CHINA'S HIGH-RESOLUTION EARTH OBSERVATION SYSTEM (CHEOS): ADVANCES AND PERSPECTIVES

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Commission III, ICWG III/IVb

KEY WORDS: High Resolution, Earth Observation Systems, GF Series Satellites, Remote Sensing Applications, Land Satellites.

ABSTRACT:

From the end of the "Eleventh Five-Year Plan", China had implemented a major project for a high-resolution Earth observation system, and completed all satellite launch tasks by 2020. CHEOS aims to build an Earth observation system with high spatial, temporal and spectral resolution in an all-round way, and actively meet the major national strategic needs of China's national defense, natural resource survey, disaster response and prevention. CHEOS has promoted the continuous maturity of high-resolution Earth observation technology in China and the wide application of high-resolution images. This paper reviews the development history of CHEOS, analyzes the technical characteristics and application status of the GF (means high resolution in Chinese) series of civil satellites, discusses the current problems and future development trends of CHEOS, and provides a reference for the subsequent promotion and application of the GF series satellites.

1. INTRODUCTION

Earth observation satellites have entered into the high-resolution era. The so-called high-resolution actually include high spatial, spectral, and temporal resolutions. High-spatial-resolution satellites can present rich ground information and details (e.g., vehicles, roofs, trails) with a resolution better than 5 m. The high-spectral resolution (i.e., hyperspectral) data can provide abundant spectral information with hundreds of narrow spectral bands (from the ultraviolet and visible to shortwave infrared) to qualitatively and quantitatively describe the physical properties of the land cover. The high-temporal resolution indicates a very small time interval or revisit circle, in order to precisely monitor the subtle change of targets of interest. The high-resolution satellite system has great potential for investigating the Earth's atmosphere, oceans, land, surface water, as well as their impacts to climate, energy, agriculture, environments, ecology, disasters, public security, etc.

At present, countries around the world are vigorously developing high-resolution Earth observation systems. Among them, the United States has formed a high-resolution earth observation system dominated by Worldview-1 (0.5 m), Worldview-2 (0.46 m), Worldview-3 (0.31 m), WorldView-4 (0.31 m) and GeoEye (0.41 m), in which the highest resolution can be finer than 0.3m, and the observation area in a single day can reach 300 km^2 (Li et al., 2021a). In addition, the United States further uses small satellite constellations, such as PlanetScope, RapidEye, SkySat, etc., to achieve extremely high temporal and spatial resolution. French SPOT (1.5-2.5 m) and Pleiades (0.5 m) series satellite constellation, which can achieve 2 revisit circles within 24 hours. Russia's Resurs-P1 (1 m), Resurs-DK1 (1 m) satellites, Japan's ALOS (2.5 m) satellites, India's CartoSAT-1 (2.5 m) and CartoSAT-2 (0.8 m) satellites, Israel's EROS-A (1.9 m) and EROS-B (0.7 m) satellites have been launched successively, continuing to promote the high-resolution earth observation technology (Tong, 2016a). Remote sensing satellites are developing towards high spatial resolution, high spectral resolution, high temporal resolution, multiple observation modes, and small agility.

In this background, the China High-resolution Earth Observation System (CHEOS) has been determined as one of the major projects in the national development strategy (2006~2020). CHEOS was initiated by the State Council of the People's Republic of China, and started to launch a series of high-resolution satellites (GF series) from 2013, and was expected to complete in 2020. The CHEOS planned to build an advanced earth observation system that could provide high spatial, temporal and spectral resolution images and had high-precision observation capabilities (better than 1m). Its mission was to achieve space-time coordinated, full-time, full-weather and worldwide coverage Earth observations, which could satisfy diverse needs in key areas such as disaster prevention, national security, land and water resources, salubrious environment, refined urban management, geographic surveying and mapping.

2020 was the final year of China's GF project. The CHEOS successfully launched 12 civilian satellites including GF-1, GF-2, and GF-7, achieving a powerful Earth observation capability. The CHEOS led by high-resolution satellites had been formed, which not only realized the sufficient supply of high-resolution images, but also ensured the autonomous and timely data collection.

