate. The sensor performance of various technologies still has limitations, for example, the spatial resolution of hyperspectral satellites can only reach the order of ten meters [20], which is difficult to meet the demand for small-scale fine monitoring (e.g., fine agriculture), and LIDAR has a limited coverage, making it difficult to conduct global monitoring.

In addition to technical problems, international forms and related policies have also constrained global collaboration to varying degrees, such as the GDPR enacted by the European Union, which restricts the circulation of sub-meter imagery, resulting in increased delays in data sharing for scientific research projects such as the Sino-European Polar Research [21]. In addition, the lack of a unified standard for remote sensing data in the international arena makes it difficult to integrate and analyze data [22].

There are also many challenges at the economic level, such as the high cost of data from many commercial satellites, with the U.S. WorldView spacecraft reaching more than $20/km [23], which is too high a financial requirement.

On the ethical level, too high a resolution may implicate the privacy of individuals or organizations, such as 0.3 m-level satellite images that can identify individual vehicle details in violation of the Osteen Data Privacy Agreement [24,25], and become one of the important issues that need to be jointly considered on the path of ever-increasing resolution for future remote sensing spacecraft.

4.2 Prospects

In terms of sensor technology, it is possible to improve and upgrade the terahertz radar technology. Terahertz waves are narrowly defined as 0.3 to 3 THz, which is in the excessive zone of microwave and infrared. Its advantage lies in the short wavelength, large bandwidth, "space time and frequency" resolution is very high, in space its imaging resolution is high, meaning that it can be observed on the object of information for a more detailed portrayal, time means that the imaging frame rate is high, real-time monitoring can be carried out, and the frequency of high resolution means that its Doppler sensitivity, which is conducive to the detection of microscopic movement and high-precision velocity estimation. Not only that, but the greater ability of terahertz waves to penetrate media such as smoke, dust, clouds and even plastics and fabrics can be used for complex environmental monitoring. Terahertz radar systems typically generate terahertz waves through solid-state electronics (e.g., Geng diodes, quantum cascade lasers) or electro-vacuum devices (e.g.,

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traveling-wave tubes, antipodal tubes), in conjunction with, e.g., photoconductive antennas in combination with laser pulses or optically pumped gas lasers for high-frequency excitation of the signal. But despite this, there are still many directions of this technology to be overcome, for example, for satellite equipment, its propagation distance is limited, the proportion of absorption by the atmosphere is too high, and secondly, the cost of hardware is too high, the cost of a prototype is more than 5 million U.S. dollars, which is usually difficult to afford the scientific research funds. Moreover, the transmit power of the current equipment is extremely low, and the power of ordinary weather radar can even reach about 1000 times of its power, and the performance of the equipment is significantly affected by the temperature, which is difficult to adapt to the complex environmental changes in space . With so many limitations, this technology still remains in the laboratory validation stage, but it is still feasible. For example, improving the device materials, such as using new materials like graphene instead of traditional semiconductors, may reduce the cost of the device, and 3D printing can also be used [26], which was previously used by MIT to build a terahertz transmitter the size of a fingernail cap at a cost of only $10. To cope with its power inefficiency, laser-assisted means can be used, such as dense plasma terahertz sources that generate ultra-strong terahertz waves by laser acceleration of the kinetic behavior of relativistic electrons at the plasma-vacuum interface [27]. For the problem of materials limited by temperature changes, self-healing materials can be developed, the United States DARPA developed a “self-healing” terahertz chip, can withstand -50 ° C to 120 ° C extreme temperature changes [28].

In terms of data processing, on-planet intelligence is a hot direction, nowadays most of the remote sensing spacecraft once launched into use, imaging parameters can not realize flexible targeted adjustment, and the mode of operation is usually the ground mission planning - data stored on the star - star transmission and ground processing, timeliness is poor. The on-board intelligence is to achieve on-board imaging parameters automatically optimized for the task requirements [29], on-board data fast processing and downlinking of the “intelligent” remote sensing spacecraft, such as the Jilin 1 high-frequency 03 star has been achieved ship dynamic tracking, the accuracy rate of 92%. Not only should it have the ability to acquire differentiated data, but also have intelligent information perception ability; not only can it acquire targeted high-quality data according to the needs of the formulation, but also can process information in real time at the same time as the data acquisition, thus greatly promoting the popularization and commercialization of remote sensing technology .

For solving ethical problems, high-resolution images can be blurred or dynamically masked from sensitive areas, such as residences and private vehicles, which can be combined with on-board intelligence for autonomous resolution processing. In addition, user and organizational authorization mechanisms can be established to implement the mode of prior authorization for sensitive areas and record data usage rights through blockchain technology [30,31]. International organizations should continue to improve relevant laws and regulations and industry standards, so that the operation of the industry receives restrictions and regulation.

At the international political level, the international community should strengthen the optimization of collaboration mechanisms, unify data standards and sharing platforms, such as promoting the ISO geographic information standard [32] to establish a global remote sensing data sharing resource base, breaking the policy barriers of the EU GDPR and other policy barriers, strengthening multilateral cooperation, relying on multilateral agreements to adjust the policy conflict , and avoiding obstruction of scientific research cooperation. A hierarchical data development system can also be established to classify data levels according to resolution, open and share in a hierarchical manner, and ensure information security .

5 Conclusion

In summary, the development of modern remote sensing spacecraft technology has demonstrated the continuous exploration and innovation of mankind in the field of Earth observation. From the early days of optical remote sensing to today’s intelligent and ultra-high-resolution technologies, remote sensing spacecraft not only play an important role in scientific research, but also provide strong support for applications such as resource management, environmental monitoring and disaster response. However, despite significant technological advances, they still faced many challenges, such as insufficient data continuity, low levels of automation, policy constraints and ethical issues.

Looking ahead, this paper summarizes several feasible development directions, such as improving sensor technology through further research and development to improve terahertz sensors, developing self-repairing materials and other solutions, upgrading equipment intelligence and data-processing capabilities through further improvement of on-board intelligent technologies, resolving ethical issues by means of formulating industry norms and other means, and strengthening international cooperation. We expect and believe that by addressing these challenges, remote sensing spacecraft will be able to better serve the global sustainable development goals, provide more accurate and efficient support for combating climate change, protecting the environment and promoting socio-economic development, and help mankind to better understand and manage our common home.

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