China’s high-resolution optical remote sensing satellites and their mapping applications

Deren Li¹, Mi Wang² and Jie Jiang³

¹State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China; ²School of Geomatics and Urban Spatial Informatics, Beijing University of Civil Engineer and Architecture, Beijing, China

ABSTRACT
Since the beginning of the twenty-first century, several countries have made great efforts to develop space remote sensing for building a high-resolution earth observation system. Under the great attention of the government and the guidance of the major scientific and technological project of the high-resolution earth observation system, China has made continuous breakthroughs and progress in high-resolution remote sensing imaging technology. The development of domestic high-resolution remote sensing satellites shows a vigorous trend, and consequently, a relatively stable and perfect high-resolution earth observation system has been formed. The development of high-resolution remote sensing satellites has greatly promoted and enriched modern mapping technologies and methods. In this paper, the development status, along with mapping modes and applications of China’s high-resolution remote sensing satellites are reviewed, and the development trend in high-resolution earth observation system for global and ground control-free mapping is discussed, providing a reference for the subsequent development of high-resolution remote sensing satellites in China.

1. Introduction
In 1957, the world’s first artificial satellite was launched by the former Soviet Union, opening the era of earth observation from space. In 1972, the United States’ first land observation satellite, Landsat-1, was successfully launched, realizing earth observation by a medium-resolution satellite. In 1986, France’s first earth resource observation satellite SPOT-1 was launched, opening the civilian market for remote sensing satellites. In 1994, the United States issued a PDD-23 order, liberating the export of 1 m high-resolution data and remote sensing satellite system, and promoting the development of high-resolution satellites.

In 1999, IKONOS, the first high-resolution commercial satellite with a resolution of 1 m, was launched in the United States, marking the beginning of a new age of commercial satellites (Li et al. 2017). The excellent observation capability of high-resolution satellites has immense military and economic benefits (Anderson et al. 2017; Dangermond and Goodchild 2020). Several countries are competing to develop a High-Resolution Earth Observation System (HREOS) (Li 2008), and many high-resolution satellites have been successfully launched, such as QuickBird, WorldView, Pleiades, CARTOSAT, etc. (Zhu et al. 2015, 2016a, 2016b; Woldai 2020). Under the joint proposal of many academicians in China’s remote sensing field, HREOS is listed as a major science and technology project (referred to as the GaoFen project) in the National Medium- and Long-term Scientific and Technological Development Planning Outline (2006–2020) (Tong 2016). The GaoFen project was launched and implemented in 2010 to build an independent and advanced HREOS, significantly promoting the improvement of the basic technology level of the entire remote sensing industry and driving the widespread development of high-resolution satellites in China (Zhao 2019).

The year 2020 is the last year of China’s GaoFen project. Over the past decade, China has independently developed, launched, and operated multiple series of high-resolution satellites, including ZiYuan series (ZY) and GaoFen series (GF) (Xu, Gong, and Wang 2014). The technology gap with foreign countries is narrowing, even reaching the leading level of similar satellites launched by other countries in the world. Private enterprises are being increasingly involved in the commercialization of remote sensing satellites, thus enriching independent high-resolution remote sensing data sources. China’s HREOS, led by GaoFen satellites and gathering various domestic satellites, has been formed to improve the sufficiency rate of independent high-resolution remote sensing data, as well as the timeliness of data acquisition.

Based on a summary and analysis of the development of China’s high-resolution satellites and commercial high-resolution satellites, this paper introduces mapping modes and applications of
China’s high-resolution satellites, which help in understanding the progress of China’s high-resolution satellite and provide a reference for the future development of high-resolution satellites.

2. China’s high-resolution remote sensing satellite development

China began to develop high-resolution remote sensing satellites since the launch of the CBERS-02B satellite in 2007. The CBERS-02B satellite, jointly manufactured by China and Brazil, was first equipped with a 2.36 m high-resolution camera (Yuan and Wang 2012). It had been in orbit for 2 years and 7 months and was decommissioned in April 2010. In 2011, China launched an independently developed ZY-1 02C satellite, whose load performance was the same as that of CBERS-02B, replacing CBERS-02B for land resources survey.