This paper systematically sorts out and summarizes the characteristics and application status of China's GF series civilian satellites, which will help to understand the progress of CHEOS and provide a reference for the further development and applications of high-resolution satellites.

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https://doi.org/10.5194/isprs-annals-V-3-2022-583-2022

2. OVERVIEW OF THE GF SATELLITES

The current CHEOS includes seven civilian satellites (Table 1). GF-1, the first satellite launched by CHEOS, can acquire panchromatic images with a spatial resolution of 2 m and multispectral images with a spatial resolution of 8 m. The GF-2 satellite, launched in 2014, can autonomously obtain 1 m panoramic images and 4 m multispectral images. Subsequently, the GF-3 to GF-6 satellites were launched successively, which cooperated with the orbiting satellites GF-1 and GF-2 to jointly promote the application of high-resolution images, marking that the high-resolution image applications of China's satellites have entered a stage of rapid development. The GF-7 satellite, launched in 2018, has improved the plane accuracy and elevation accuracy, which can draw a 1:10,000 topographic map (Sun et al., 2020). This achievement can fill the gap of civilian satellite data in local areas. From 2018 to 2021, the successors of GF-1 and GF-3 were launched successively. Multi-satellite networking forms a satellite constellation, which improves the revisit period and spatial resolution. So far, CHEOS contains multi/hyperspectral, optical/radar, Sun/Earth-synchronous orbit, LiDAR (Light Detection and Ranging), thermal infrared sensors, which constitutes a comprehensive high-resolution Earth observation platform. The characteristics of the GF satellites are introduced as follows.

2.1 The GF-1 Satellite

GF-1 was launched in April 2013, which was configured with two panchromatic cameras, a multispectral camera, four multispectral medium-resolution and wide-field cameras. All cameras can observe the earth simultaneously or separately. The most notable merit of GF-1 is its wide field view (WFV) mode, which can achieve large swath width (800 km) and quick revisit (4 days). By large roll, it can achieve quick coverage in 2 days, greatly superior to its counterparts.

The GF-1 satellite has broken through the optical remote sensing technology such as high spatial resolution, high temporal resolution, advanced attitude control technology, high-reliability satellite technology with a life span of 5 to 8 years, high-resolution data processing and applications and other key technologies (Tong et al., 2016b). The successful launch of GF-1 is of great significance for promoting the improvement of China's satellite technology and improving the self-sufficiency of high-resolution images.

In 2018, the GF-1 02/03/04 satellites were successfully launched, forming China's first civil high-resolution optical satellites constellation with the orbiting GF-1 satellite. Each satellite carries two 2/8m optical cameras. Compared with GF-1, GF-1 02/03/04 satellites have a longer design life. The daily revisit circle of the three satellites has been increased from 8 to 16 days, and the cumulative imaging time has increased by 25%. In addition, the three satellites can be evenly distributed in the Earth's orbit, which is beneficial for a quick revisit. Thanks to the "geese array" arrangement, the three satellites can also help achieve stereo mapping and large-scale imaging. The operational constellation jointly constructed with GF-1 and the three satellites can shorten the earth coverage period to 11 days.

2.2 The GF-2 Satellite

The GF-2 spacecraft was launched in August 2014. The strength of GF-2 is the very high spatial resolution (0.8 m). It is the China’s first sub-meter level civilian optical satellite. It employs two Panchromatic (PAN) /multi-spectral (MS) cameras with a swath of 45 km. In addition to its sub-meter resolution, the GF-2 also has high location accuracy. By introducing high-precision satellite orbit position determination, attitude determination and high stability and rapid roll attitude control, the positioning accuracy of GF-2 satellite without ground control points is designed to reach 20-35 m. The track design with wide earth coverage and high revisit rate can realize the revisit period of no more than 5 days in any region of the world. The use of GF-2 image data signifies that China's remote sensing satellites have entered the sub-meter "high resolution era".

