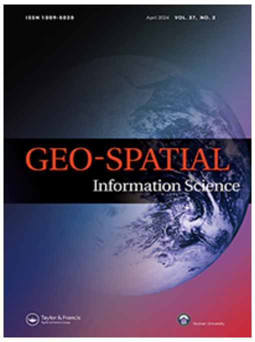

Geo-spatial Information Science

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tgsi20

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To cite this article: Deren Li, Mi Wang, Haonan Guo & Wenjie Jin (12 Apr 2024): On China’s earth observation system: mission, vision and application, Geo-spatial Information Science, DOI: 10.1080/10095020.2024.2328100

To link to this article: https://doi.org/10.1080/10095020.2024.2328100

GEO-SPATIAL INFORMATION SCIENCE
https://doi.org/10.1080/10095020.2024.2328100

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On China’s earth observation system: mission, vision and application

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ABSTRACT
China’s Earth Observation(EO) System has undergone significant development since the 1970s, as China has dedicated substantial efforts to advancing remote sensing technology. With fifty years of development, China has successfully narrowed the remote sensing technology gap with foreign countries through collaborative endeavors of the government and enterprises. At present, China has constructed a comprehensive EO system that has been proven indispensable for driving economic growth and facilitating sustainable development. This paper provides an overview of the development, missions, andapplications of China’s EO system, while also exploring future directions and technical trends of China’s EO system.

ARTICLE HISTORY
Received 26 September 2023
Accepted 4 March 2024

KEYWORDS
Remote sensing satellites; China’s earth observation system; space-based systems; intelligent information service

1. Introduction

China officially started its first satellite development program in 1965. After 5 yr of dedicated efforts, China achieved a momentous feat with the successful launch of its first satellite, DFH-1, on 24 April 1970, at 9:35 p.m. This achievement made China the fifth country that send a satellite into space following the Soviet Union, the United States, France, and Japan. Notably, the successful development of DFH-1 also positioned China as the third country capable of independently developing and launching satellites, signifying a remarkable leap forward in China’s technological capabilities and scientific achievements (Li, Wang, and Jiang 2020).

In 1975, China successfully developed and launched its first recoverable remote sensing satellite, denoting a precedent of remote sensing for Earth observation in China (Xu, Gong, and Wang 2014). Over the ensuing decades, China has demonstrated its capability to independently develop and launch more than 500 satellites, encompassing seven satellite series including meteorological satellites, ocean satellites, resources and high-resolution satellites, commercial satellites, scientific satellites, communications and broadcasting satellites, and navigation and positioning satellites (Li, Wang, and Jiang 2020).

Among the satellites, there are currently more than 200 remote sensing satellites for earth observation-(EO), forming three comprehensive remote sensing systems catering to land, ocean, and meteorology observation, as well as a series of resource (ZY), high-resolution (GF), meteorological (FY), surveying, mapping, and commercial constellations (Guo, Dong, and Liu 2020; Li, Wang, and Jiang 2020). These satellites leverage a wide range of remote sensing technologies, including visible, infrared, hyperspectral imaging, synthetic-aperture radar (SAR), laser, and other advanced technologies (Zhang et al. 2018b). The evolution of EO satellites from experimental mode to operational service mode has attracted the active participation of private enterprises, leading to the commercialization of remote sensing satellites that further diversify remote sensing data sources. Through collaborative efforts between the government and the enterprises, China has made remarkable strides in narrowing the technological gap with foreign countries. The development of remote sensing technology boosts the practice of remote sensing in over a hundred forms of applications (Li, Yao, and Shao 2022) such as land resources management, disaster warning, atmospheric and water environment monitoring, yield estimation, national defense, and deep space exploration (Zeng et al. 2020; Zhang et al. 2018a; Zhong et al. 2021a). The versatile and expansive applications of China’s EO system demonstrate its pivotal role in addressing social challenges and fostering Sustainable Development Goals(SDGs) (Li, Shao, and Zhang 2020).

The paper aims to provide a comprehensive overview and analysis of the forefront development and application of different remote sensing satellite series within China’s EO system. Additionally, it seeks to offer insights into the future development of China’s EO system, potentially exploring directions of further research and technological advancements that may advance the field in the coming years. We hope it

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helps readers gain a deeper understanding of China's EO system, its current state, applications, and future directions.

2. Development of China's earth observation system

2.1. Overview of China's earth observation system

Since the first attempt at a film-based recoverable remote sensing satellite in 1975, remote sensing has been listed as one of the national key development projects of China. Since then, China has developed and launched over 200 remote sensing satellites and undergone a leap from film-based to transmission-based photoelectric imaging, from experimental application mode to operational service mode, and from single-modal imaging to multimodal imaging (Li et al. 2020).

The mission of China's EO system encompasses several key objectives. First, it aims to utilize outer space peacefully, emphasizing the peaceful and cooperative use of space resources for the benefit of all nations. Second, the system aims to enhance China's science and technology innovation capacity, driving advancements in remote sensing technology and related fields. Third, it seeks to contribute to the development of the economy and society by providing valuable data and insights for various domains, including agriculture, urban planning, and environmental management. Finally, the system is designed to serve the sustainable development of humankind, supporting global efforts in areas such as climate change, disaster management, and resource conservation (Huang and Wang 2020).

The remote sensing satellite data of China's EO system are distributed to the responsible ministry or agencies according to the purpose of applications for data pre-processing, management, and distribution. Aiming at benchmarking the world-leading EO systems such as Landsat and Sentinel, the data are pre-processed into multiple levels with a similar format as the existing products and thus serve users at home and abroad. The meteorological satellite data are managed and distributed by the National Satellite Meteorological Center(NSMC); the ocean satellite data are managed by the National Satellite Ocean Application Service(NSOAS); the resource satellite data, the high-resolution satellite data, and the environment monitoring satellite data are managed by the China Centre For Resources Satellite Data and Application (CRESDA). Commercial satellite data, such as Beijing, Jilin, and SuperView series, are commercially available for providing data service. In this section, we introduce different series of China's EO satellites and their applications.

2.2. Development of China's meteorological satellites

China started the research and development of meteorological satellites in 1977. The satellite research program, namely the Fengyun(FY, which denotes wind and cloud in Chinese) program, is set up to provide reliable and sustained meteorological observation in operation (Gao, Tang, and Han 2021; Tang, Qiu, and Ma 2016; Xian et al. 2021). As listed in Table 1, the Fengyun satellite constellation currently includes 7 satellites in orbit in operation, 3 LEO orbits for observation in the early morning, morning, and afternoon, as well as 4 GEO orbits that cover areas ranging from 79°E to 133°E. The Fengyun data service system has accumulated data from various Fengyun satellites in the National Satellite Meteorological Center (NSMC). The accumulated data volume has reached 22 PB with an increment of 21 TB data volume daily. With rich real-time and historical observation data, users can enjoy real-time data service through direct broadcast and the CMACast system.

The meteorological data can also be transmitted by non-real-time data services such as websites, cloud services, FTP services, or manual services. The Fengyun program has become an important component of the World Meteorological Organization (WMO) Space Program.

Table 1. In-orbit fengyun meteorological satellites.

Type	Satellite Name	Status	Positioned Longitude/Equatorial crossing time
Geostationary Satellite	FY-2G	In orbit	99.5°E(Before 1 June 2015) 105°E(1 June 2015 to 9 April 2018) 99.2°E(After 16 April 2018)
	FY-4A	In orbit	104.7°E
	FY-2H	In orbit	79°E
	FY-4B	In orbit	133°E
Polar Satellite	FY-3C	In orbit (degraded performance)	10:15 AM descending node
	FY-3D	In orbit	2:00 PM ascending node
	FY-3E	In orbit	05:30 AM descending node
	FY-3G	In orbit (commissioning phase)	Inclined orbit
	FY-3F	In orbit (commissioning phase)	Inclined orbit

Table 2. Payload of FY-3E satellite.

Acronym	Full name	Channels
MERSI-LL	Medium Resolution Spectral Imager-LL	7
HIRAS-II	Hyperspectral Infrared Atmospheric Sounder-II	3041
MWTS-III	Micro-Wave Temperature Sounder-III	17
MWHS-II	Micro-Wave Humidity Sounder-II	15
GNOS-II	GNSS Radio Occultation Sounder-II	50
WindRAD	Wind Radar	4
SSIM	Solar Spectral Irradiance Monitor	4345
SIM-II	Solar Irradiance Monitor-II	3
X-EUVI	Solar X-ray and Extreme Ultraviolet Imager	8
Tri-IPM	Triple-angle Ionospheric PhotoMeter	6
SEM	Space Environment Monitor	421

The FY-3E satellite, launched in 2021, is the world 's first meteorological satellite in early morning orbit for civil service, filling the observing gap in the early morning (Shao et al. 2022). As illustrated in Table 2, it is equipped with 11 payloads that support the monitoring of wind, water vapor, refined structure of solar, city light, etc. A satellite network combining FY-3E, FY-3D, and FY-3C (will be replaced by FY-3F) forms the layout for China's new generation polar orbit meteorological satellites that observe simultaneously on early morning, morning, and afternoon orbits. The satellite network can provide complete global coverage data for numerical weather forecasting every 6 h, which effectively improves the accuracy and timeliness of global numerical weather prediction, and is of great significance to improve the global meteorological EO system (Ren et al. 2023).

