

Chapter 3

Remote Sensing Satellites for Digital Earth



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Abstract The term remote sensing became common after 1962 and generally refers to nonintrusive Earth observation using electromagnetic waves from a platform some distance away from the object of the study. After more than five decades of development, humankind can now use different types of optical and microwave sensors to obtain large datasets with high precision and high resolution for the atmosphere, ocean, and land. The frequency of data acquisition ranges from once per month to once per minute, the spatial resolution ranges from kilometer to centimeter scales, and the electromagnetic spectrum covers wavebands ranging from visible light to microwave wavelengths. Technological progress in remote sensing sensors enables us to obtain data on the global scale, remarkably expanding humanity's understanding of its own living environment from spatial and temporal perspectives, and provides an increasing number of data resources for Digital Earth. This chapter introduces the developments and trends in remote sensing satellites around the world.

Keywords Remote sensing · Digital Earth · Satellite · Earth observation

3.1 Development of Remote Sensing

Remote sensing is a core technology for Earth observation. It covers information collection, in-orbit processing, information storage and transmission, ground reception, processing for applications, calibration, verification, applied research, and basic research, providing fundamental data resources for Digital Earth (Guo 2012).

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3.1.1 Overview of Remote Sensing

3.1.1.1 Remote Sensing Platforms

Remote sensing refers to various observation and exploration activities of the environment involving humans and photoelectronic devices carried by satellites, spacecraft (including space shuttles), aircraft, near-space vehicles, and various terrestrial platforms. Artificial satellites that carry sensors to capture images of Earth's surface are referred to as remote sensing satellites. Satellites can successively observe the whole globe or an assigned part of it within a defined time period (Guo et al. 2016). Aircraft often have a definite advantage because of their mobilization flexibility. They can be deployed wherever and whenever weather conditions are favorable. Satellites and aircraft collect the majority of base map data and imagery used in remote sensing, and the sensors typically deployed on these platforms include film and digital cameras, light-detection and ranging (LiDAR) systems, synthetic aperture radar (SAR) systems, and multispectral and hyperspectral scanners. Many of these instruments can also be mounted on land-based platforms such as vans, trucks, tractors, and tanks. In the future, the Moon will also be an ideal remote sensing platform (Guo et al. 2014a, 2018).

3.1.1.2 Remote Sensing Sensors

There are several types of Earth observation sensors: photographic sensors, scanning imaging sensors, radar imaging sensors, and nonimaging sensors. Photographic sensors work like a digital camera. Scanning imaging sensors capture two-dimensional images by scanning point by point and line by line in a time sequence. These are widely used today; such sensors can be further divided into surface scanning and image scanning sensors. Imaging radar is an active sensor that emits electromagnetic waves to form a lateral profile. Currently, most Earth observation satellites carry SAR systems that feature very high resolutions.

In the early stage of spaceborne Earth observation, traditional film-based imaging devices, return beam vidicon (RBV) TV cameras, and optical scanners were the main devices used for Earth observation. Images obtained from these devices were mainly color and black-and-white representations of Earth's surface and cloud layer, covering the visible light and near infrared ranges. After the first land observation satellite, Landsat 1, was launched in 1972, the new multispectral scanner (MSS) it carried sent data that was processed in the form of a digital time sequence array. This marked a progressive step in the development of digital image processing.

Compared with optical remote sensors, SARs work in various weather conditions and can penetrate some surface objects. In contrast to passive sensor systems that only receive reflected solar light or infrared radiation, radar systems act as active sensors and emit electromagnetic waves on their own. A radar sensor sends pulses of energy to the Earth's surface and part of that energy is reflected and forms return

signals. The strength of the return signal depends on the roughness and dampness of the Earth's surface and the inclination of surface objects toward the waves sent by radar.

3.1.2 Development of Remote Sensing Satellites

Based on a life cycle of approximately thirteen years, Earth observation satellites have gone through four generations (Fig. 3.1) (Zhou 2010).

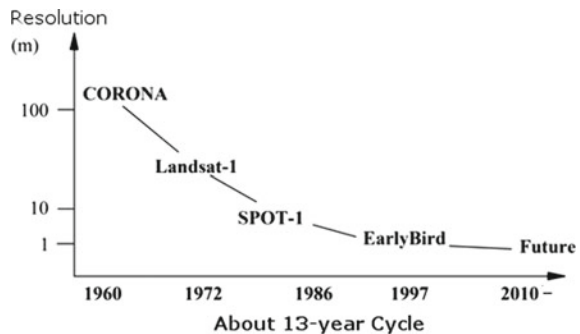
(1) The first generation, beginning spaceborne Earth observation: 1960–1972

CORONA, ARGON, and LANYARD were the first three imaging satellite observation systems. Data obtained from these satellites were used for detailed terrestrial reconnaissance and regional mapping. In the early years, satellite images were made by combining hundreds or even thousands of photos, most of which were black-and-white, with a small number of color photos or three-dimensional image pairs. These images covered most parts of Earth. For example, images obtained using the KH-5 camera covered most of the Earth's surface with a 140-m pixel resolution. However, these images did not form systematic observations like those achieved later with Landsat data.

(2) The second generation, experimental and tentative application: 1972–1986

Landsat-1 was launched on July 23, 1972, marking the start of modern satellite-carried Earth observation. It provided a novel high-resolution Earth image database to international science organizations, making further exploration of Earth's resources possible. Landsat-1 carried an MSS that received four bands with wavelengths from 0.5 to 1.1 μm with a spatial resolution of 80 m, frame width of 185 km, and revisit cycle of eighteen days. Notably, Landsat-1 transmitted data in digital form for the first time. The foundation for multispectral processing was laid in the 1970s and organizations involved in this field included NASA, Jet Propulsion Laboratory (JPL), United States Geological Survey (USGS), Environmental Research Institute of Michigan (ERIM), and Laboratory for Applications of Remote Sensing (LARS). Ten years

Fig. 3.1 History of the thirteen-year cycle of Earth observation satellite development (Zhou 2010)



later, Landsat accommodated four more MSS wavebands as Landsat TM emerged during 1982–1984 with a spatial resolution of 30 m covering seven spectral bands. Soon afterwards, the famous SPOT HRV system was launched in 1986 with a spatial resolution of 10 m for the panchromatic wavebands and 30 m for three other multispectral bands.