2.3 The GF-3 Satellite

GF-3 is China’s first C-band multi-polarized SAR satellite with a resolution of 1 m, which was launched in 2016. It is also the highest resolution C-band multi-polarization satellite around the world. Its main advantages involve high-spatial-resolution, all-time and all-weather observation, and multiple imaging modes. The microwave image obtained by the GF-3 satellite has good performance, not only can obtain the geometric information of the target, but also support the user's high quantitative inversion application. The GF-3 satellite has 12 imaging modes, including spotlight, strip map and scan, with four polarization capabilities. In addition, the combination of a large swath width and the advantages of high spatial resolution, GF-3 can not only achieve a large-scale census, but also a detailed survey of specific areas, which can meet the needs of different users for different imaging.

The GF-3 satellite has been fully optimized in the system design. Its main advantages include high resolution, large wide imaging, multiple imaging modes, and long-life operation. The main technical indicators have reached or exceeded the international level of similar satellites, significantly improving China's Earth Remote Sensing Observation capability. In summary, GF-3 is an important foundation for the CHEOS to achieve the space-time coordination, all-weather, all-day Earth observation goal.

2.4 The GF-4 Satellite

The GF-4 satellite is China's first high-resolution earth observation satellite in Earth-synchronous orbit with the highest resolution in the world. It was successfully launched in December 2015. A panchromatic/multispectral camera with a resolution better than 50 m (single-view imaging swath width better than 500 km) and a mid-wave infrared camera with a resolution better than 400 m (single-view imaging swath width better than 400 km) are equipped. The GF-4 has a smart operation mode (universal, continuous, regional and maneuvering), making it very suitable for disaster management.

2.5 The GF-5 Satellite

The GF-5 satellite, launched in May 2018, is the only hyperspectral satellite of CHEOS and also the only one that provides the thermal infrared (TIR) sensor. The GF-5 satellite carried AHSI, VIMS, GMI, AIUS, EMI and DPC payloads for the first time. It has very strong ability of monitoring atmospheric environment, and providing sufficient data for analyzing the China’s air pollution. The GF-5 satellite has a hyperspectral camera that combines both wide coverage and wide spectral bands, and can acquire 330 spectral bands at 60 km swath width and 30 m spatial resolution. Moreover, the four TIR channels, whose spatial resolution (40 m) is much better than the existing TIR sensors,

Satellite	Sensors	Band Number	Spatial Resolution / m	Swath Width / km	Launch	Revisit	Orbit Altitude / km	Sensors
GF-1	panchromatic	1	2	60	2013	4 days	645	sun-synchronous
	multispectral	4	8					
	Multispectral (Wide field view)	4	16	800		2 days		
GF-2	panchromatic	1	0.8	45	2014	5 days	631	sun-synchronous
	multispectral	4	3.2					
GF-3	synthetic aperture radar (SAR)	1	1~500	5~650	2016	3 days	755	Sun-synchronous return to twilight
GF-4	visible and near-infrared	5	50	400	2015	20 sec-onds	36,000	Earth-synchronous
	middle-wave infrared	1	400					
GF-5	Advanced Hyperspectral Imager (AHSI)	330	30	60	2018	5 days	708	sun-synchronous
	Visual and Infrared Multispectral Sensor (VIMS)	12	20/40					
	Greenhouse-gases Monitoring Instrument (GMI)	4	NA					
	Atmospheric Infrared Ultra spectral (AIUS)	NA	NA					
	Environment Monitoring Instrument (EMI)	NA	>48km（perpendicular to track）×13km（along track）					
	Directional Polarization Camera (DPC)	8	Better than 3.5km (at nadir)					
GF-6	panchromatic	1	2	90	2018	4 days	645	sun-synchronous
	multispectral	4	8					
	Multispectral (Wide field view)	8	16	800		2 days		
GF-7	dual-line array camera (DLC)	1	backward: 0.65; forward: 0.8	20	2019	5 days	505	sun-synchronous
	multispectral	4	2.6					
GF-1 02/03/04	panchromatic	1	2	66	2018	2 days	645	sun-synchronous
	multispectral	4	8					
GF-3 02	SAR	1	1	NA	2021	1 days	755	sun-synchronous

‘NA’ = not available

Table 1. Specifications of the GF satellite series.

such as ASTER (90 m), Landsat-8 (100 m), MODIS (1 km), are potential for monitoring urban environments, human activity, heat island, and mineral exploration, etc.