The FY-4 satellite series opened a new era for China's new generation of stationary meteorological satellites (Yang et al. 2016). The FY-4A and FY-4B satellites form a dual satellite network that monitors the atmosphere and clouds at high frequencies, obtains atmospheric vertical information, and generates various atmospheric physical parameters and quantified products. The FY-4B satellite, launched in 2021, supports full disk observation every 15 min, regional sounding every 2 h, and regional observation every minute. The observation data are widely used in weather prediction, disaster weather warnings, climate prediction services, ecological environment monitoring, and other fields (Kong et al. 2023). Moreover, the network further meets the meteorological service needs of China and the countries and regions along the Belt and Road for meteorological monitoring and forecasting, emergency disaster prevention, and mitigation.

China's first low inclined orbit precipitation measurement satellite, FY-3 G satellite, was launched on 16 April 2023. The main payload precipitation measurement radar was first developed in China and is mainly used for providing three-dimensional structure information of precipitation in global middle and low latitude regions. Its application of precipitation monitoring in catastrophic weather systems will make outstanding contributions to reducing the potentially destructive impact of catastrophic weather.

With the availability of high spatial-temporal meteorological EO data captured by Fengyun-series satellites, it has a broad application in many fields. For example, driven by the concept of "Beautiful China", fully automatic time-series cloud detection results are developed based on FY-3D data. This daily cloud detection product of China is highly accurate with a total accuracy higher than 96.5%, with a missed detection rate of less than 4% and an error rate of less than 8%. Moreover, it is feasible to realize the synthesis of clear-sky images using massive monitoring images from FY meteorological satellites to serve disaster response, resource surveying, and environmental monitoring. In the 2022 Beijing Winter Olympics, a super-resolution reconstruction technique is applied to the FY-3D images to improve the image quality from 250 m spatial resolution to 100 m. The high-quality data provides all-around support for weather monitoring for the Beijing Winter Olympics. Furthermore, the high-quality FY data also support varied applications such as monitoring changes of ice in the Inner Mongolia section of the Yellow River, generating high-frequency agricultural vegetation quantitative products (Figure 1), frequent monitoring of disaster events such as floods occurred in Madagascar and Pakistan, dynamic analysis of Poyang Lake's drying up, etc.

China's in-orbit meteorological satellites are increasing in number and diversity. To meet the requirement of high stability and reliability of meteorological observations, it is important to deploy reference-type missions for intercalibrate measurements from multiple satellite platforms for harmonizing global satellite observations. An expert team on Earth observation and navigation of the Ministry of Science and Technology (MOST) proposed the concept of the Chinese Space-based Radiometric Benchmark (CSRB) in 2006. The goal of CSRB is to launch a reference-type satellite named LIBRA in around 2025 (Zhang et al. 2020), which will offer measurements with solar irradiance traceability for the outgoing radiation from the Earth and the

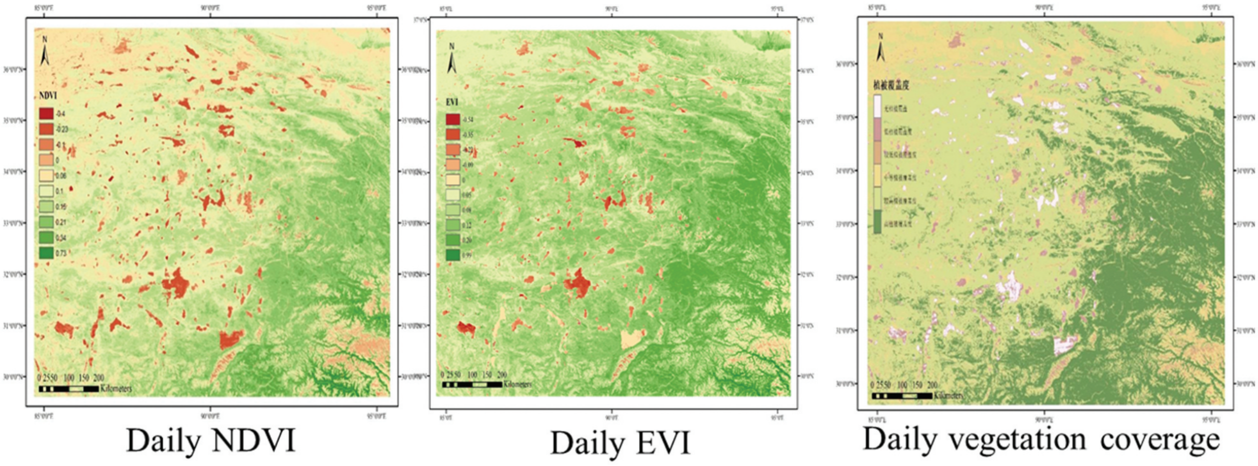


Figure 1. Daily agricultural vegetation quantitative products based on FY-3D super-resolution reconstruction products.

incoming radiation from the Sun with high spectral resolution. The CSRB project was approved in 2014 and keeps going well. The key technology of the CSRB project will also be used in the development of the next generation of Fengyun satellites. Moreover, with sustained satellite design and reliable data accuracy (Zhang et al. 2022a), the FY series has been one important component of the global observation system and will contribute to WMO members continuously with the open data policy.

2.3. Development of China's ocean satellites

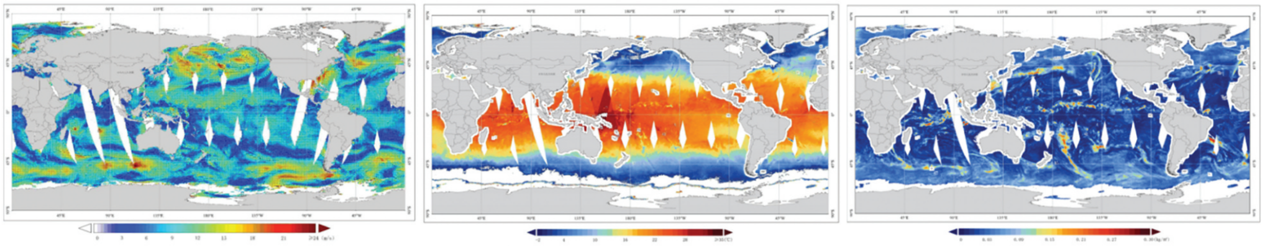
The ocean satellite series of China is named the Haiyang (HY) series, which denotes the ocean in Chinese. The HY series includes three types of satellites, HY-1 for the ocean color satellite missions, HY-2 for the ocean dynamic satellite missions, and HY-3 for the ocean monitoring satellite missions. Up to now, China has launched 12 HY satellites and 10 of them are in orbit, as shown in Table 3. The three types of satellites of the HY series are introduced in succession.

The objective of the HY-1 series is to measure the ocean color, sea surface temperature, and coastal zone dynamic changing information of global oceans, which includes HY-1C and HY-1D satellites in orbits (Pan, He, and Zhu 2004). A constellation of these two satellites observes the ocean in the morning (10:30AM ±30 min) and afternoon (1:30PM ±30 min), respectively. The typical products generated by the HY-1 series include the ocean color and temperature, Chlorophyll-a Concentration, vegetation indexes, suspended sediment concentration, etc.

The HY-2 series is designed to monitor ocean dynamic environment parameters in the microwave region (Jiang et al. 2012), such as ocean surface winds, sea surface height, significant wave height, sea surface temperature, etc. It has two experimental satellites, HY-2A and CFOSAT in orbit, three operational satellites, the polar orbit satellite HY-2B, and inclined orbit satellites HY-2C and HY-2D in operation. The three operational satellites HY-2B, HY-2C, and HY-2D form China's first ocean dynamic monitoring constellation and can support the frequent observation of global ocean dynamics such as sea surface height, significant wave height, sea surface wind, temperature, vapor, cloud liquid water, etc (Figure 2). The constellation can cover more than 80% of the ocean areas of the world in 6 h and almost all the ocean areas of the world in 12 h for sea surface wind observation missions. The Chinese-French Oceanography Satellite(CFOSAT) of the HY-2 series is a joint mission of China and France with the goal of monitoring the ocean surface winds and waves. It achieves high-precision synchronous observation of the global sea surface wind field

Table 3. In-orbit HY series ocean satellites.

	Satellite	Series	Status
1	HY-1A	Ocean Color Satellites（HY-1）	Stopped working
2	HY-1B		Stopped working
3	HY-1C		In orbit
4	HY-1D		In orbit
5	HY-2A	Ocean Dynamic Satellites（HY-2）	In orbit
6	HY-2B		In orbit
7	HY-2C		In orbit
8	HY-2D		In orbit
9	CFOSAT		In orbit
10	GF-3	Ocean Monitoring Satellites（HY-3）	In orbit
11	C-SAR 01		In orbit
12	C-SAR 02		In orbit



(a) Sea surface wind (b) Sea surface temperature (c) Water vapor

Figure 2. Examples of typical products of HY-2 satellites (http://www.nsoas.org.cn/).

Table 4. Quantitative evaluation of joint adjustment.

Adjustment method		Plane accuracy(m) Medium error	Plane accuracy(m) Maximum error	Elevation accuracy(m) Medium error	Elevation accuracy(m) Maximum error
Before adjustment		**5.26**	**24.3**	**4.36**	**15.24**
After adjustment	Adjustment without laser altimetry data	**2.64**	**5.23**	**4.25**	**7.66**
	Adjustment with laser altimetry data aided	**2.58**	**5.16**	**2.88**	**6.74**

and wave direction spectrum for the first time internationally.