(3) The third generation, wide application: 1986–1997

After 1986, the technology and applications of satellite Earth observation developed rapidly. SPOT-1, launched on February 22, 1986, carried a high-resolution visual sensor and was the first use of pushbroom linear array sensors. It was also the first satellite system capable of cross-track three-dimensional observation. Later, the ESA launched the ERS-1 SAR on July 17, 1991. ERS-1 was an active microwave satellite that provided images with a spatial resolution of 30 m. Japan launched its JERS-1 in February 1992 with an L-band SAR, building up the overall observation capacity of SARs. Data provided by these active microwave sensors played an important role in enhancing the observation and understanding of environmental and climatic phenomena, and supported the categorization of sea ice and research on the coastal zone.

(4) The fourth generation, high-resolution and hyperspectral imaging: 1997–2010

This comprises the latest generation of Earth observation satellites equipped with the most advanced technologies that are still gradually maturing. The main features are a spatial resolution of 1 m or less, coverage of 200 wavebands ranging from 0.4 to 2.5 μm in wavelength, a spectral resolution of 10 nm, revisit cycles less than three days, capability of multiangle and three-dimensional observation, and precise spatial positioning with GPS. The major advantage of high-resolution imaging is that it allows for identification of buildings, roads, and modern construction projects as well as change detection. As a result, high-resolution imagery products are mainly used in GIS and special-purpose mapping.

At this stage, attention was primarily focused on spatial and temporal resolutions, spectral coverage, orbital height, revisit capability, mapping bandwidth, image dimensions, capacity for three-dimensional observation, imaging models, data storage, and the market demand for satellites.

(5) The fifth generation, a new era of satellite Earth observation

Next-generation Earth observation satellites are expected to be highly intelligent and integrate Earth observation sensors, data processing devices, and communication systems. Global surveying and real-time environmental analysis of Earth will become possible. More experts as well as casual users will be involved in remote sensing, photogrammetry and GIS, and data inversion products will also be updated more frequently. To achieve real-time data acquisition, improve applications and spare casual users the trouble of understanding complicated data processing, image providers will offer mature imaging products that directly meet various demands (Guo et al. 2014b).

3.2 Land Observation Satellites

Land observation satellites have been developed for land resource investigation, terrestrial environment research, crop condition forecasting, and natural disaster monitoring. Terrestrial variables have a specific “ground object spectrum” and radiation scattering; terrestrial variables can be retrieved by considering the direction, scale, and sensitivity to establish the relationship between electromagnetic waves and ground surface variables for space observation.

3.2.1 *US Land Observation Satellites*

The United States launched its first land satellite, Landsat 1, on July 23, 1972. For the first time in human history, satellites were consistently providing Earth images with a certain resolution, making it possible to use satellites to survey Earth’s resources. Since then, the country has launched seven satellites in the Landsat series (the launch of Landsat 6 failed). They are currently the world’s most widely used land observation satellites (Table 3.1).

Later, the United States launched a series of high-resolution commercial remote sensing satellites. The IKONOS satellite, launched on September 24, 1999, was the world’s first commercial remote sensing satellite providing high-resolution images. After that, the country launched the QuickBird, WorldView-1, GeoEye-1, and WorldView-2 satellites in October 2001, September 2007, September 2008, and October 2009, respectively, with improved resolutions from 0.61 to 0.41 m (multi-spectral) (Aguilar et al. 2013).

3.2.1.1 Landsat Program

The Earth Resources Satellite Program involves a series of Earth observation satellites jointly managed by NASA and the United States Geological Survey (USGS). These satellites collect information about Earth from space. They have been providing digital photos of Earth’s continents and coastal regions for more than 40 years, enabling researchers to study Earth from various aspects and evaluate the impacts of natural and human activities on the dynamics of the Earth system.

(1) Landsat 7

Landsat 7 moves around Earth on a near-polar sun-synchronous orbit, with an orbital altitude of 705.3 km and an operation cycle of 98.9 min, covering Earth once every sixteen days. During the day, it operates on a descending orbit, crossing the equator at 10:00 AM. The orbit is adjusted so that orbital inclination is kept within a certain limit and the deviation of the satellite transit time from the nominal time is kept within ± 5 min.

Table 3.1 Land satellites launched by the United States

Satellite code	Type of orbit	Orbital altitude (km)	Orbital period (min)	Orbital inclination (°)	Launch date
Landsat-1	Sun-synchronous orbit	917	103.1	99.2	1972.6.23
Landsat-2	Sun-synchronous orbit	917	103.3	99.2	1975.1.22
Landsat-3	Sun-synchronous orbit	917	103.1	99.1	1978.3.5
Landsat-4	Sun-synchronous orbit	705	98.9	98.2	1982.7.16
Landsat-5	Sun-synchronous orbit	705	98.9	98.2	1984.3.1
TRMM	Inclined orbit	405	93.5	35	1997.11.27
Landsat-7	Sun-synchronous orbit	705	98.9	98.2	1999.4.15
Terra	Sun-synchronous orbit	705	99	98.2	1999.12.18
ACRIMSAT	Sun-synchronous orbit	716	90	98.13	1999.12.20
GRACE	Polar orbit	400	94	89	2002.3.17
Aqua	Sun-synchronous orbit	705	98.8	98.2	2002.5.4
ICESat	Inclined orbit	600	97	94	2003.1.12
SORCE	Inclined orbit	600	90	40	2003.1.25
Suomi NPP	Sun-synchronous orbit	824	101	98.7	2011.10.28
Landsat-8	Sun-synchronous orbit	705	99	98.2	2013.2.12

Table 3.2 ETM+ bands

Waveband	Wavelength range (μm)	Ground resolution (km)
1	0.45–0.515	30
2	0.525–0.605	30
3	0.63–0.690	30
4	0.75–0.90	30
5	1.55–1.75	30
6	10.40–12.50	60
7	2.09–2.35	30
Pan	0.52–0.90	15

The ETM+ of Landsat 7 was developed based on the TM of Landsats 4 and 5 and the ETM of Landsat 6. It is a multispectral vertical-orbit scanning radiometer that performs Earth imaging directly facing the nadir and obtains high-resolution ground images. Its scanning width is 185 km. Similar to the previous Landsats, the EMT+ uses a scan line corrector to eliminate the interline overlap or interline spacing caused by the scanning operation or orbital motion.

In the visible and near-infrared (VNIR) range, ETM+ has four color bands and one panchromatic band. Each of the six sounder arrays in the visible, near-infrared and SWIR bands has sixteen sounders staggered along the orbital direction, and each sounder corresponds to a ground area of 30×30 m. The LWIR sounder array has eight sounders, each corresponding to a ground area of 60×60 m, with a resolution twice as high as that of the previous thermal infrared TM. The panchromatic band was a new addition to Landsat 7. The sounder array consists of 32 sounders, each corresponding to a ground area of 15×15 m. The bands of ETM+ are described in Table 3.2.