In 2012, the first civilian high-resolution optical transmission mapping satellite of China, ZY-3, was launched (Li 2012). The Three-Line Array Camera (TLC) it is equipped with can achieve three-view stereo imaging with a resolution of 2.1 m in nadir view and 3.5 m in forward view and backward view. ZY-3 stereo images can be used to produce a topographic map with a scale of 1:50,000. In 2016, ZY-3 02 satellite was launched, operating in a network with the launched ZY-3 satellite. The resolution of the forward and backward images increased from 3.5 m to 2.5 m.

In 2013, the first satellite of the GaoFen project, GF-1, was launched, with the following imaging characteristics: high resolution of 2 m and width of 800 km (Cheng et al. 2017). In 2014, the first civilian submeter remote sensing satellite, GF-2, which has a spatial resolution better than 1 m (Huang et al. 2018), was launched. Subsequently, high-resolution geostationary satellite GF-4 with a maximum data rate of three image captures per minute (Wang et al. 2017a), hyperspectral satellite GF-5 with integrated observation capability of land and atmosphere (Sun et al. 2018), the first precision agriculture observation satellite GF-6 with ultra-large imaging width (Wang et al. 2019), stereo mapping satellite GF-7 with submeter resolution (Tang et al. 2019), etc. were launched successively.

In 2018, the first civilian high-resolution satellite constellation of China was launched, consisting of three satellites named GF-1 02/03/04 with the same performance and status (Zhu et al. 2018). After these three satellites were networked, they achieved an imaging ability of 15 days of global coverage and 2 days of revisit. These three satellites also cooperate with the GF-1 satellite launched in 2013 and can achieve 11 days of worldwide coverage and 1 day of revisit.

The main imaging parameters of the high-resolution remote sensing satellites launched in China are listed in Table 1. The spatial resolution, band number, and revisit period of remote sensing satellites are continually improving and the spectral range and coverage of observation are continually expanding. Figure 1 shows three GF-6 satellite images, including a panchromatic image, a multispectral image, and an ultra-wide coverage image. Figure 1(a) shows the panchromatic image with a resolution of 2 m acquired on 9 September 2019, covering Shijiazhuang, China. Figure 1(b) shows a multispectral image with a resolution of 8 m, corresponding to Figure 1(a). Figure 1(c) shows an 800-km-wide WFV image acquired by the GF-6 satellite on 6 May 2019, covering Tianjin, Beijing, Hebei, and northern Shanxi.

3. China’s commercial high-resolution remote sensing satellite development

With the rapid and continuous development of the aerospace industry, it is difficult for a high-resolution satellite built solely by the government to meet the growing demand for sub-meter high-resolution remote sensing data. In 2014, the State Council issued the Guiding Opinion on Innovation of Investment and Financing Mechanisms in Key Fields to Encourage Social Investment (document No. 60), which led private capital in China to participate in the application and development of the satellite industry. A large number of innovative enterprises focusing on commercial satellite research and development, as well as use, have emerged, such as Chang Guang Satellite Technology Co., Ltd. (CGSTL), Zhuhai Obita Aerospace Technology Co., Ltd. (Obita), Beijing Space View Technology Co., Ltd. (BSVT), and 21st Century Aerospace Technology Co., Ltd. (21AT). These continually promote the development of commercial high-resolution satellite constellations. At present, China’s commercial high-resolution remote sensing satellite constellations constructed by social financing mainly include TripleSat, Jilin-1, Zuhai-1, and SuperView-1. The detailed satellite load parameters are listed in Table 2.

In 2015, a British-made TripleSat constellation was launched (Wen et al. 2017), consisting of three optical remote sensing satellites with 1 m panchromatic and 4 m multispectral imaging ability. This satellite constellation can achieve 1 day of revisit.

In 2015, four of the Jilin-1 series satellites were launched with one rocket. Jilin-1 is China’s first truly independent commercial remote sensing satellite series (Zhong and Bao 2019). The four satellites are as follows: one optical satellite named GXA with 0.72 m panchromatic and 2.88 m multispectral imaging ability, two ultra-clear video satellites named
Since 2016, three batches of 12 satellites were launched. The first batch includes two video satellites named OVS-1A and 1B, which can obtain high-resolution color video data with a resolution better than 1.98 m. The second batch consists of one video satellite named OVS-2 and four hyperspectral satellites named OHS-01, 02, 03, and 04. The spatial resolution of the OVS-2 satellite has been increased from 1.98 m of OVS-1 to 0.9 m. The OHS-01, 02, 03, and 04 satellites can acquire hyperspectral data in 256 bands. The satellite data and types of the third batch are the same as those of the second batch.