The HY-3 series, also denoted as ocean monitoring satellite missions, aims to provide high-resolution microwave images of global oceans and monitor ocean objects and events such as ships, ice, oil spills, waves, winds, Enteromorpha, etc. A total of three satellites including GF-3, C-SAR 01, and C-SAR 02, form a polar-orbit SAR satellite constellation. These satellites are equipped with C-band Synthetic Aperture Radar and are able to revisit the same region within less than 1 d.

2.4. Development of China's resource satellites

Driven by the "Medium and Long-Term Development Plan for National Civil Space Infrastructure (2015–2025)" of China, Chinese resource satellites have provided significant support for resource management applications such as urban planning, agricultural production, forestry maintenance, emergency relief, and many other fields. The first resource satellite ZY-1 01 satellite, also known as China Brazil Earth Resources Satellite (CBERS-01), was launched in 1999, marking the beginning of the era of transmission-based remote sensing satellites (Lino, Lima, and Hubscher 2000). Till now, the ZY-1 series has developed into a series of satellites with multispectral, hyperspectral, visible, and infrared imaging technologies, which satisfy the demand for large-scale land and resource monitoring. Moreover, the ZY series satellites have responded to international major natural disaster requests multiple times under the charter 'International Charter Space and Major Disasters, providing assistance for the prediction and rescue of major natural disasters worldwide (Jones et al. 2015).

In 2012, China successfully launched the ZY-3 satellite, which is China's first civilian high-resolution three-dimensional mapping satellite that provides 2 m stereo images and 6 m multi-spectral images for stereo mapping and generating three-dimensional information. Further on, ZY3–02 launched in 2016 and ZY3–03 launched in 2020 form a satellite network with the ZY3-01 satellite, which facilitates its national stereoscopic mapping ability with higher accuracy and lower revisit times. Based on ZY-3 satellite trilinear array data, researchers from Wuhan University have developed a remote sensing multi-node automatic processing system to realize precise global 1:50,000 topographic mapping without ground control points (Yang et al. 2017), which fully meets the mapping requirements in overseas and no man's land. The evaluation accuracy of the generated DSM is 4 m; the plane accuracy of DOM is 3.5 m. Furthermore, a block adjustment without GCP using ZY-3 and Laser Altimetry data is designed (Li, Wang, et al. 2023). The elevation accuracy with laser data-aided adjustment is obviously higher than that without laser data-aided adjustment (Zhang et al. 2018c), as listed in Table 4. The elevation accuracy of ZY-3 uncontrolled adjustment can be further improved to within 3 m (Zhang et al. 2021). Up to now, China has finished 1:50,000 global mapping with more than 100 million square kilometers.

2.5. Development of China's high-resolution satellites

The major special project of the China High-Resolution Earth Observation system is one of the 16 major science and technology projects identified in the "National Medium and Long-term Science and Technology Development Plan (2006–2020)". The system aims to improve China's observation capability of all-weather, all-time, and global coverage (Li, Wang, and Jiang 2020). In order to improve China's remote

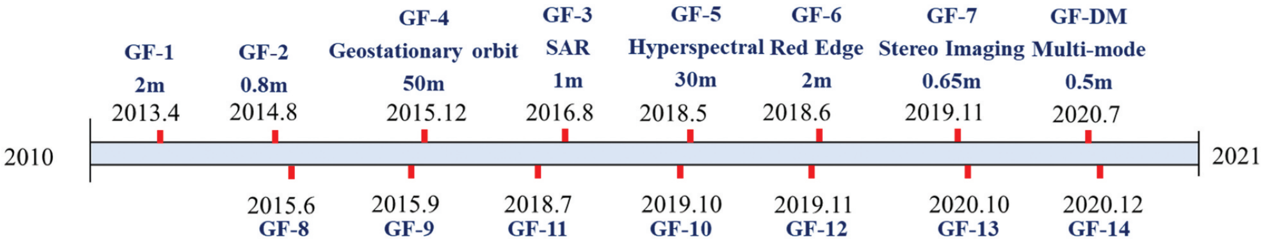


Figure 3. Development of Gaofen satellite series.

sensing technology and to satisfy the increasing remote sensing data requirement from economic and social, applicational, a technical program, namely "Gaofen", was kicked off in 2011. "Gaofen" means high-resolution in Chinese, which refers to realizing high spatial-spectral-temporal resolution observation of the Earth. At present, there are 8 high-resolution satellite series, denoted as GF (Figure 3), for civilian use, ranging from GF-1 to GF-7 and GF-DM, are introduced in this section.

As the first civilian high-resolution constellation, GF-1 contains 4 satellites that are equipped with optical payload with 2 m PAN and 8 m multispectral bands. GF-2 is the first civilian optical remote sensing satellite independently developed by China with a spatial resolution better than 1 m. Apart from high spatial resolution, the optimized design of wide-field imaging and high revisit rate of GF-2 satellite can achieve a revisit period of no more than 5 d in any region of the world with a satellite side-sway of ±23 °. GF-4 is a geostationary orbit satellite launched in 2015, which is equipped with optical payloads of 50 m multispectral bands and 400 m medium infrared band. GF-5 satellite was launched in 2018, which is equipped with optical payloads of 50 m multispectral bands and a 400 m medium infrared band (Zhong et al. 2021a). The payloads of GF-5 satellite include an advanced hyperspectral imager, visible and infrared multi-spectral sensor, environment monitoring instrument, greenhouse gases monitoring instrument, atmosphere infrared ultra-spectral spectrometer, and directional polarization camera. These payloads fully support the ecological environment and mineral resource monitoring, inland water and land surface imaging, temperature monitoring, gas monitoring, atmospheric composition profile monitoring, and cloud and aerosol monitoring. GF-6 is China's first agricultural high-resolution observation satellite equipped with optical payloads with 2 m PAN, 8 m multispectral bands, and a 16 m multispectral medium-resolution wide frame camera, which is capable of detecting the red edge spectrum for crop monitoring.

The GF-3 satellite constellation is a radar satellite constellation with three satellites, GF-3 01, GF-3 02, and GF-3 03. The satellites offer single-, dual-, and full-polarization methods with 12 imaging modes. The GF-3 01 satellite, launched on 10 August 2016, is the first C-band multi-polarization SAR satellite and the first high-resolution civilian SAR satellite in China. To meet the needs of rapid observation on land and sea, GF-3 02 and GF-3 03 satellites were launched in 2021 and 2022 respectively, which reduces the revisit interval from 0.6 d to 0.2 d. Led by the research team at Wuhan University, China's first global orthophoto map with an accuracy test better than 10 m is produced from GF-3 SAR images of 10 m spatial resolution. The product has shown its wide application value in audit, agriculture, forestry, water conservancy, environment, disaster, marine, etc (Zhang et al. 2022). Based on the accumulated knowledge and technology from SAR image processing, the first land deformation rate map of China is produced from the Sentinel-1 satellite. The validation from more than two thousand GNSS CORS station data shows that the error is 4.818 mm/y (Wang et al. 2022a, 2022b).

GF-7 satellite is the first optical stereo mapping satellite with sub-meter resolution in China. It is mainly used to obtain high spatial resolution stereo mapping remote sensing data and high-precision laser altimetry data and realize 1:10000 scale stereo mapping. The composition of a dual line array camera and two-beam laser altimeter in the surveying and mapping system of GF-7 satellite makes it possible to realize Laser optical composite mapping by associating "invisible" laser and "visible" images. The validation result in Table 5 shows that the accuracy is improved under composite surveying and mapping of GF-7 satellite stereo image and laser measuring point. With GF-7, it is feasible to generate the 3D model and digital surface model(DSM) of the city and nature (Tang et al. 2020).

Table 5. Accuracy evaluation of compositing GF-7 satellite stereo image and laser measuring point.

	Adjustment accuracy of free network(m)		Composite surveying and mapping processing accuracy(m)	
Terrain type	plane	altitude	plane	altitude
flat ground	6.59	3.07	6.24	0.42
hill	3.81	4.67	3.5	0.66
mountain country	4.32	2.86	4.41	0.74
alpine land	8.11	5.00	8.43	1.19

Driven by the “Medium and Long Term Development Plan for National Civil Space Infrastructure (2015–2025)”, the high-resolution multi-mode satellite (GF-DM) satellite was launched in July 2020 and was put into operation in January 2021. The satellite is equipped with high-resolution cameras, atmospheric synchronous correctors, and other operational payloads, achieving 8 multispectral spectral bands and 1 panchromatic band with a maximum resolution of 0.5 m, marking the highest resolution images obtained by China’s civilian satellites. Moreover, the GF-DM satellite can flexibly achieve various imaging modes such as multi-target imaging, multi-angle imaging, and stereo imaging in the same orbit. It can quickly switch from standby mode to imaging mode within 10 s after receiving the command.

Analysis Ready Data (ARD) as recommended by the Committee on Earth Observation Satellites (CEOS) has shown great application value in fostering long-time series analysis at a large scale with minimum additional user effort (Baraldi et al. 2022; Dwyer et al. 2018). To promote the use of Chinese satellite data, the Gaofen-1 data covering China and surrounding areas have been processed into ARD (Zhong et al. 2021b). During processing, some major challenges hamper the effective and efficient generation of ARD, including geolocation offset, radiometric inconsistency, and atmospheric effect (Zhong et al. 2021b). With further in-depth studies conducted to better address the challenges, we hope that more Chinese ARD are produced to supplement the spectral-spatiotemporal resolution of existing ARD, and better support the achievement of SDGs.