(2) Landsat 8 (LDCM)

Landsat 8, also referred to as LDCM, carries two main payloads: one operational land imager (OLI) and one thermal infrared sensor (TIRS). Compared with the payloads of previous Landsats, the performance of the OLI and TIRS are much improved.

Landsat 8 can capture at least 400 images per day (its predecessors could only capture 250). This is because Landsat 8 is more flexible in monitoring an area (Ali et al. 2017). Previous Landsats could only monitor a certain swath of land directly under their flight path, but the remote sensor of Landsat 8 can capture information about land that deviates from the flight path by a certain angle, which the previous Landsats could do only in subsequent laps. This advantage helps capture imagery needed for multitemporal comparison (such as images concerning disasters).

The main parameters of Landsat 8 are: a Worldwide Reference System-2 (WRS-2) flight path/line system, a sun-synchronous orbital altitude of 705 km, global coverage cycle of sixteen days (except for high-latitude polar regions), 233 orbits per cycle, an orbital inclination of 98.2° (slightly to the right), an operation cycle of 98.9 min, and a 170×185 km imaging area. The satellite crosses the equator at 10:00 AM \pm

15 min. Its image directory is prepared in the same way as those of Landsats 4, 5 and 7, and it supports the ability to capture the main image and images that deviate from the nadir point to a limited extent (± 1 flight path/line).

3.2.1.2 GRACE Satellite Program

The Gravity Recovery and Climate Experiment (GRACE) satellite program aims to obtain the features of medium and long waves of Earth's gravity field and the time-varying characteristics of the global gravity field (Melzer and Subrahmanyam 2017) and to sound the atmospheric and ionospheric environment. The GRACE satellite was launched on March 17, 2002 from the Plesetsk Launch Center in northern Russia. Its working principle is shown in Fig. 3.2.

The satellite adopts a low-low satellite-to-satellite tracking mode with two simultaneously launched low Earth orbit satellites that travel on the same orbit with a distance of 220 km in between them. Satellite-borne GPS receivers can accurately determine the orbital position of the two satellites and measure their distance and the changes in distance accurate to the micron level. A triaxial accelerometer is used to measure nonconservative forces. The observation data of each satellite, including the data of gravity-related measurements and GPS occultation measurements, are transmitted to the ground station via S-band radio waves.

The scientific objectives of the GRACE satellite project are (1) to determine Earth's mediumwave and longwave gravity field with a geoid precision of 0.01 cm and 0.01 mm for 5,000 km and 500 km wavelengths, respectively, which is two orders of magnitude higher than that of the CHAMP satellite (Ditmar 2004); (2) to

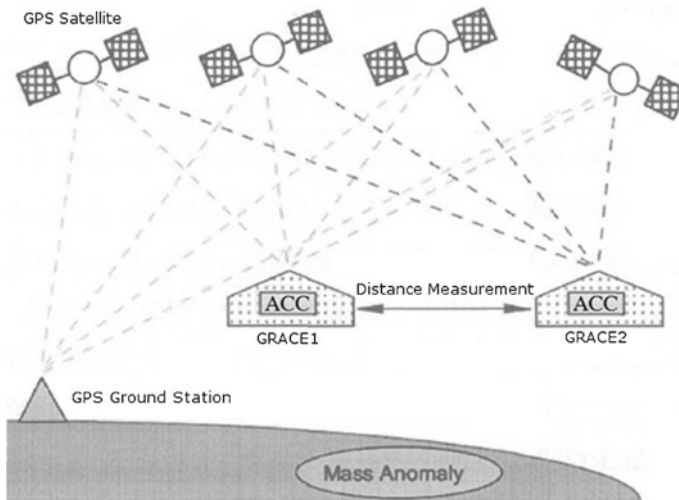


Fig. 3.2 GRACE working principle (Lu 2005)

determine changes in the global gravity field based on observation data from 2 to 4 weeks or longer, with an expected geoid determination precision of 0.001 mm/y; and (3) to sound the atmospheric and ionospheric environment. As the GRACE satellites provide highly accurate information about Earth's mediumwave and longwave gravity field and its time-dependent changes, they mark the beginning of a new era of satellite-based gravity research (Liu 2009).

3.2.1.3 Commercial Remote Sensing Satellites

On September 24, 1999, the IKONOS satellite was successfully launched at Vandenberg Air Force Base, marking the start of the era of high-resolution commercial satellites. On March 31, 2015, IKONOS was retired after 15 years of over service, a working lifetime more than twice of that in the design. IKONOS was a commercial satellite that acquired 1-m resolution panchromatic images and 4-m resolution multispectral images. Additionally, the resolution of the integrated color image with the panchromatic and multispectral images was up to 1 m. The IKONOS revisit period was 1–3 days imaging from the 681 km orbit.

The QuickBird satellite was launched in October 2001 with a panchromatic spatial resolution of 0.61 m and multispectral resolution of 2.44 m. The WorldView-1 satellite, launched on September 18, 2007, was the commercial imaging satellite with the highest resolution and the fastest response speed in the world at that time. WorldView-1 has an average revisit period of 1.7 days in a sun-synchronous orbit at an altitude of 496 km and inclination angle of 98°. The large-capacity panchromatic system can capture images up to 550,000 km² with 0.5-m resolution every day. The satellite also has high geolocation accuracy and quick response, which provides quick aiming at the target to effectively perform on-track stereo imaging. Its acquisition capacity is four times that of the QuickBird satellite. Parameters of the WorldView-1 satellite are shown in Table 3.3.

WorldView-2, launched in October 2009, was the first commercial remote sensing satellite in the world to provide 8-band high resolution data, greatly enhancing the customer service ability of DigitalGlobe. In June 2014, with the consent of the US Department of Defense and the State Department, the US Department of Commerce formally approved DigitalGlobe's application for the sale of 0.25-m resolution satellite image data.

With the implementation of the new policy, WorldView-3, the third-generation remote sensing satellite, was successfully launched in August 2014 and is the world's first commercial multipayload, hyperspectral and high resolution satellite, providing 0.31-m panchromatic imagery and 1.24-m multispectral imagery. The WorldView-4 commercial remote sensing satellite was launched in November 2016 and has greatly improved the overall data acquisition capability of the DigitalGlobe constellation group. It can image any point on the Earth 4.5 times a day, with a ground sampling distance (GSD) of less than 1 m.