2.6 The GF-6 Satellite

GF-6 is China's first low-orbit optical remote sensing satellite for precision agricultural observation. It was launched in June 2018. GF-6 is twinned with GF-1. They have the same spatial resolution and swath width, but GF-6 provides a "red edge" band to depict the spectral properties of the land cover. GF-6 and GF-1, as satellite constellations, mainly serve agriculture and rural areas, natural resources, emergency management, ecological environment, etc.

2.7 The GF-7 Satellite

The multi-angle imaging mode of GF-7 is similar to ZY-3 (China's first high-resolution stereo mapping satellite), but the spatial resolution of GF-7 (0.8 m) has been significantly raised, compared to ZY-3 (2.5 m). The high-resolution multi-angular data can accurately simulate the topography and Earth surface. The GF-7 satellite realizes stereo mapping through the combined mapping of stereo camera and laser altimeter, serving natural resources survey and monitoring, basic surveying and mapping, etc.

3. ADVANCES ON THE APPLICATIONS OF GF SATELLITES

Due to the rich sensor types and high-resolution data supply of the GF series civil satellites, the GF satellites have been successfully applied in a wide variety of fields since they were put into use. Among them, it mainly serves the fields of national disaster monitoring and mitigation, resource investigation and monitoring, urban refined management, national security, environmental monitoring, national strategic planning and major project monitoring. Each satellite focuses on a different field of application due to its unique design.

The applications of GF-1 are significantly more compared to other GF satellites due to its early launch. Its data are widely applied in the fields of land dynamic monitoring, environment monitoring, disaster monitoring and mitigation, etc. The images acquired by the GF-1 WFV sensor were found effective for agricultural monitoring and water resources monitoring. The GF-1 WFV data can capture the spectral differences between Ulva and Sargassum (Xiao et al., 2021), and can be applied to monitor macroalgal disasters, red tides, etc. GF-1 WFV images have enhanced quantization level, high signal-to-noise ratio, and high radiometric sensitivity compared to its predecessors (e.g., Chinese HJ-1, Landsat-7 ETM+), and presented promising accuracy for monitoring the suspended particulate matter from Poyang Lake, China (Li et al., 2015). GF-1 WFV data provide efficient estimates of fractional vegetation cover, which is an essential input parameter for climate, hydrological, and other land surface models (Jia et al., 2016). In addition, GF-1 WFV can also be used to estimate biophysical parameters such as evapotranspiration, soil moisture, soil organic carbon density, etc., which play a crucial role in crop yield forecasting, water resource management, and climate change research. GF-1 WFV images have also been attempted for retrieving high spatial resolution aerosol optical properties (e.g., aerosol optical depth), which can significantly influence the Earth atmospheric radiative balance, and have important climatic and environmental effects (Bao et al., 2016). GF-1 images presented great potential in the disaster response and assessment. It was reported that GF-1 multispectral images were successfully applied to monitoring the barrier lake formed by the landslides, in the Ms 6.5 earthquake in Ludian county, Yunnan Province, China on August 3, 2014 (Chen et al., 2017a). And GF-1 was also applied to the monitoring of seismic deformation induced by the Mw 6.9 Yutian earthquake in Xinjiang, China on February 12, 2014 (Li et al., 2016). GF-1 also provided data on the floods in Northeast China, smog in North China and earthquake in Pakistan during the test period.

GF-2 satellite images can provide more ground details and spatial (e.g., structural and textural) information, by courtesy of their higher spatial resolution (sub-meter level). It provides data support for the fields of dynamic monitoring of land use, refined urban management, traffic planning, agriculture and forestry resource management. GF-2 images can realize scene-level and pixel-level land use classification (Tong et al., 2020), extract different styles of rural settlements (Zheng et al., 2017), extract urban black and odorous water bodies (Shen et al., 2019), etc., which play an essential role in land and urban-rural refined management. GF-2 images are effectively applied in forestry and agricultural resource monitoring due to their easy availability and high resolution. It is widely used to estimate woody aboveground biomass (Shi et al., 2021), forest growing stem volume (GSV) (Li et al., 2021b), and monitor the distribution of winter wheat and agricultural greenhouses, which are of great significance for scientific management of agriculture and forestry, ecosystem dynamics monitoring, and environmental change research. GF2 images can also be used to road extraction, traffic density estimation, etc., providing a reference for road network planning.