2.6. Development of environment monitoring satellites

“Lucid waters and lush mountains are invaluable assets” is one major principle behind China’s modernization drive, thus China has developed satellites for environment monitoring, disaster prevention, and carbon monitoring to pursue the SDGs raised by the United Nations (Zhang et al. 2019). Early in 2008, China launched the environment and disaster monitoring optical satellites HJ-1A and HJ-1B. Together with the radar satellite HJ-1C launched in 2012, they formed a constellation of three satellites to realize large-scale, all-weather, all-time dynamic monitoring of the ecological environment and disasters (Zhong et al. 2021a). Equipped with a wide coverage CCD camera, infrared multispectral scanner, hyperspectral imager, and Synthetic-aperture radar, the satellites form a complete series of EO constellations with high spatial, spectral, and temporal resolution with wide coverage. HJ-2A, HJ-2B, and HJ-2E, launched in 2019, 2019, and 2022, respectively, are the successor of the HJ-1 series with a longer design life and updated payload.

The atmospheric environment monitoring satellite was launched on 16 April 2022, and is operated normally and stably in orbit. The satellite carries out regional air quality and environment monitoring and provides data support for China’s comprehensive monitoring of the atmospheric environment, global climate change research, crop yield estimation, and agricultural disaster monitoring (Wang et al. 2021). The aerosol and carbon detection LiDAR payload is the world’s first sensor that is capable of acquiring all-day, high-precision global CO_2 column concentration data with an accuracy better than 1 ppm. On 4 August 2022, the Goumang satellite was launched to provide remote sensing services and improve the efficiency and accuracy of carbon sink measurement. The combination of Radar, multispectral camera, hyperspectral detector, and polarization imager endows the Goumang satellite with the capacity to monitor forest carbon sinks in both active and passive ways. It provides important support for China’s efforts to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 (Zhuang et al. 2022).

SDGSAT-1, the world’s first remote sensing satellite for sustainable development goal, Successfully launched on 5 November 2021. It provides data support for monitoring, evaluating, and scientific research on SDGs by characterizing traces of human activity and quantifying indicators that characterize the interaction between humans and nature (Guo et al. 2022). The satellite is equipped with high-performance low light, thermal infrared, and multispectral imagers. The low light imager has the ability to simultaneously obtain 10 m of panchromatic band and 40 m of low light bands. The thermal infrared imager can recognize surface temperature changes of 0.2°C with a resolution of 30 m. The multispectral imager can support the monitoring of vegetation growth and water quality through the red edge and deep blue band imaging design. SDGSAT-1 can provide strong support for urban sustainable development research.

2.7. Development of China’s commercial satellites

In 2015, China announced the “Medium and Long Term Development Plan of National Civil Space Infrastructure (2015–2025)”, which encouraged private enterprises to develop commercial aerospace, It marked the transition of China’s aerospace industry from single government-driving to a joint combination of government-driving and market-driving approaches. Moreover, China brought the satellite Internet into the scope of "new infrastructure" in 2020, and many provinces and cities have introduced policies and measures to encourage the commercialization of aerospace. China's commercial remote sensing has made great progress.

To list a few, the Jilin-1 satellite constellation is the core project under construction by Changguang Satellite Technology Co., Ltd. There are more than 100 satellites in orbit in the "Jilin-1" satellite constellation in space, making it the largest commercial optical remote sensing satellite constellation in China. It can provide rich remote sensing data and product services for fields such as agriculture, forestry, meteorology, oceans, resources, environmental protection, urban construction, and scientific experiments.

The SuperView satellite constellation is the first independently developed commercial remote-sensing satellite constellation in China. It is working on a "16 + 4 + 4+X" constellation, which is a 0.5 m high-resolution ratio commercial remote sensing satellite system consisting of 16 0.5 m-resolution ratio optical satellites, 4 high-end optical satellites, 4 microwave satellites with several video, hyperspectral, and other satellites. SuperView-1 01/02/03/04 satellite was successfully launched in 2016 and 2018. SuperView NEO-1 01/02 and SuperView NEO-2 01/02 were successfully launched in 2022. According to the plan, China's four-dimensional new-generation commercial remote sensing satellite system will be fully completed in 2025. By then, the system will have the capability of 25 high revisits a day worldwide, a high acquisition capability with a daily acquisition area of more than 30 million square kilometers, and an emergency delivery capability within 2 h.

The Beijing-2 civil and commercial remote sensing satellite constellation is composed of three 0.8 m Panchromatic and 3.2 m multispectral optical remote sensing satellites. Launched in July 2015, it can provide remote sensing satellite data and spatial information products with global coverage, and space and time resolution ratio. The Beijing-3 commercial remote sensing satellite project is conducted to work with the Beijing-2 remote sensing satellite constellation system in orbit to improve the satellite's ability to obtain efficient intelligent EO data with high agility and mobility.

The Zhuhai-1 satellite constellation is a commercial remote sensing micro nanosatellite constellation launched and operated by Zhuhai Obit Aerospace Technology Co., Ltd. The constellation is planned to consist of 34 satellites, including video satellites, hyperspectral satellites, radar satellites, high-resolution optical satellites, and infrared satellites. By June 2023, the Zhuhai-1 constellation has launched 12 satellites with four video satellites and eight hyperspectral satellites. The constellation can currently cover the world in 22.5 d and revisit specific regions in 1 d.

2.8. Applications of China's EO system

China's 50 years of development in China's EO system led to the accumulation of a large amount of EO data. Based on the fruitful EO data accumulation, the data-driven deep learning technique is playing an increasingly important role in automatic remote sensing image interpretation for various fields such as resource management, ecological environment monitoring, agriculture monitoring, and disaster emergency response (Guo et al. 2021; Zhu et al. 2017). This section introduces some applications of EO data for China's sustainable development.

EO data can be applied to large-scale natural resource mapping. Taking Jiangsu Province as an example, the deep learning model was trained with historical natural resource data of Nanjing City. 1 m natural resource remote sensing mapping of the entire Jiangsu Province within 3 d, with an overall mapping accuracy of 84.44%. Furthermore, a Chinese soil spectral library was constructed, which includes over 80,000 soil spectra from 15 provinces, 7 soil orders, and 20 land use types nationwide, providing important basic reference data for remote sensing monitoring and soil quality assessment (Hong et al. 2019, 2022; Wu et al. 2022). By integrating spectral libraries, multi-platform observation data, and remote sensing models, high-precision mapping of multiple types of natural resource assets can be achieved, and thus support ecological benefits evaluation.

In the field of agriculture monitoring, Zhuhai-1 hyperspectral data, together with multi-temporal Sentinel-2 data and unmanned aerial vehicle data, is successfully applied to crop mapping in Hubei Province. A deep learning network that combines multi-temporal and hyperspectral features is constructed to map crop information from multi-source remote sensing data. EO also helps monitor the situation of crops affected by disasters (Li, Wang, and Yang 2022). In response to the requirements of agricultural greenhouse mapping, a dense target deep learning extraction network (Chen et al. 2023; Ma et al. 2021) was designed to map agricultural greenhouses nationwide from a 0.5 m resolution EO image database with a size of 59.785 TB (Figure 4). In 2021, based on the investigation of flood disasters from multi-temporal images, the real-time monitoring of flood disasters is proposed to evaluate the distribution of crops affected by the disaster of each city and county, providing accurate estimation and timely assistance in agricultural disaster management.

China's EO data is also applied to national and global land cover mapping. Land cover mapping of Central Asia has been finished based on the ZY-3

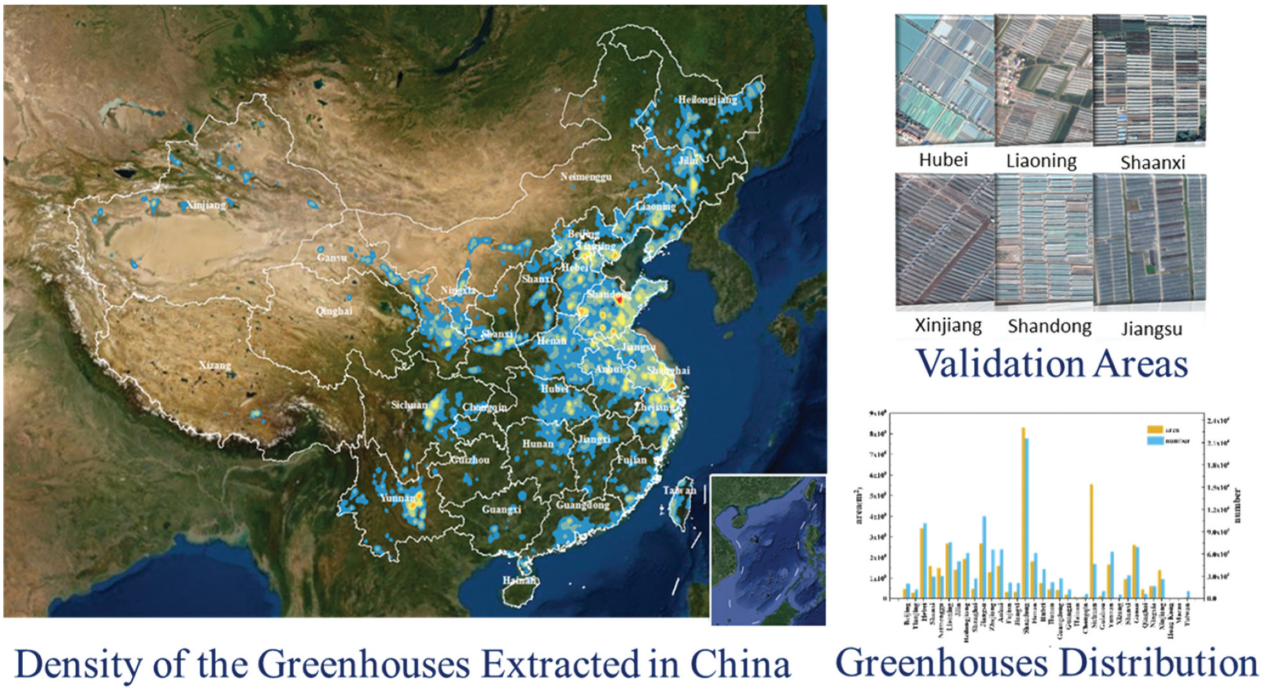


Figure 4. Illustration of nationwide greenhouses mapping in China.