Table 3.3 WorldView-1 satellite parameters

Parameter	Value
Orbit	Solar synchronization at a height of 450 km
Satellite size, weight and power supply	3.6 m high, 2.5 m wide; the total span of the solar panels is 7.1 m; weight of 2500 kg; 3.2 kw solar cells
Remote sensor band	Panchromatic
Resolution	Subsatellite point: 0.45 m (GSD)
Swath	Subsatellite point: 16 km
Altitude measurement and control	Tri-axial stability
Data transmission	Image and auxiliary data: 800 Mbit/s, X-band
Data acquisition for each orbit	331 Gbit
Maximum continuous imaging area of a single-circle orbit	60 × 60 km (equivalent to 4 × 4 square images); 30 × 30 km (equivalent to 2 × 2 square images)
Revisit period	While imaging with 1 m GSD: 1.7 days

3.2.1.4 Satellite Images for Google Earth

Google Earth's images come from multisource data composed of satellite images and aerial data. Its satellite images mainly come from the QuickBird commercial satellite, GeoEye satellite and IKONOS satellite of the DigitalGlobe Company of the United States, as well as the SPOT-5 satellite of France.

The GeoEye series of satellites are the next generation of the IKONOS and OrbView satellites. The GeoEye-1 satellite, launched on September 6, 2008 from Vandenberg Air Force Base in California can acquire black-and-white (panchromatic) imagery with 0.41-m resolution and color (multispectral) imagery with 1.65-m resolution, and can accurately locate the target position with 3 m accuracy. Therefore, it has become the most powerful commercial imaging satellite with the highest resolution and accuracy in the world. The GeoEye-1 satellite runs in a solar synchronous orbit with an altitude of 681 km and inclination angle of 98°, an orbit period of 98 min and a revisit period of less than 3 days. The satellite's launch mass was 1955 kg, and the design life is 7 years. The payload of the GeoEye-1 satellite is a pushbroom imaging camera consisting of an optical subsystem (telescope module, aperture 1.1 m), a focal plane module and a digital electronic circuit. The main parameters of the GeoEye-1 satellite are shown in Table 3.4.

Table 3.4 The main parameters of the GeoEye-1 satellite

Parameter		Values
Resolution		Subsatellite point panchromatic: 0.41 m, side-looking 28° panchromatic: 0.5 m, subsatellite point multispectral: 1.65 m
Swath		Subsatellite point: 15.2 km; single scene 225 km ² (15 × 15 km)
Camera mode		Panchromatic and multispectral simultaneous (panchromatic fusion), monochromatic and monochromatic
Revisit period		2–3 days
Wavelength	Panchromatic	450–800 nm
	Multispectral	Blue: 450–510 nm
		Green: 510–580 nm
		Red: 655–690 nm
	Near-infrared: 780–920 nm	

3.2.2 European Land Observation Satellites

3.2.2.1 ESA Satellites

(1) *CryoSat-2*

On April 8, 2010, the ESA launched *CryoSat-2* using a Dnepr rocket. As one of the primary missions of the European Earth Observation Program (EOP), *CryoSat* uses a radar altimeter to measure the thickness of Earth's land ice and sea ice sheets, especially polar ice and oceanic floating ice, to study the effects of global warming. Earlier, in October 2005, the launch of *CryoSat-1* was unsuccessful due to a rocket failure.

SIRAL is the main payload of *CryoSat-2*, weighing 62 kg (Dibarboure et al. 2011). It is mainly used to observe the internal structure of ice shields and study sea ice and landforms. SIRAL has three measurement modes: the low-resolution measurement (LRM) mode, which is only used to measure relatively flat polar and oceanic ice sheets; the SAR mode that is used to measure sea ice with an along-track resolution of 250 m; and the InSAR mode that is used to study ice sheets in more complex and steep areas with a measurement accuracy of 1 to 3 cm (Wingham et al. 2006). In contrast to traditional radar altimeters, the delay Doppler radar altimeter (DDA) adopted by SIRAL can emit continuous pulse trains and can make efficient use of Earth's surface reflection power via full Doppler bandwidth. SIRAL was designed based on existing instruments but has improved performance compared with the radar altimeters on board ERS-1, ERS-2 and ENVISAT. SIRAL has two pairs of Cassegrain antennas that are used to transmit radar signals and receive signals reflected from the ground to obtain accurate information about polar and sea ice thickness. SIRAL can accurately measure irregular and steep edges of land ice, and can obtain data from sea and river ice. The characteristics of SIRAL are shown in Table 3.5.

Table 3.5 SIRAL characteristics

Parameter	Mode of measurement		
	LRM	SAR	InSAR
Receiving chain	1 (left)	1 (left)	2 (left and right)
Sampling interval (m)	0.47	0.47	0.47
Bandwidth (MHz)	350	350	350
Pulse repetition frequency (PRF) (Hz)	1,970	17.8	17.8
Transmitter pulse width (μ s)	49	49	49
Effective echo width (μ s)	44.8	44.8	44.8
Pulse duration (ms)	None	3.6	3.6
Color synchronization pulse	None	64	64
Color synchronization pulse period (ms)	None	11.7	46.7
Tracking pulse bandwidth (MHz)	350	350	40
Average tracking pulse/46.7 ms	92	32	24
Data transmission rate (Mbps)	0.051	11.3	11.3 (2)
Power consumption (W)	95.5	127.5	127.5

(2) *Copernicus Program*

The Copernicus program, formerly Global Monitoring for Environment and Security (GMES), was a major space development program launched by the European Union in 2003. Its main purpose is to ensure Europe's sustainable development, enhance international competitiveness, security and to realize real-time dynamic monitoring of the environment by coordinating, managing and integrating the observation data of existing and future European and non-European (third-party) satellites.

In terms of EOS infrastructure development, the GMES program is divided into three parts. The first part is the space-based observation for which ESA is responsible. New satellites will be launched and the existing satellites are divided into six mission groups (see Table 3.6). The second part is the ground-based observation for which the European Environment Agency (EEA) is responsible. The third part is data sharing, which calls for building capacity for comprehensive and sustainable observation data applications and the construction of network entrances for data access; data services are mainly provided by the ESA, French Space Agency (CNES), and EUMETSAT.