### 4. High-resolution optical satellite mapping mode development and application

With the continuous improvement in the performance and variety of high-resolution satellites, mapping by high-resolution satellite has emerged as a successful means to obtain necessary geographic information, an essential national fundamental strategic resource (Li and Wang 2020; Li, Shao, and Zhang 2020). Based on the principle of photogrammetry, mapping by a high-resolution optical satellite mainly complete the elevation survey by obtaining the same-orbit or different-orbit visual stereo images from SP01 and SP02 with a resolution of 1.12 m, and one smart verification satellite named LQ with a resolution of 5 m. Then, six video satellites named SP03–08, two multispectral satellites with 26 bands named GP01 and GP02, three panchromatic and multispectral optical satellites named GF03a, 02A, and 02B, and one wide swath-width satellite named KF01 were successively launched. After 9 launches, 16 satellites of Jilin-1 constellation are in orbit and operate in a network (Zhong et al. 2020), which can revisit any place in the world 5–7 times a day, providing sufficient remote sensing data for various fields.

In 2016, the SuperView-1 01 and 02 satellites were successfully launched with one rocket. In 2018, the SuperView-1 03 and 04 satellites were launched. Four of the SuperView-1 series satellites, with the same design parameters, operate in the same orbital network with a resolution of 0.5 m and can revisit any target for 1 day (Wang, Jin, and Zhu 2018). The SuperView-1 satellite constellation is China’s first commercial satellite constellation that can achieve high agility and multi-mode imaging. BSVT is responsible for the global commercial operation of this constellation. It will be completely built by 2022.

Since 2017, a commercial micro-nano satellite constellation of Zhuhai-1 has been launched (Jiang et al. 2019). Obita plans to launch 34 satellites for this satellite constellation. Thus far, three batches of 12 satellites were launched. The first batch includes two video satellites named OVS-1A and 1B, which can obtain high-resolution color video data with a resolution better than 1.98 m. The second batch consists of one video satellite named OVS-2 and four hyperspectral satellites named OHS-01, 02, 03, and 04. The spatial resolution of the OVS-2 satellite has been increased from 1.98 m of OVS-1 to 0.9 m. The OHS-01, 02, 03, and 04 satellites can acquire hyperspectral data in 256 bands. The satellite data and types of the third batch are the same as those of the second batch.