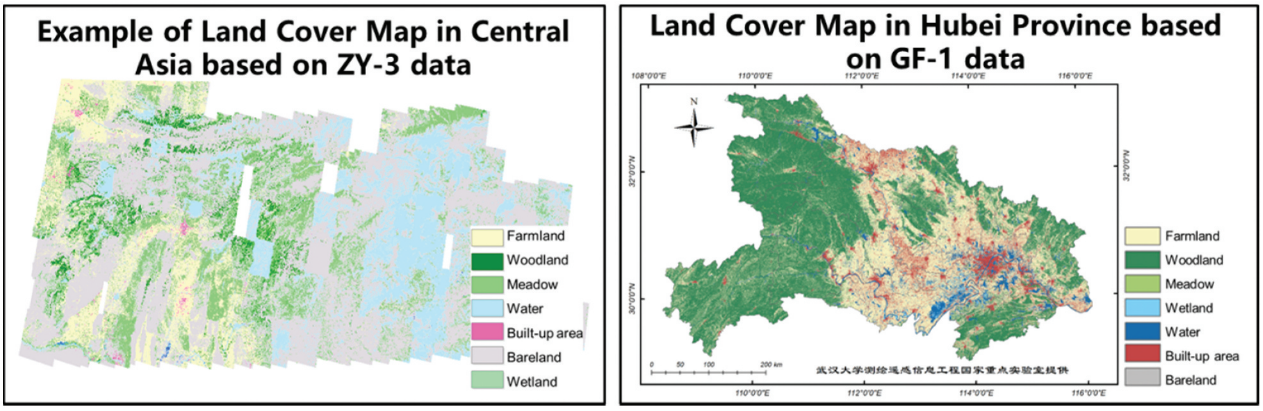


Figure 5. Land cover mapping examples in central Asia and Hubei Province, China.

satellite data, which provides data support for China's Belt and Road Initiative (Figure 5). Furthermore, a land-cover classification algorithm is proposed to generate fine-grained land-cover maps from multi-source high-resolution remote sensing images (Tong et al. 2020; Tong, Xia, and Zhu 2023). Based on their proposed large-scale GF-2 image GID dataset, the framework has shown great capacity in transferring to multi-source images such as GF-1, JL-1, and ZY-3 images (Figure 6).

In the case of disaster management, China's EO data, the Luojia-3 01 satellite data, has provided timely data services for the assessment of disasters such as earthquakes and collapse in Türkiye, Syria, Afghanistan, and China. In October 2023, Luojia-3 01 satellite data supported the United Nations's assessment of the earthquake disaster in Zendeh Jan district, Afghanistan (Figure 7). Destroyed buildings were successfully identified through comparison to historical remote sensing images. China's EO data were also used to monitor the water body changes in the disaster area of the rainstorm in Zhengzhou in July 2021, providing decision-making reference for emergency management (Figure 8). To realize timely disaster response, the first on-orbit intelligent processing system has been applied to disaster monitor and evaluation. The system is capable of searching and identifying forest fire points automatically in real-time. By further combing Beidou's short message transmission, it takes only 13 s from satellite observation, and on-orbit processing, to ground terminal messaging, which shortens the response time from hour-level to second-level.

Based on the accumulated data and technologies, a remote-sensing cloud computing platform, LuoJiaAI platform, is proposed (Zhang et al.

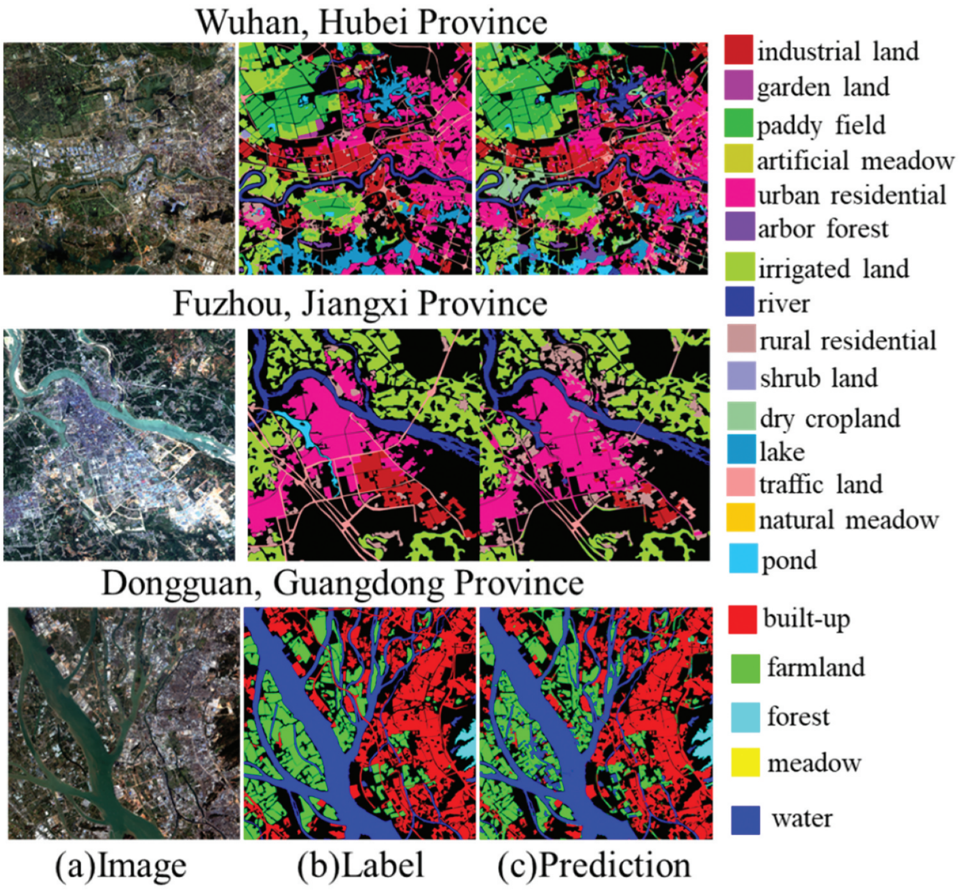


Figure 6. Land cover mapping from multi-source images(GF-1, JL-1, ZY-3).

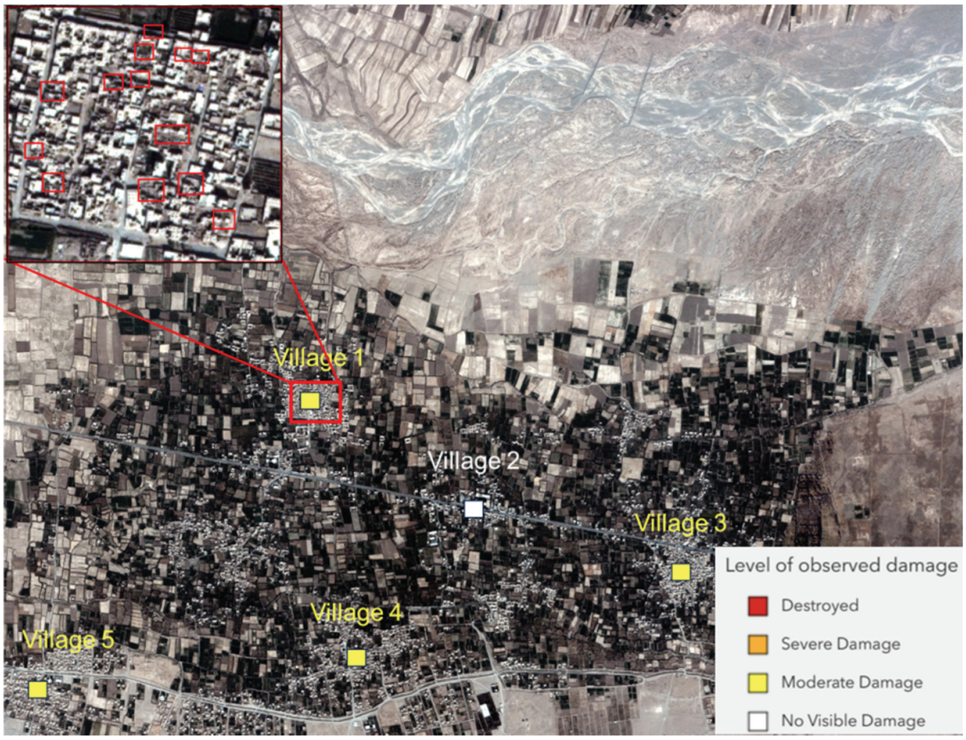


Figure 7. Luojia-3 01 satellite supports the earthquake disaster assessment in Afghanistan.