3.2.2.2 France's Satellites

On February 22, 1986, France launched its first Earth resources observation satellite, SPOT-1. Thus far, seven SPOT satellites have been sent into space. The sounders adopted by these satellites have unique characteristics and the imaging method is also unique. Additionally, SPOT satellites are the world's first remote sensing satellites

Table 3.6 The Copernicus (GMES) space segment

Satellite	Function	Purpose	Launch date
Sentinel 1	SAR imaging	Continuous all-weather monitoring of ships and oil spills, other applications	Sentinel 1A: 2014.4.3 Sentinel 1B: 2016.4.25
Sentinel 2	Multispectral imaging	Land applications such as for cities, forests, agriculture, etc.	Sentinel 2A: 2015.6.23 Sentinel 2B: 2017.3.7
Sentinel 3	Ocean and land monitoring	Ocean color, vegetation, sea surface and land surface temperatures, sea wave height, etc.	Sentinel 3A: 2016.2.16 Sentinel 3B: 2018.4.25
Sentinel 4	Geosynchronous orbit—atmospheric monitoring	Monitoring of atmospheric composition and boundary layer pollution	
Sentinel 5	Low-orbit atmospheric research satellite	Monitoring of atmospheric composition	Sentinel 5P: 2017.10.13
Sentinel 6	Non-sun-synchronous orbit at 1,336 km mean altitude	Providing reference continuity and a high-precision ocean topography service after Jason-3	

to have stereo imaging capability. Basic information on the SPOT series is shown in Table 3.7.

The CNES launched the SPOT-5 remote sensing satellite in May 2002, with a design life of five years and total mass of 3,030 kg. Compared with the first four SPOT satellites, SPOT-5 has significantly improved observation capability and incorporated new instruments (Table 3.8), including the following: (1) An HSR with a panchromatic spectral resolution of 10 m, (2) two HRGs with working bands that differ from HRV and HRVIR, and (3) a VEGETATION-2 imager that could achieve global coverage almost every day with an imaging resolution of 1 km.

SPOT-6 was launched by India's Polar Satellite Launch Vehicle on flight C21 on September 9, 2012 and SPOT-7 was launched on PSLV flight C23 on June 30, 2014. They form a constellation of Earth-imaging satellites designed to provide continuity of high-resolution, wide-swath data up to 2024. EADS Astrium took the decision to build this constellation in 2009 based on a perceived government need for this kind of data. SPOT-6 and SPOT-7 are phased in the same orbit as Pléiades 1A and Pléiades 1B, which are at an altitude of 694 km, forming a constellation of 2-by-2 satellites that are 90° apart from one another.

Table 3.7 SPOT satellite information

Satellite	Launch date	Sensor	Service period (year)	Width (km)	Altitude (km)
SPOT-1	1986.02.22	Stereo imaging system with a pushbroom scanner (HRV)	1986–1990	2 × 16	830
SPOT-2	1990.01.22	Stereo imaging system with a pushbroom scanner (HRV)	1990–2006	2 × 16	830
SPOT-3	1993.09.26	Improved HRV, solid altimeter, laser reflector	1993–1996	110–2,000	832
SPOT-4	1998.03.24	Improved HRV, HRVIR	1998–2013	110–2,200	1,334
SPOT-5	2002.05.03	HRG, HRVIR, HSR	Still in operation	60 × 60–60 × 120	830
SPOT-6	2012.09.09	Multispectral Imagery	Still in operation	60 × 60	695
SPOT-7	2014.06.30	Multispectral Imagery	Still in operation	60 × 60	695

Table 3.8 Technical parameters of the three sensors on board SPOT-5

Type of remote sensor	Waveband	Wavelength range (μm)	Resolution (m)	Width (km)
HRG	Panchromatic	0.49–0.69	2.5 or 5	60
HRVIR	Multispectral	0.49–0.61	10	60
		0.61–0.68	10	60
		0.78–0.89	10	60
		1.58–1.75	20	60
		0.43–0.47	1,000	2,250
		0.61–0.68	1,000	2,250
		0.78–0.89	1,000	2,250
		1.58–1.75	1,000	2,250
HSR	Panchromatic	0.49–0.69	10	120

3.2.2.3 Germany's Satellites

CHAMP is a small satellite mission for geoscience research, atmospheric studies, and applications headed by the German Research Centre for Geosciences (GFZ) (GFZ 2018; Guo et al. 2008). As a near-polar, low Earth orbit satellite equipped with high-precision, multifunction, completely satellite-borne instruments (magnetometer, accelerometer, STAR sensor, GPS receiver, laser mirror, ion drift meter). CHAMP had a design life of five years, and ended on September 19, 2010. Its shape and onboard instruments are shown in Fig. 3.3. It could simultaneously measure Earth's gravitational and magnetic fields with high precision and detect their temporal and spatial changes (Baduraet al. 2006).

The CHAMP mission had three main goals: (1) to accurately determine the long-wavelength characteristics of the Earth's gravitational field and its temporal changes; (2) to estimate, with unprecedented accuracy, temporal and spatial variations of the magnetic field of the Earth's main body and crust, and all components of the magnetic field; and (3) to study temperature, water vapor, and electrons using a large amount of globally distributed GPS signal refraction data generated by the atmosphere and ionosphere.

TerraSAR-X is a German SAR satellite mission for scientific and commercial applications that was launched on June 15, 2007. The project is managed by the DLR (German Aerospace Center). In 2002, EADS Astrium GmbH was awarded a contract to implement the X-band TerraSAR satellite (TerraSAR-X) on the basis of a public-private partnership agreement (PPP). In this arrangement, EADS Astrium funded part of the implementation cost of the TerraSAR-X system.

The science objectives are to make multimode and high-resolution X-band data available for a wide spectrum of scientific applications in fields such as hydrology, geology, climatology, oceanography, environmental and disaster monitoring, and cartography (DEM generation) using interferometry and stereometry.

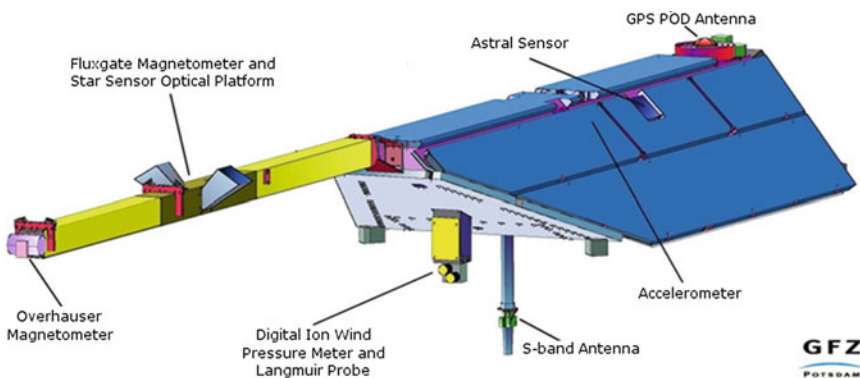


Fig. 3.3 CHAMP satellite structure (GFZ 2018)

3.2.3 China's Land Observation Satellites

3.2.3.1 Resource Satellites

Resource satellites are used to survey the Earth's natural resources and carry out scientific research on the Earth system. China has developed a series of satellites for land observation.