The C-band SAR GF-3 satellite is not affected by weather and climate, and has the characteristics of full polarization, high spatial resolution, and wide-swath imaging. It is an effective tool for studying oceans and glaciers. Li et al. (2018) reported the capability of GF-3 quad-polarized data for sea surface wind retrievals and wave mode retrievals of sea surface waves. Ren et al. (2017) validated the ability of GF-3 in each polarization for extracting ocean wind. Furthermore, its capability of observing the ocean wave fields (including wave height, wavelength, and direction) was also reported (Yang et al., 2017, Wang et al., 2018). GF-3 was effective to detect marine targets, such as ship and sea ice, etc. (Wang et al., 2021, Tianyu et al., 2021). Moreover, GF-3 images can also perform glacier dynamic monitoring to accurately identify the locations of ice lakes, rivers and glacial crevasses.

China is one of the countries that suffer from a variety of natural disasters, e.g., drought, typhoon, flood, earthquake. GF-4 is very potential for disaster management, because of providing dense time-series data for the slow process disasters (e.g., drought) as well as their anomaly change detection (Fan et al., 2016). More importantly, GF-4 is capable of providing emergency response for flood, fire, and earthquake, due to its Earth-synchronous orbit design and large planar-array staring imaging system. GF-4 images can be applied to monitor the speed and direction of typhoon's top clouds, and provide early warning for typhoon disasters (Liu et al., 2019). It can also capture minute variations and fine details of tidal suspended sediment, which is helpful to study the effect of tides on suspended sediments (Chen et al., 2021). In addition, its potential for ship detection and maritime traffic surveillance has been verified, benefiting from the short interval between the acquisition times (Zhang et al., 2017).

GF-5 is equipped with 6 different designed payloads, which are widely used in atmospheric aerosol, greenhouse gas and other environmental elements monitoring and surface temperature retrieval research. EMI has been used to measure the distribution of nitrogen dioxide (NO_2) over the world (Yang et al., 2017), while AIUS has been applied to measure O_3 and other trace gases in the upper troposphere and stratosphere over Antarctica. DPC can realize multi-angle earth observation and shows promising potential in aerosol retrieval. The VIMS payload can acquire four-channel TIR images with a spatial resolution of 40 meters. It can be widely used in land surface temperature and sea surface temperature retrieval with high accuracy (root mean square error less than 1K) (Xin et al., 2017). Additionally, the AHSI payload provides potentially new hyperspectral data with 330 visible and near-infrared spectral bands. Its shortwave infrared data is reported to have a high signal-to-noise ratio (SNR) and is suitable for large-area lithology mapping (Bei et al., 2020). Its higher spectral resolution data of 5 nm proved to be a great contributor to distinguishing mangrove species (Wan et al., 2020).

New features such as red edge band, wide field view, and high-frequency imaging make the GF-6 widely used in the field of precision agricultural observation. Multi-temporal WFV data can be used for vegetation index time series research, which is of great significance for revealing crop phenology information. The addition of red edge band improves rice mapping and growth monitoring capabilities (Jiang et al., 2021). Furthermore, the multi-temporal data of GF-6 and GF-1 can be used to accurately identify abandoned jujube fields, providing a basis for adjusting agricultural production and controlling pests and diseases.

Multi-view and multi-spectral satellite images can clearly describe the plane and vertical information of the city. Therefore, the application of GF-7 mainly focuses on the acquisition of urban 3D information, such as DSM production and 3D modeling of urban buildings. For instance, Luo et al. (2021) obtained building footprints from GF-7 satellite imagery and extracted building heights from digital surface models.