### Table 1. Main parameters of China’s high-resolution remote sensing satellites.

| Series | Satellite name | Launch date | Orbit altitude/km | Revisit period | Sensor name | Band number | Resolution/m | Swath width/km |
|--------|----------------|-------------|--------------------|---------------|-------------|--------------|--------------|----------------|
| ZY     | CBERS-02B      | 19 September 2007 | 778               | 3 days        | HR          | 1            | 2.36         | 27             |
|        |                |             |                   |               | CCD         | 5            | 20           | 113            |
|        |                |             |                   |               | WFI         | 2            | 258          | 890            |
|        | ZY-1 02C       | 22 December 2011 | 780               | 3 days        | HR          | 1            | 2.36         | 54             |
|        |                |             |                   |               | P/MS        | 4            | 5/10         | 60             |
|        | CBERS-04       | 7 December 2014 | 778               | 3 days        | Infrared MS | 4            | 40/80        | 120            |
|        |                |             |                   |               | MS          | 4            | 20           | 120            |
|        |                |             |                   |               | WFI         | 4            | 73           | 866            |
| ZY-1 02D | 12 September 2019 | 778          | 3 days            |               | P/MS        | 9            | 2.5/10        | 115            |
| ZY-3 01  | 9 January 2012 | 506         | 5 days            |               | HS          | 166          | 30           | 60             |
|        |                |             |                   |               | TLC         | 1            | 2.1/3.5      | 52             |
|        |                |             |                   |               | MS          | 4            | 6.8          | 52             |
| ZY-3 02  | 30 May 2016   | 505         | 3–5 days          |               | TLC         | 1            | 2.1/2.5      | 51             |
|        |                |             |                   |               | MS          | 4            | 5.8          | 51             |
| GF     | GF-1           | 26 April 2013 | 645               | 4 days        | P/MS        | 5            | 2/8          | 60             |
|        |                |             |                   |               | WDV         | 2            | 16           | 800            |
|        |                |             |                   |               | P/MS        | 5            | 0.8/3.2      | 45             |
|        | GF-2           | 19 August 2014 | 631               | 5 days        | SAR         | 1            | 1–500        | 5–650          |
|        |                |             |                   |               | VNIR        | 5            | 50           | 400            |
|        | GF-3           | 10 August 2016 | 755               | 3 days        | MIR         | 1            | 400          | 400            |
|        |                |             |                   |               | AHSI        | 330          | 30           | 60             |
|        | GF-4           | 29 December 2015 | 36,000          | 20 secs        | VMS         | 12           | 20/40        | 60             |
|        |                |             |                   |               | MS          | 4            | 3.2          | 20             |
|        | GF-5           | 9 May 2018    | 705               | 5 days        | P/MS        | 5            | 2/8          | 90             |
|        | GF-6           | 2 June 2018   | 645               | 4 days        | WDV         | 2            | 16           | 800            |
|        |                |             |                   |               | P/MS        | 5            | 2/8          | 66             |
|        | GF-7           | 3 November 2019 | 505              | 5 days        | DLC         | 1            | 0.8/0.65     | 20             |
|        |                |             |                   |               | MS          | 4            | 3.2          | 20             |
|        | GF-1 02/03/04  | 31 March 2018 | 645               | 2 days        | P/MS        | 5            | 2/8          | 66             |
|        | TIHui (TH)     | 24 August 2010/ | 500              | 1 days        | P/MS        | 5            | 2/10         | 60             |
|        | TH-1 01/02/03  | 6 May 2012/   |                   |               | TLC         | 1            | 5            | 60             |

Note: HR: high resolution; CCD: charge-coupled device; WFI: wide field imager; P: panchromatic; MS: multispectral; WDV: wide-field of view; SAR: synthetic aperture radar; VNIR: visible and near-infrared; MIR: medium wave infrared; AHSI: advanced hyperspectral imager; VMS: visual and infrared multispectral sensor; DLC: dual-line array camera.
different views in the same region. Mapping modes have three main forms: TLC, DLC, and Single-Line Array/Area Array Camera (SLC/SAC). This section considers typical domestic mapping satellites as examples to introduce high-resolution optical satellite mapping mode and application.
### 4.1. ZY-3 mapping satellite

The ZY-3 satellite is China’s first-generation high-resolution civilian stereo mapping satellite. The TLC mounted on the satellite is the earliest spaceborne photogrammetry method adopted in China. TLC consists of forward, backward, and nadir linear array push-broom sensors. The stereo imaging mode of the TLC is shown in Figure 2. The Nadir sensor is vertical to the point under the satellite, the forward sensor is tilted forward by +22° from the nadir sensor, and the backward sensor is tilted backward by −22°. TLC is pushed continuously along the flight direction to generate three overlapping strip images with a width of 52 km. Thus, three-view stereo images of the same ground point are obtained. Based on the construction of strict object-image space relations, the object coordinates of the corresponding image points in stereo images can be calculated by forward intersection. Then, a topographic map can be drawn.

The spatial resolution of the nadir sensor is 2.5 m, while that of the forward and backward sensors is 3.5 m. A nadir image has a relatively high spatial resolution and the projection difference caused by terrain relief can be minimized by imaging vertical to the ground. Nadir images are used to produce high-resolution orthophotos, and three-view stereo images are used to calculate elevation. The ZY-3 satellite is also equipped with a 6.8 m multispectral sensor, including blue, green, red, and near-infrared spectral bands. After the fusion of multispectral images and high-resolution panchromatic images, the interpretation accuracy of ground objects can be improved. Since its launch in 2012, ZY-3 satellite data have been used in many mapping applications, fully supporting the major national surveying and mapping projects, such as the dynamic update of the national 1:50,000 primary geographic information database, the first national geographic census, and the production of 1:25,000 data surface models in western areas (Tang, Chang, and Li 2014).