(1) CBERS satellites

The China-Brazil Earth Resource Satellites (CBERS) were jointly developed by China and Brazil using their combined investment in accordance with an agreement signed by both countries in 1988. CBERS was shared by the two countries after being put into operation. The first CBERS (CBERS-1) was successfully launched in 1999 as China's first-generation transmission-type Earth resource satellite. CBERS-02 was the successor to CBERS-01 and had the same function, composition, platform, payload, and nominal performance parameters as its predecessor. CBERS-02 was launched from the Taiyuan Satellite Launch Center on October 21, 2003.

The payload and orbital parameters of CBERS-01/2 are listed in Table 3.9 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004). The CBERS-1/02 payload included three kinds of sensors: a charge-coupled device (CCD), an infrared multispectral scanner (IRMSS), and a

Table 3.9 Basic parameters of the CBERS-01/2 sensors

	CCD camera	Wide field imager (WFI)	Infrared multispectral scanner (IRMSS)
Type of sensor	Pushbroom	Pushbroom (discrete camera)	Oscillating scanning (forward and reverse)
Visible/near infrared band (μm)	1: 0.45–0.52 2: 0.52–0.59 3: 0.63–0.69 4: 0.77–0.89 5: 0.51–0.73	10: 0.63–0.69 11: 0.77–0.89	6: 0.50–0.90
Shortwave infrared band (μm)	N/A	N/A	7: 1.55–1.75 8: 2.08–2.35
Thermal infrared band (μm)	N/A	N/A	9: 10.4–12.5
Radiation quantization (bit)	8	8	8
Swath (km)	113	890	119.5
Number of pixels per band	5,812 pixels	3,456 pixels	Bands 6, 7 and 8: 1,536 pixels; band 9: 768 pixels
Spatial resolution (nadir) (m)	19.5	258	Bands 6, 7 and 8: 78 m; band 9: 156 m

Table 3.10 CBERS-02B technical parameters

Payload	Band no.	Spectral range (μm)	Resolution (m)	Swath (km)	Side view ability	Repetition period (d)	Data transmission rate
Panchromatic multispectral camera	B01	0.45–0.52	20	113	$\pm 32^\circ$	26	2×53
	B02	0.52–0.59	20				
	B03	0.63–0.69	20				
	B04	0.77–0.89	20				
	B05	0.51–0.73	20				
High-resolution camera (HR)	B06	0.5–0.8	2.36	27		104	60
Wide field imager (WFI)	B07	0.63–0.69	258	890		5	1.1
	B08	0.77–0.89	258				

wide field imager. Other loads included a high-density digital recorder (HDDR), a data collection system (DCS), a space environment monitor (SEM), and a data transmission system (DTS).

(2) *CBERS-02B*

CBERS-02B was an Earth observation satellite jointly developed by China and Brazil. The satellite was sent into orbit on September 19, 2007 from the Taiyuan Satellite Launch Center, and the first batch of Earth observation images was received on September 22, 2007. The satellite is no longer in operation. Its technical parameters are shown in Table 3.10.

CBERS-02B was equipped with three spatial resolutions: high, medium, and low. A combination of the CCD and HR images sent back from the satellite helped accurately identify and interpret residential areas, roads, forests, mountains, rivers, and other ground features. It could monitor the expansion of urban areas and provide a basis for urban planning and construction. Furthermore, it could provide support for decision making for precision agriculture. CBERS-02B could also be used to produce detailed maps such as dynamic land use maps and to update large-scale topographic maps.

(3) *ZY-1 02C*

The ZY-1 02C resource satellite was launched on December 22, 2011. It weighs approximately 2,100 kg and had a design life of three years. ZY-1 02C carries a panchromatic multispectral camera and a high-resolution panchromatic camera.

The satellite has two notable features. First, its 10-m resolution P/MS multispectral camera boasts the highest resolution of the multispectral cameras installed on China's civilian remote sensing satellites. Second, the two 2.36-m resolution HR cameras it carries make the monitoring swath as wide as 54 km, which greatly increased the data coverage and significantly shortened the satellite's repetition period. ZY-1 02C's payload parameters are shown in Table 3.11 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004).

Table 3.11 ZY-1 02C sensor parameters

Parameter		P/MS camera	HR camera
Spectral range (μm)	Panchromatic	B1: 0.51–0.85	0.50–0.80
	Multispectral	B2: 0.52–0.59	
		B3: 0.63–0.69	
		B4: 0.77–0.89	
Spatial resolution (m)	Panchromatic	5	2.36
	Multispectral	10	
Width (km)		60	Single camera: 27; double camera: 54
Side view ability ($^{\circ}$)		± 32	± 25
Repetition period (d)		3–5	3–5
Coverage period (d)		55	55

(4) ZY-3

The ZY-3 resource satellite was launched on January 6, 2012. It weighs approximately 2,650 kg and had a design life of five years. The satellite’s mission is to continuously, reliably, and rapidly capture high-resolution stereo images and multispectral images of all parts of the country for a long period of time.

ZY-3 is China’s first high-resolution civilian optical transmission-type stereo mapping satellite that integrates surveying, mapping, and resource investigation functions. The onboard front-view, rear-view, and vertical-view cameras can capture stereoscopic pairs in the same region from three different viewing angles to provide a wealth of three-dimensional geometric information. The image control and positioning precision are greater than one pixel. The swath of the front-view and rear-view stereoscopic pairs is 52 km wide and the baseline-height ratio is 0.85–0.95. The vertical image is 2.1 m, meeting the demand for 1:25,000 topographic map updates. ZY-3’s payload parameters are shown in Table 3.12 (China Center for Resource Satellite Data and Applications 2012; China Academy of Space Technology 2004).

In 2012, ZY-3 sent back 1,590 batches of raw data, totaling 250 TB. The valid data covered 7.5 million square kilometers in China and 30 million square kilometers across the world. Imagery of Dalian, China, captured by the ZY-3 satellite is shown in Fig. 3.4.