4. COMPARISON OF GF SATELLITES AND OTHER MAINSTREAM SERIES SATELLITES

CHEOS is a government-funded Earth observation program that has launched several different kinds of satellites for research. The Landsat program funded by NASA and USGS is the longest-running Earth observation program, with eight Landsat satellites launched between 1972 and 2013. Landsat 8 is currently in service and is widely used thanks to its rich data reserves. The Sentinel satellites are dedicated satellites of the European Copernicus program, and a total of 6 different types of satellites have been launched. Compared with Landsat's focus on terrestrial observations, CHEOS and Sentinel have a wider range of applications, including oceanographic, meteorological, and terrestrial observations. CHEOS is independently developed by China. The data quality of the GF satellites is comparable to or even exceeds the international leading level, and the service life is longer, which makes GF satellites have great application potential.

4.1 Optical Satellites Comparison

GF-1, GF-2, Lansat8, Sentinel-2A are optical satellites with the advantages of high data accuracy and rich imaging bands. They are widely used in land resource management, change monitoring, precision agriculture and other fields. The specific design parameters are shown in Table 2. These four satellites are in good operating condition, with high data quality and free to use, which are complementary data sources.

GF-1 and GF-2 have high data consistency, but there are certain differences with Lansat8 and Sentinel-2A. As shown in Table 2, the multispectral data of GF-1 and GF-2 have the highest spatial resolution among these four satellites, reaching 8 m and 4 m, respectively. The higher the spatial resolution of the image, the easier it is to capture the spectral information of small objects, so the dynamic range of apparent reflectance in the same area will be larger. In addition, GF-1 and GF-2 have the highest temporal resolution, and the revisit period is only 4 days. Except for the difference in spatial resolution, GF-1 and GF-2 have roughly the same parameters and high similarity.

Lansat8 and Sentinel-2A have abundant imaging bands. Sentinel-2A has more comprehensive spectral resolution at the red edge and NIR than Landsat8. In addition, Sentinel-2A has designed bands such as aerosol, cirrus, and short-wave infrared, which are beneficial to identify vegetation, snow, clouds, ice, etc. Sentinel-2A has stronger application potential than Landsat in global vegetation ecological monitoring. Relevant studies have shown that the signals of GF-1 and GF-2 in the visible light band are higher than that of Landsat8, and slightly lower than that of Landsat8 in the NIR band (Yang, 2018, Yang Tianpeng, 2017). This is because Landsat8 removes the negative effect of water vapor absorption at 0.825 μm in the NIR band. The spectral range of GF-1 and GF-2 in the visible light band is wider than that of Sentinel-2A. The wider the spectral range, the more energy the sensor gets.

In summary, GF-1 and GF-2 have advantages in temporal and spatial resolution, and can obtain more sensor capabilities in the visible light band. While it may be useful in the NIR band to improve the spectral range to eliminate the signal trough caused by the influence of water vapor.

4.2 SAR Satellites Comparison

Both Sentinel-1 and GF-3 satellites are C-band SAR satellites, and the technical parameters are compared in Table 3. Sentinel-1 has lower resolution (4 m) and fewer working modes (Strip map, Interferometric Wide, Extra Wide, Wave mode). Both SAR satellites are widely used in ocean monitoring, disaster reduction and other fields. In the sea wind field inversion, Wan et al. (2021) found that Sentinel-1 and GF-3 achieved comparable inversion results (root mean square error less than 2 m/s). This shows that the GF-3 satellite has satisfactory data quality and has great potential in the field of marine research. Because SAR can provide intensity and phase information, both satellites can achieve good results in co-seismic deformation monitoring(Chen et al., 2020), which is beneficial to help earthquake prevention and disaster mitigation.

In addition to the above-mentioned satellites, there are several satellites operating in the GF and Sentinel series. Both in Earth-synchronous orbit, the spatial resolution of GF-4 (50 m) is better than that of Sentinel-4 (8 km), and the revisit is much lower than Sentinel-4. Therefore, GF-4 has potential in disaster response. GF-5 and Sentinel-5 are designed for tasks such as atmospheric monitoring, but GF-5 has a higher spatial resolution. Besides, GF-5 is a hyperspectral satellite equipped with 6 kinds of payloads such as AHSI, which is lacking in Sentinel series. GF-5 can be used for various studies such as temperature inversion. In addition, Sentinel-3 and Sentinel-6 are mainly used for marine monitoring. The radar altimeter onboard Sentinel-6 is capable of mapping sea level, but satellites dedicated to ocean monitoring are lacking in the GF series. Finally, the GF-7 is a stereoscopic imaging satellite that captures three-dimensional information and is essential for urban management, which is currently missing from the Sentinel series.