Considering 150 TLC images covering Shandong Province as test data (shown in Figure 3), the mapping accuracy of the ZY-3 satellite was tested by using 1090 field-measured high-precision Global Positioning System (GPS) checkpoints. The geometric positioning accuracy of the ZY-3 images before and after Block Adjustment (BA) without Ground Control Points (GCPs) is shown in Table 3. Before BA, the positioning accuracy of the images was weak, and there was no obvious systematic error. After BA, the Root Mean Square Error (RMSE) of the plane and elevation was better than 5 m and the overall accuracy of the images was uniform. At the same time, elevation accuracy of ZY-3 could be further improved to within 3 m by using Laser Altimeter Data (LAD) acquired by Geoscience Laser Altimeter System (GLAS) equipped on Ice, Cloud, and Land Elevation Satellite (ICESat) to assist in the BA.

With the support of processing technologies like BA without GCPs and high-performance computing, Wuhan University and other centers have studied large-scale and high-precision mapping technology and software without GCPs, demonstrating applications using tens of thousands of TCL images from the ZY-3 satellite throughout the country (Yang et al. 2017; Wang et al. 2017b). A high-precision mapping result of ZY-3 is shown in Figure 4(a). International cooperative research on high mountain mapping was carried out by the Beijing University of Civil Engineering and Architecture, Leibniz University Hannover, the European Academy of Sciences and Arts in Salzburg, and Environmental Systems Research Institute (ESRI). China has completed high mountain mapping of the Nanga Parbat region in the westernmost part of the Himalayas using ZY-3 images, based on the mapping technology developed by Wuhan University and domestic software, as shown

![Figure 2. TLC stereo imaging mode.](image-url)
in Figure 4(b). This mapping result will be compared with the historical maps made by Germany from 1930 to the 1980s and maps produced by using other satellite imagery and software by ESRI. Environmental changes in this region in recent decades will be analyzed later.

4.2. GF-7 mapping satellite

The GF-7 satellite is China’s second-generation civilian high-resolution stereo mapping satellite. Its main task is to realize civilian 1:10,000 scale satellite stereo mappings in China. The DLC it is equipped with has a sub-meter resolution (Liu et al. 2018). The forward sensor is tilted forward by +26° to acquire a panchromatic image with a resolution of 0.8 m. The backward sensor is tilted backward by −5°, which can obtain panchromatic and multispectral images with resolutions of 0.65 m and 2.6 m, respectively. Stereo imaging mode of DLC is shown in Figure 5. DLC is pushed along the flight direction to generate two overlapping strip images with a width of 20 km to obtain a two-view stereo image of the same ground point. Similar to the TLC of ZY-3, the object point coordinates can be calculated by the forward intersection of the corresponding image points for DLC. However, the difference between TLC and DLC is that TLC can achieve a three-view crossing, while DLC can achieve a two-view crossing.

The DLC of the GF-7 satellite adopts an asymmetrically designed imaging intersection. Forward and

| Mapping accuracy without GCPs | Plane error/m | Elevation error/m |
|------------------------------|---------------|------------------|
| Before BA                    | RMSE | Max | RMSE | Max |
| Without LAD                  | 5.26 | 24.3 | 4.36 | 15.24 |
| With LAD                     | 2.64 | 5.23 | 4.25 | 7.66  |
| After BA                     | 2.58 | 5.16 | 2.88 | 6.74  |

Table 3. Mapping accuracy of ZY-3 satellite.

Figure 3. ZY-3 TLC images covering Shandong Province.

Figure 4. High mountain mapping results by China. (a) High-precision mapping result. (b) Mapping result of Nanga Parbat region.
backward panchromatic images can be used to generate stereo images and backward images with approximately vertical imaging can be used to produce orthophotos. To solve the problem of 1:10,000 scale mapping in China’s “fewer control points” region, GF-7 is also equipped with a 2-beam laser altimeter, which can obtain LAD with an elevation accuracy better than 1 m. LAD can assist in BA processing in subsequent ground processing, thus improving the satellite’s elevation mapping accuracy further. The GF-7 satellite has passed in-orbit testing. Its preliminary evaluation shows that the performance of the GF-7 satellite can satisfy the accuracy of 1:10,000 scale mapping (Cao et al. 2020).