2023). It is composed of a large-scale remote sensing sample database(LuoJiaSET), and a well-designed deep learning framework(LuoJiaNET). By considering the spatiotemporal-spectral characteristics of remote sensing data, LuoJiaAI reaches outstanding performance on various remote sensing interpretation tasks, showing great potential in varied mapping applications.

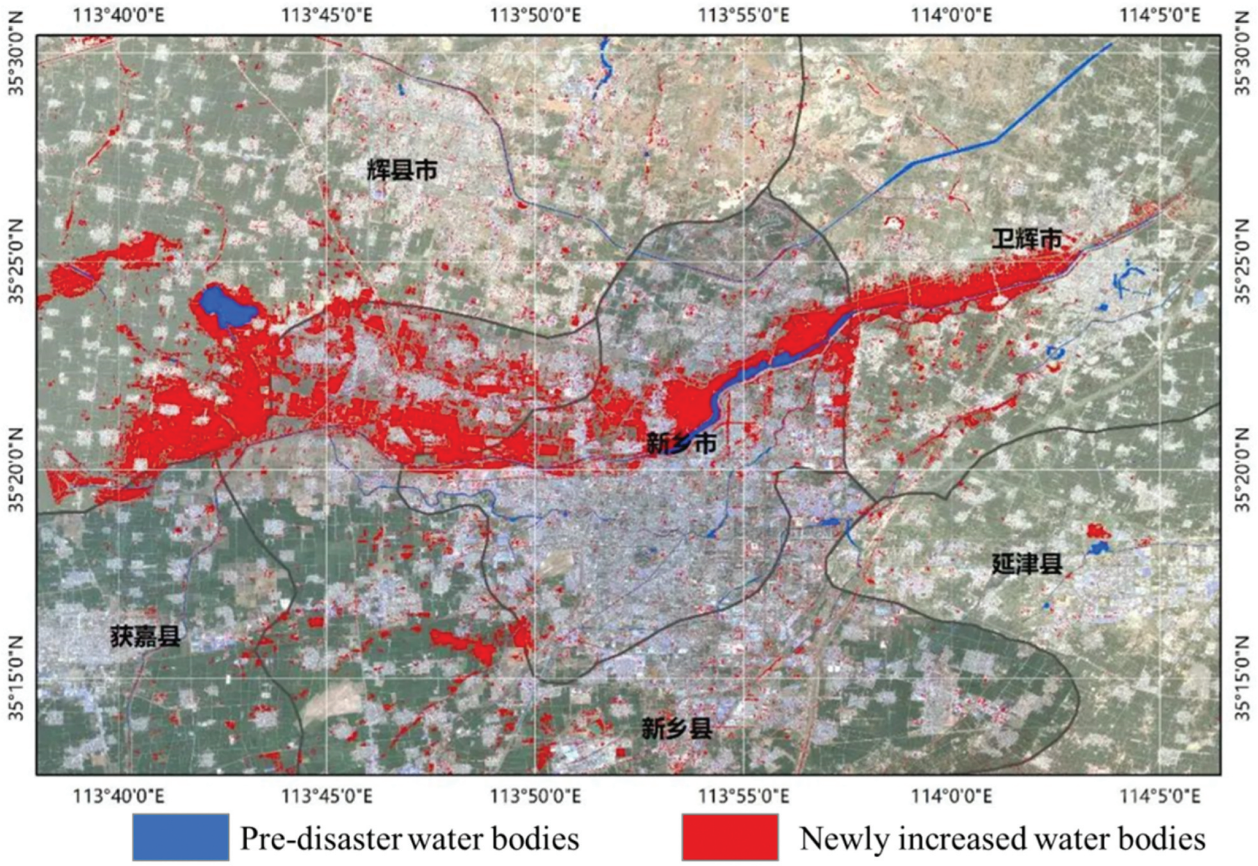


Figure 8. Monitoring flooded regions in Henan Province, China in 2021.

3. Future trends of China's EO development

3.1. From earth observation satellite to earth observation brain

China is currently operating more than 200 remote sensing satellites in orbit with the capability of obtaining global coverage of 16 m resolution optical data or global revisit of 2 m resolution optical data within 1 d. With the constellation composed of multiple satellites operating simultaneously in orbit, it is estimated that the amount of data obtained per day reaches hundreds of terabytes (TB). However, the traditional remote sensing image data acquisition and processing mode, which involves a tedious process of data acquisition, data transmission, ground station reception, processing, and product distribution, cannot meet the current requirements for remote sensing information acquisition (Wijata et al. 2023). In order to provide real-time, high-quality, and highly reliable spatial information for decision-making, the Earth observation system will enter a new era of intelligent perception and cognition similar to those of the brain (Li, Shen, et al. 2017), forming an Earth Observation Brain (EOB).

EOB is an intelligent earth observation system that simulates the perception and cognitive process of the human brain. By combining Geomatics, computer science, brain cognitive science, and other fields of knowledge, EOB is a real-time intelligent Earth observation system that integrates measurement, calibration, target perception, and cognition to serve users with a space-based spatial information network. In essence, EOB utilized technologies such as in-orbit image processing and satellite-ground coordinated calculation to analyze to obtain useful information and knowledge from geospatial data of remote sensing satellites, communication navigation constellations, airships, and aircraft. The information and knowledge serve user decision-making through real-time Earth observation and service under the satellite-ground collaboration. In the future, EOB can observe when, where, and what changes in what object and push this right information to the right people at the right time and right place (4 right services).

The Luojia-3 01 satellite, China's first internet intelligent remote sensing satellite launched on 15 January 2023, has achieved a breakthrough in achieving EOB by actively discovering and identifying targets of interest through in-orbit processing. It is the world's first intelligent remote-sensing satellite that is capable of providing intelligent and real-time remote sensing information service (Li, Wang, and Yang 2022). The satellite can perform cloud detection, object detection, moving object tracking, scene classification, change detection, etc. in orbit. Compared to the traditional remote sensing satellites that perform data analysis after data transmission, the high accuracy of Luojia-3 01 satellite in-orbit object detection and moving object tracking meets the needs of most real-time intelligent analysis applications. Meanwhile, the intelligent processing unit carried by the Luojia-3 01 satellite provides an open satellite algorithm platform for deep learning models, with 9 apps pre-installed in orbit, including object detection, change detection, and image compression. Users can flexibly update and uninstall onboard intelligent app algorithms according to different task requirements. Combined with deep learning algorithms, it makes the satellite more intelligent and provides a guarantee for real-time intelligent services for geospatial information.

3.2. Space-based real-time intelligent information service

At present, China has constructed advanced space-based systems for navigation, remote sensing, and communication. These systems, however, are operated in isolation with separate information, leading to the latency of services. Thus, it is urgent to develop the space-based real-time intelligent information system PNTRC that integrates Positioning and Navigation, Timing, Remote sensing, and Communication for fast, accurate, and flexible space-based information comprehensive services on a global scale (Li and Shen 2020). The development of the PNTRC system will push forward the aerospace information service to not only professional users but also public users (Li, Shen, et al. 2017).

PNTRC will consist of hundreds of low-orbit high-resolution optical and radar small satellites with remote sensing and navigation enhancement functions, forming a space-based network. It cooperates with high-resolution remote sensing, navigation, and communication satellite networks in orbit, and integrates with the internet and mobile network as a whole. With the joint support of space-based Big data, cloud computing, artificial intelligence, and the fifth generation of mobile communication technology, PNTRC provides users with accurate, intelligent, and real-time space-based information services from satellites to terminals.

Scientists in China have been working toward the realization of PNTRC. For example, the Collaborative Innovation Center of Geospatial Technology (INNOGST) has successively planned and launched a series of satellites, including “Luojia 1-01”, “Luojia 2-01”, and “Luojia 3-01” satellites, to validate the integration of communication, navigation, and remote sensing services, which will be introduced in succession.

Luojia 1-01 satellite, a Low Earth Orbit (LEO) satellite for nighttime light observation launched on 2 June 2018, provides nighttime light images that have been applied in a wide range of emergency services (Li et al. 2019), urbanization monitoring researches (Ou et al. 2019; Wang, Fan, and Wang 2020; Xia et al. 2020), etc. It is equipped with China’s first set of low-orbit navigation enhancement payloads that provide real-time orbit and timing for the satellite, achieving autonomous maintenance of the spacetime datum on board. Furthermore, experiments on Luojia 1-01 have demonstrated that low-orbit navigation enhancement technology can enhance the signals for BeiDou and GPS navigation satellite systems (Chen et al. 2022) at meter and centimeter levels.