Satellites	GF-1	GF-2	Landsat 8(OLI)	Sentinel-2A(MSI)
Spatial Resolution / m	8	4	30	10
Radiometric Resolution / bit	10	10	12	10
Launch	2013	2014	2013	2015
Revisit	4	4	16	10
Bands	4	4	7	12
Wavelength / μm				
Blue	0.45~0.52	0.45~0.52	0.45~0.52	0.44~0.54
Green	0.52~0.59	0.52~0.59	0.53~0.60	0.54~0.58
Red	0.63~0.69	0.63~0.69	0.63~0.68	0.65~0.68
Near Infrared (NIR)	0.77~0.89	0.77~0.89	0.85~0.89	0.76~0.91

Table 2. Parameters of four optical satellites.

SAR Satellites	GF-3	Sentinel-1
Spatial Resolution / m	1	5
Swath Width / km	5~650	400
Launch	2016	2014(Sentinel-1A) 2016(Sentinel-1B)
Revisit	3	12
Orbit Altitude / km	755	693
Mode	12	4

Table 3. Parameters of GF-3 and Sentinel-1.

To sum up, GF series satellites have a variety of sensors, such as optical/SAR, multi/hyperspectral, low-orbit/high-orbit, thermal infrared, and their application fields are wider than Sentinel. It is worth mentioning that the temporal and spatial resolution of the GF series is generally better than that of the Sentinel series, which can provide high-quality data to meet practical application needs.

5. PROBLEMS AND PROSPECTS

China's industry of remote sensing has achieved a leapfrogging development, under the implementation of CHEOS. GF satellite data are playing an important role in the domestic market, and a large number of major and key technologies (e.g., data acquisition, processing, and applications) on the high-resolution Earth observation have been broken through. However, there are still problems and prospects.

5.1 Problems

1) Preprocessing of the GF images can be further improved. For instance, although the China Centre for Resources Satellite Data and Application (CRESDA) has published the radiometric calibration coefficients of GF-4, the accuracy and uncertainty have been not verified. Therefore, users tend to employ the cross-calibration as an alternative to calibrate GF-4 images by referring to other satellite data, e.g., Landsat (Chen et al., 2017b). This problem also occurred for other GF satellites. Another major issue is that the geo-positioning accuracy of the GF images is not very satisfactory, which may lead to serious problems for image matching, image mosaicking, and time series analysis.

2) The Earth observation ability of the GF satellites deserves further investigation and development. In particular, the hyperspectral camera of GF-5 can provide over 300 spectral channels, therefore, it is anticipated whether its radiometric model is accurate and application requirements can be satisfied. It should be also noticed that the system of the optical satellites has been effectively established. But relatively, development of the SAR satellites is still not complete, and there is only one radar satellite (GF-3) in the CHEOS. In addition to the unbalanced development of sensor types, there are also current shortcomings such as similar orbital heights and overlapping spectral ranges (Sun et al., 2020).

3) At present, much satellite related research focuses on the data processing, but the application research is relatively lacking. For example, GF series satellites are used in the fields of atmospheric aerosol, forestry and agricultural resource monitoring, land use monitoring, etc., but they have not shown their due advantages in the fields of mineral resources survey and ocean monitoring. Part of the reason for the lack of literature and imbalances comes from the short development history of Chinese remote sensing satellites and insufficient data accumulation, which results in an imperfect data distribution and sharing mechanism.

5.2 Perspectives

CHEOS is currently a research program, aiming to solve a series of key and difficult scientific and technological problems related to the high-resolution Earth observation. In future, it may evolve to an engineering project, e.g., national spatial data infrastructure, which can meet major national strategic needs such as national defense, resources and environment, agriculture, forestry, disaster prevention and mitigation, etc.

Moreover, the advance and development of the CHEOS rely on multi-sectoral association, especially the collaboration between universities and national ministries/commissions. Universities and institutes can play an important role in developing the generic technologies, and training the talents. It is worth noting that the international impact of the CHEOS is not very large, partly due to the data privacy policy.

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