4.3. Single-line array/area array mapping satellite

Unlike professional mapping satellites, such as ZY-3 and GF-7, high-resolution remote sensing satellites equipped with a single camera have specific mapping capabilities. These satellites, equipped with a SLC or a SAC, mainly use attitude maneuvers to conduct multi-view observations of the same object, such as the SuperView-1 satellite and Jilin-1 video satellite. The stereo imaging modes of SLC and SAC are shown in Figures 6 and 7, respectively. During a satellite’s flight along one orbit, the imaging attitude of the satellite is adjusted, while the SLC pushes and...
scans the same object along the satellite’s flight direction. With attitude conditions permitting, SLC can obtain image pairs with multiple base-height ratios. SAC does not need to push and scan and one exposure can obtain one image. Through attitude adjustment, SAC can also achieve multi-view imaging for the same region (Zhong and Bao 2019).

Mapping satellites equipped with SLC or SAC for multi-view stereo observation require high-stability attitude control and high-precision attitude and orbit parameter measurement. Although the resolution of SLC and SAC can reach the sub-meter level, they have weak geometric control strength compared to the stable mapping modes of TLC and DLC. Considerable ground control is required for SLC and SAC to achieve large-scale mapping. Moreover, the imaging width of SLC and SAC is limited by its sub-meter resolution, for example, the swath width of the SuperView-1 satellite with a spatial resolution of 0.5 m is only 12 km. Therefore, the mapping object of SLC and SAC is mainly oriented to the small local region of the crucial target.

5. Conclusions

Herein we reviewed the development of China’s high-resolution remote sensing satellites and their applications in mapping. The development of China’s high-resolution remote sensing satellites has made significant progress. Single satellite performance is increasing, multi-satellite networking has emerged as a trend, and satellite commercialization is steadily advancing. With the beneficial supplement of commercial high-resolution remote sensing satellites, high-resolution remote sensing satellite observation system is becoming increasingly abundant and complete. There is an increasing number of high-resolution satellite mapping modes, including TLC, DLC, and SLC/SAC, which can meet the mapping requirements of 1:50,000 worldwide and 1:10,000 nationwide. However, the task of global coverage and mapping updating remains arduous. A ground control-free mapping system needs to be further developed and new mapping technologies, such as radar satellite interferometry and laser altimeter, must be continuously broken to complement the traditional optical satellite mapping means. High-resolution remote sensing satellite observation system needs to be further improved to better serve the mapping application.

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Notes on contributors

Deren Li is a professor and chair of the Academic Committee of the State Key Laboratory for Information Engineering in Surveying, Mapping, and Remote Sensing, Wuhan University. He was selected as a member of Chinese Academy of Sciences in 1991 and a member of Chinese Academy of Engineering in 1994. He got his PhD degree from University of Stuttgart, Germany. He was awarded the title of honorary doctor from ETH, Switzerland in 2008. His research interests include photogrammetry and remote sensing, global navigation satellite system, geographic information system, and their innovation integrations and applications.
Mi Wang is a professor at the State Key Laboratory of Information Engineering in Surveying, Mapping, and Remote Sensing, Wuhan University. He received the PhD degree from Wuhan University in 2001. His research interests include high-resolution remote sensing satellite ground processing and the integration and rapid update of photogrammetry and GIS.

Jie Jiang is a professor at School of Geomatics and Urban Spatial Informatics, Beijing University of Civil Engineer and Architecture. She received the PhD degree from China University of Mining and Technology (Beijing) in 2000. Her research interests include satellite remote sensing information extraction, network geographic information service, and indoor and outdoor navigation geographic data model.

Data availability statement

The raw data used to support the findings of this study have not been made available and shared at this time as the data also form part of an ongoing study: The ZY-3 data used and other China satellite data can be queried and downloaded from the website of China Centre for Resources Satellite Data and Application (CRESDA) (http://www.cresda.com/CN/).

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