On 21 May 2023, the CZ-2C carrier rocket successfully lifted off from Jiuquan Satellite Launch Center, deploying the “Luojia-2-01” satellite into its intended orbit. Overall, the Luojia 2-01 satellite is a scientific experimental satellite with high performance and advanced features. It is the world’s first Ka-band high-resolution SAR satellite. With a shorter wavelength than the existing SAR bands, Ka-band SAR obtains richer details of the object such as detailed flow information of ground objects (see Figure 9), water bodies, vegetation information, and precipitation information (see Figure 10), which meets various application needs such as flood evaluation and prevention. As for navigation enhancement, it conducted the world’s first international joint experiment on signal and information enhancement of LEO satellites, aiming to explore and validate key technologies for achieving seamless and instant high-precision positioning services worldwide.

Luojia-3 satellite, China’s first internet intelligent remote sensing satellite was launched on 15 January 2023 (Li, Wang, et al. 2023). It is the world’s first intelligent remote-sensing satellite that is capable of providing intelligent and real-time remote sensing information service. The launch of the Luojia-3 01 satellite is another innovative practice of integrated navigation and remote sensing intelligent remote sensing satellite, following the successful international first low-orbit navigation signal enhancement experiment of the Luojia-1 satellite. Luojia-3 satellite innovatively integrates the satellite with 5 G mobile communication, connecting the bidirectional link between satellites and mobile phones (Figure 11). It can achieve global minute-level intelligent services from remote sensing data to mobile phones and also support providing real-time intelligent services for remote sensing information to the general public. It has taken a milestone step toward the realization of PNTRC space-based real-time intelligent information service.

Despite effectiveness and widespread application, the existing navigation, communication, and remote

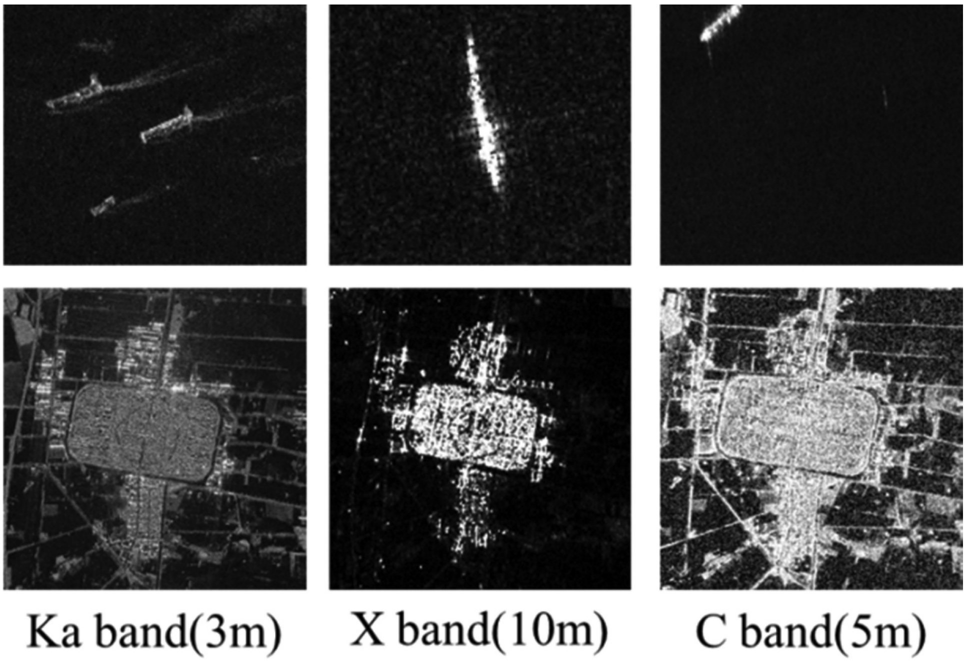


Figure 9. Comparison among Ka-band, X-band, and C-band.

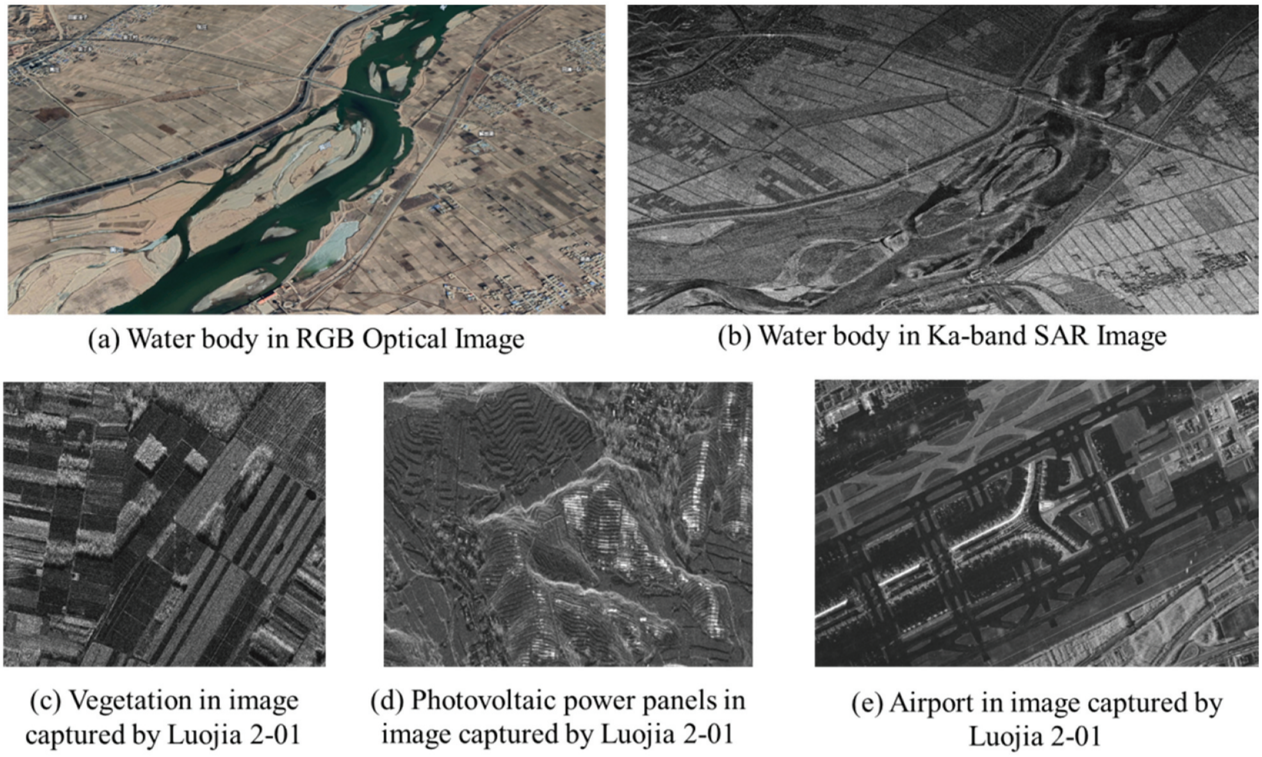


Figure 10. Comparison of Luojia 2-01 and other satellites. (a) Google earth image, (b)–(e) illustration of images captured by Luojia 2-01 satellite.

sensing information services still cannot meet the global timely application needs of professional and public users. To address these issues, the construction of low-cost satellite mega-constellations that integrate PNTRC for all-day, all-weather, and global information services has become a trend worldwide. In the United States, the Starlink satellite network project is promoted by SpaceX, which aims to establish satellite mega-constellations for global Internet coverage. Moreover, the system is planned to provide remote sensing services globally by integrating communication and Earth observation technologies in the future. OneWeb in the UK also plans to build a large-scale low-orbit satellite constellation for providing global internet coverage and serving users in remote areas. In China, the 14th Five-Year Plan proposes the requirements for constructing a global coverage and efficient spatial infrastructure system for

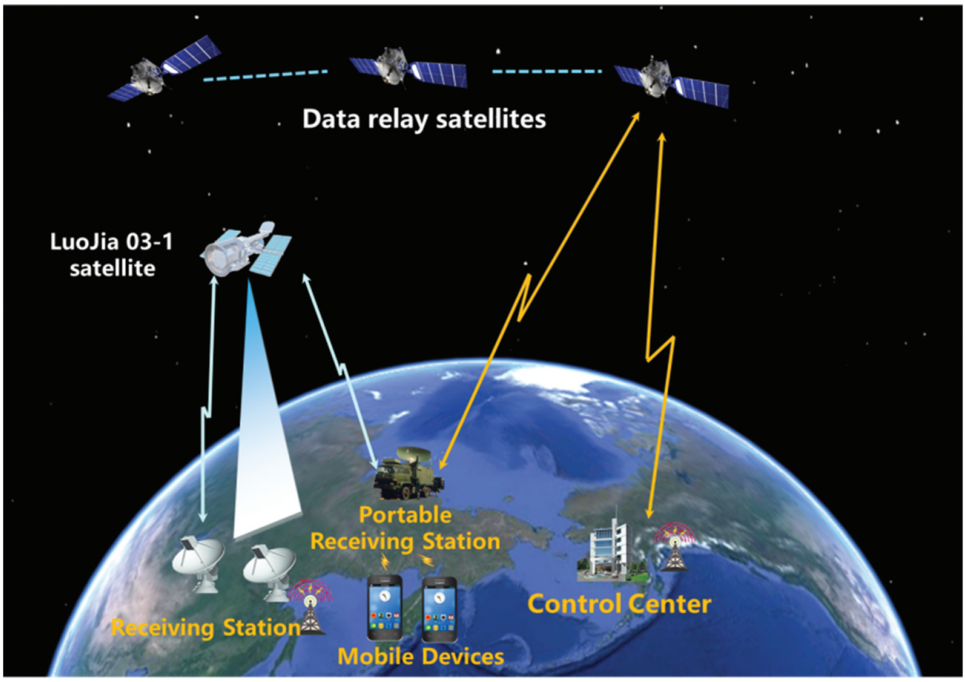


Figure 11. Intelligent and real-time remote sensing information service of Luojia3-01.