3.2.3.2 Environment and Disaster Reduction Satellites

The environment and disaster reduction satellites are collectively referred to as the “China Small Satellite Constellation for Environment and Disaster Monitoring and Forecasting” (“Small Satellite Constellation” for short). The constellation is capable of using visible, infrared, microwave remote sensing and other means of observation

Table 3.12 ZY-3 sensor parameters

Platform	Payload	Band no.	Spectral range (μm)	Spatial resolution (m)	Width (km)	Side view ability ($^{\circ}$)	Revisit time (d)
ZY-3	Front-view camera	–	0.50–0.80	3.5	52	± 32	3–5
	Rear-view camera	–	0.50–0.80	3.5	52	± 32	3–5
	Vertical-view camera	–	0.50–0.80	2.1	51	± 32	3–5
	Multispectral camera	1	0.45–0.52	6	51	± 32	5
2		0.52–0.59					
3		0.63–0.69					
4		0.77–0.89					



Fig. 3.4 Image of Dalian, China, acquired by the ZY-3 satellite

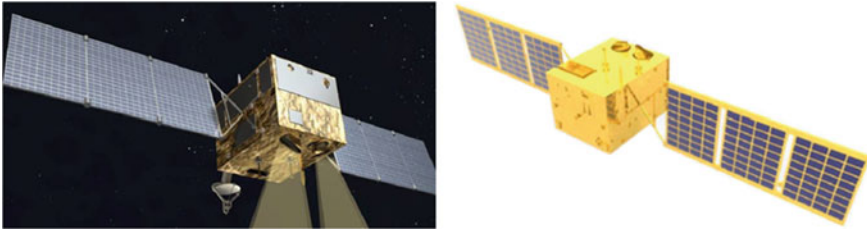


Fig. 3.5 The HJ-1A (left) and HJ-1B (right) satellites

to meet the needs of all-weather, 24-h observation and forecasting of natural disasters and environmental events.

(1) *HJ-1A/B*

The HJ-1A and HJ-1B environment and disaster reduction satellites were launched at 11:25 on September 6, 2008. HJ-1A carries a CCD camera and hyperspectral imager (HSI) and HJ-1B is equipped with a CCD camera and infrared scanner (IRS). HJ-1A and HJ-1B are equipped with the same type of CCD camera. The two cameras were placed symmetrically across the nadir, equally dividing the field of view. The cameras make parallel observations to achieve pushbroom imaging in four spectral bands with a 700-km Earth observation swath and a ground pixel resolution of 30 m. Additionally, the HSI on HJ-1A realizes pushbroom imaging in 110–128 spectral bands with a 50-km Earth observation swath and a ground pixel resolution of 100 m. HSI has a side view ability of $\pm 30^\circ$ and an onboard calibration function. The IRS on board HJ-1B completes imaging in four spectral bands (near, short, medium and long) with a 720-km Earth observation swath and a ground pixel resolution of 150/300 m. The two satellites are shown in Fig. 3.5.

(2) *HJ-1C*

HJ-1C is China's first S-band small SAR and environment and disaster reduction satellite, launched on November 9, 2012. HJ-1C has a mass of 890 kg and a sun-synchronous orbit at an altitude of 500 km. The local time of the orbital descending node is 18:00. Together with HJ-1A and HJ-1B, HJ-1C constitutes the first stage of China's environment and disaster reduction satellite constellation.

HJ-1C is equipped with an S-band SAR. Its payload works in two modes (strip mode and scanning mode) and employs a 6×2.8 m foldable mesh parabolic antenna. The SAR antenna was unfolded once HJ-1C entered orbit. It went into a swath imaging work mode after preparation. The onboard SAR has two imaging swaths: 40 and 100 km. The SAR's single-view spatial resolution is 5 m and the four-view spatial resolution is 20 m. Most of the HJ-1C's SAR images are taken in a multiview mode. The HJ-1C satellite is shown in Fig. 3.6.

The payload parameters of HJ-1C are shown in Table 3.13 (Satellite Environment Center, Ministry of Environmental Protection 2010a).

Fig. 3.6 The HJ-1C satellite

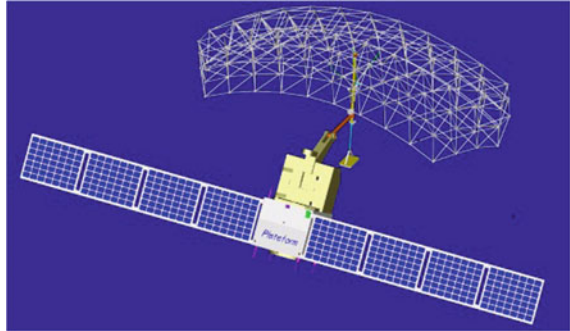


Table 3.13 HJ-1C’s payload parameters

Parameter	Value
Operating frequency (MHz)	3,200
Side view	Side-looking
Spatial resolution (m)	5 m (single-view); 20 m (four-view)
Width of imaging swath (km)	40 (strip mode); 100 (scanning mode)
Radiometric resolution (dB)	3
Polarization mode	VV
Viewing angle (°)	25–47

3.2.3.3 Satellites of the High-Resolution Earth Observation Program

Globally, the United States was the first country to develop high-resolution Earth observation systems. Other countries such as Israel, France, and India have only one or two of these satellites each. Currently, China has no high-resolution satellites. According to the China Geographic Surveying and Mapping Information and Innovation Report (2012), although China has achieved success in satellite remote sensing technology, it is still behind in high-resolution civilian remote sensing satellite technology and its commercial applications.

GF-1 (Gaofen-1) was the first satellite of China High-resolution Earth Observation System (CHEOS) and was launched using an LM-2D rocket from the Jiuquan Satellite Launch Center on April 26, 2013. GF-1’s development helped China master key technologies such as high spatial resolution, multispectral sensors, optical sensors, wide coverage, multipayload image mosaic fusion, precise and stable altitude control, and high-resolution data processing. Additionally, the development of GF-1 helped improve the capability for independent development of high-resolution satellites, and enhanced the self-sufficiency of high-resolution remote sensing data. The design life of GF-1 is five to eight years (Ding 2013).



Fig. 3.7 GF-2 image (resolution: 0.8 m)

On April 28, 2013, GF-1 began imaging and sending data. Data were received by the RADI Miyun Ground Station and processed by the China Center for Resource Satellite Data and Application. The first batch of images included four types: 2 m panchromatic, 8 m multispectral, 16 m multispectral, and 2 m panchromatic fused with 8 m multispectral.