communication, navigation, and remote sensing, which supports the application needs of multiple fields. China's low-orbit satellite mega-constellation is now under construction, including the "Hongyan" and "Hongyun" constellation plans. In the EO field, existing remote sensing satellites capture and transmit data in discretization and cannot provide continuous spatiotemporal observation data for users. The low-orbit mega-constellation, however, will contain thousands of satellites with multiple types of payload, and thus provide continuous data services for multi-modal, large-scale, and sequential observation needs. To push forward the construction of satellite mega-constellations, a global real-time satellite constellation namely the Orient Smart Eye project is led by Wuhan University, started in 2022. Based on the technical foundation of low-orbit navigation enhancement, in-orbit real-time processing, and intelligent services from the Luojia series satellites, the Orient Smart Eye project is designed to provide global and ultra-high resolution EO images in an efficient, timely, and accurate manner (Li 2023). The project includes four phases: building a test system by 2024, a local system by 2025, a region system by 2027, and a global system by 2030. The system will provide hyperspectral images that cover the world every 5 d and offer high spatial-temporal EO images with spatial resolution higher than 0.3 m and temporal resolution higher than 5 min. As a result, it can serve B2B, B2G, and B2C businesses across a wide range of fields. At present, the first phase of the project is in progress, which aims to build a "1 + 2" constellation demonstration service system. Two world-leading hyperspectral satellites and an intelligent remote sensing optical satellite are to be launched, forming a satellite network that supports general surveys and detailed investigations.

By benchmarking the international first-class operational hyperspectral satellites such as Sentiniel-2 and Landsat, the hyperspectral satellites OSE-HS 01/02 of the Orient Smart Eye project are designed to possess track similarity, spectral compatibility, and data stability as the widely-used satellites such as Landsat and Sentiniel. Beyond this, OSE-HS 01/02 hyperspectral satellites will be equipped with more advanced indicators and wider applications. Specifically, it contains more spectral bands, higher resolution, a larger field of view, and is lower in weight. Moreover, it supports not only daytime hyperspectral imaging but also nighttime light imaging and covers both land and ocean regions. The satellites can achieve uncontrolled geometric positioning accuracy of sub-satellite point within 10 m, and relative positioning accuracy of sub-satellite point images within 1.5 pixels. In terms of observation capability, it will provide 5 m visible light bands (0.4 ~ 1.0 μm), 20 m shortwave infrared bands (0.9 ~ 1.7 μm), and 20 m nightlight bands, with an imaging width of 300 km. A detailed comparison of OSE-HS 01/02 with Sentiniel-2A/2B and Landsat-8/9 is presented in Table 6.

Overall, the construction of the PNTRC system involves seven key technological challenges to overcome: low-orbit satellite-based navigation enhancement, space-Earth Integration communication network, multi-source EO data in orbit processing, space-based information intelligent services, space-based resource scheduling and network security, multi-payload integrated platform, and the

Table 6. Comparison of Sentiniel-2A/2B, Landsat-8/9, OSE-HS 01/02.

Parameter	Sentinel-2A/2B	Landsat-8/9	OSE-HS01/02
Orbit	786 km	705 km	786 km
Width	290 km	185 km	300 km
Resolution	10 m/20 m/60 m	15 m/30 m/100 m	5 m/20 m
Spectral band	4/6/3	1/9/1	17/5
Data rate	1.36 Gbps	440 Mbps	28 Gbps
Data transmission rate	450 Mbps	384 Mbps	2×900 Mbps
Weight	1200 kg	1512 kg	~230 kg
Global coverage capability	5 d	8 d	5 d
AI	Unsupported	Unsupported	Support
Constellation deployment method	2A: 2015.6.23 2B: 2017.2.7	L8: 2013.2.11 L9: 2021.9.27	2024.6 One arrow two satellites
Life	D7 years/R12 years	D5 years/R10 years	D5 years

construction of spatiotemporal datum. The development of the PNTRC system will push forward the aerospace information service to professional and public users.

3.3. Deep space explorations

With 50 yr of development, China has accumulated rich and mature observation technologies, which play an important role in Chinese deep space explorations. Chang'e-4 mission, the fourth mission of China's Lunar Exploration Project and the second mission for landing and roving, the Yutu-2 rover was launched on 8 December 2018, and achieved a historic first for a soft landing on the moon's far side. As one of the key techniques, remote sensing mapping, navigation, and positioning technologies provided support for CE-4's landing, patrolling exploration, engineering tasks, and studies on topography, geomorphology, and mineral discovery. Mapping, topographic and geomorphologic analysis were conducted for the landing site region based on Chang'e-4 orbiter data. DOM of the landing site (in Lambert conformal conic projection) was produced using 100 LROC NAC images, which is of the highest resolution in this region. DOM made by the descent camera imagery has a spatial resolution of up to 0.03 m. Furthermore, monoscopic visual-based measurement provides the decision support for the separation of the rover and the lander base. Visual-based navigation, positioning, fine mapping, and obstacle recognition of exploration points guide the Yutu-2 rover traveled up to 1500 m until February 2023. Remote sensing technology also makes significant contributions to morphological evolution and mineral inversion in the landing area. For example, the evolution process of the landing area was studied by combining DEM measuring and numerical simulation, the space weathering effect and lunar soil maturity were assessed with Yutu-2 spectral data, the rock source in the landing area was revealed, etc.

In the CE-5 mission, China's first lunar probe that implements lunar surface sampling and return, remote sensing supported the mapping of the landing area and positioning of the landing site. The precise and timely lander location is a key parameter for making the plans of the ascender taking off from the lunar surface and the orbiter rendezvous and docking with the orbiter-returner combination. In the CE-5 mission, descent images, LROC NAC images, and other images taken by the landers were utilized to combine the radio-tracking method for lander localization. Moreover, the DOM of the landing site generated from the descent image has a spatial resolution of 0.1 m, which helps to provide geologic context for the CE-5 lunar samples analysis, such as topographic and geomorphologic analysis, crater counting, and dating. The combination of remote sensing analysis and sample analysis in the CE-5 mission brings about regional geological evolution and chronological model improvement.

Remote sensing mapping, navigation, and positioning techniques support the implementation of engineering missions and scientific research in the Tianwen-1 mission, China's first independent Mars exploration mission. Positioning and localization of Tianwen-1's landing site were made from image data including orbital images and related maps, sequential descent images, and NaTeCam images. The geomorphic landmarks on the horizon such as mountain peaks and crater rims were identified from the panoramic images taken before the rover left the lander; landmarks in the orbital DOM were identified to match the landmarks between the orbital images and rover images by the simulated NaTeCam images; the lander position was estimated through the landmark azimuth angles obtained with the rover images and location of the landmark on the orbiter images by analytical intersection method. The final landing site is the same as the previous localization result, demonstrating the effectiveness of image-based navigation and positioning. Remote sensing-based mapping, positioning, and navigation have demonstrated their effectiveness in previous missions and will play a more important role in China's deep space exploration in the future.

4. Conclusions

This paper reviews China's progress in the EO system and its applications in recent decades. The development of China's EO program had a later start than other major EO programs in the US and Europe, so it learned from and referred to the design experiences of these major EO systems in the world. Beyond this, China's EO system design takes the actual conditions of China, such as the complex terrain, contradiction between population and arable land, frequent natural disasters, etc, into consideration. Drawing on the experience of foreign countries, since 2014, the commercial aerospace industry has developed rapidly, increasing the quantity, quality, and intelligence of EO satellites, which push forward the integration of artificial intelligence and onboard data processing techniques for realizing B2C services. Over the past decades, the spatiotemporal-spectral resolution of China's EO system has been remarkably improved, and thus can better support the sustainable development goals(SDGs) through international science & technology cooperation such as the Dragon program and the WMO space program. It has been proven by practice that the EO system in China is helpful for economic construction and the improvement of living quality efficiently. In fact, a comprehensive earth observation system is essential for the social and economic development of all nations. With the advent of the Internet of Things era, developing and applying PNTRC will undoubtedly push forward satellite collaboration with countries around the world. Furthermore, constructing an Internet intelligent EO system based on PNTRC, onboard processing, and artificial intelligence will provide fast, accurate, and flexible services for various fields. The success of the Luojia series satellites has proven the realization of multi-mode, intelligent, real-time, and open EO services. We hope that the development of the upcoming Oriental Smart Eye Constellation can promote the innovative development of satellites in China.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Fundamental Research Funds for the Central Universities [Grant No. 2042022dx0002].

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Data availability statement

Part of the Chinese remote sensing satellite data is publicly available, the links are provided: the meteorological FY series data (http://www.nsmc.org.cn/), the high-resolution satellite, resource satellite, and environment monitoring satellite data (https://data.cresda.cn/), the ocean satellite data(http://www.nsoas.org.cn/). The commercial satellite data can be purchased from their corresponding websites.

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