GF-2 was launched successfully from Taiyuan Satellite Launch Center using an LM-4B carrier rocket on August 19, 2014. The successful launch was a result of special high-definition projects, indicating that Chinese remote sensing satellites were entering a submeter “high-definition era”. GF-2’s spatial resolution was 1.0 m and the swath width was 45 km, which was the largest imaging width of similar satellites of other countries (Fig. 3.7). GF-2 will be used for geographic and resource surveillance, environmental and climate change monitoring, precision agriculture, disaster relief, and city planning. The satellite is equipped with two cameras with the same resolution. The GF-2 camera can “twist its neck” to observe a range of $\pm 35^\circ$ in 180 s. GF-2 can swivel on its axis 35° to either side. Additionally, GF-2’s five-year lifetime is longer than that of most other Chinese satellites, but the desired goal is eight years.

The GF-3 satellite is a new high-resolution SAR imaging satellite launched by an LM-4C rocket at 06:55 on August 10, 2016. It blasted off at the Taiyuan Satellite Launch Center in Taiyuan, the capital of northern China’s Shanxi Province. As China’s first C-band SAR imaging satellite that is accurate to one meter, it covers the globe with an all-weather, 24-h observation service and will be used for disaster warning, weather forecasting, water resource assessments, and the protection of maritime rights. With 12 imaging modes, the high-definition observation satellite can take wide pictures of the Earth and photograph detailed scenarios of specific areas. GF-3 is also China’s first low orbit remote sensing satellite that has a lifespan

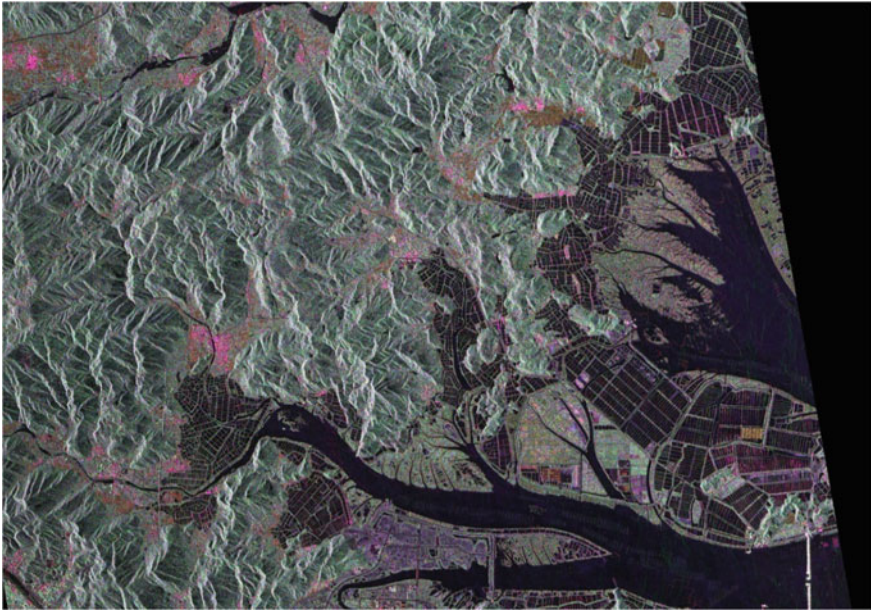


Fig. 3.8 GF-3 image (full polarization)

of eight years. It provides high-definition remote sensing data for its users over long periods of time. GF-3 is a polar orbit satellite with a high spatial resolution (Fig. 3.8) that can play a role in observing slowly changing objects such as water bodies, ice, and snow.

On June 26, 2015, China successfully launched the high-definition Earth observation satellite GF-8 into orbit from the Taiyuan Satellite Launch Center. GF-8 is an optical remote sensing satellite used in land surveying, urban planning, land delineation, highway and railway network design, crop yield estimation, disaster prevention and reduction, and other fields. The GF-9 satellite was launched from the Jiuquan Satellite Launch Center using an LM-2D carrier rocket on September 14, 2015. GF-9 is also an optical remote sensing satellite under CHEOS. The satellite can provide pictures with a ground pixel resolution of less than 1 m. It will be used in land surveying, urban planning, road network design, agriculture, and disaster prevention and relief.

On December 29, 2015, GF-4 was launched from the Xichang Satellite Launch Center in the southwestern province of Sichuan on board an LM-3B carrier rocket. It was the 222nd flight of the Long March rocket series. In contrast to GF-1 and GF-2, which orbit at low elevations (600–700 km) around Earth, GF-4 orbits 36,000 km away and moves synchronously with Earth. It can spot an oil tanker at sea using the CMOS camera, and features the best imaging capability among global high-orbit remote sensing satellites. GF-4 is China's first geosynchronous orbit HD optical imaging satellite and the world's most sophisticated HD geosynchronous orbit remote

Table 3.14 GF satellite parameters

Satellite	Sensor
GF-1	2 m panchromatic/8 m multispectral/16 m wide-swath multispectral
GF-2	1 m panchromatic/4 m multispectral
GF-3	1 m C-SAR
GF-4	50 m stationary gazing camera
GF-5	Visible shortwave infrared hyperspectral camera Full-spectrum spectral imager Atmospheric aerosol multiangle polarization detector Atmospheric trace gas differential absorption spectrometer Main atmospheric greenhouse gas monitor Ultrahigh-resolution infrared atmospheric sounder
GF-6	2 m panchromatic/8 m multispectral/16 m wide-swath multispectral
GF-7	High space three-dimensional mapping instrument

sensing satellite. It will be used for disaster prevention and relief, surveillance of geological disasters and forest disasters, and meteorological forecasting.

The GF-5 and GF-6 satellites were launched on May 9 and June 2, 2018, respectively. GF-5 was designed to run on a sun-synchronous orbit and carries six payloads: an advanced hyperspectral imager (AHSI), a visual and infrared multispectral imager (VIMI), an atmospheric infrared ultraspectral sounder (AIUS), a greenhouse gases monitoring instrument (GMI), an environmental trace gases monitoring instrument (EMI), and a directional polarization camera (DPC). The GF-6 satellite has a similar function to the GF-1 satellite but has better cameras, and its high-resolution images can cover a large area of the Earth, according to the State Administration of Science, Technology and Industry for National Defence. GF-6 can observe the nutritional content of crops and help estimate the yields of crops such as corn, rice, soybeans, cotton and peanuts. Its data will also be applied in monitoring agricultural disasters such as droughts and floods, evaluation of agricultural projects and surveying of forests and wetlands.

Parameters of the GF satellites are shown in Table 3.14.

3.2.3.4 Remote Sensing Microsatellites

Microsatellites are a new type of satellite that is low-cost and has a short development time and more flexible operation than conventional spacecraft that are heavy, costly, and time-consuming to develop. The spatial and temporal resolutions of Earth observation can be significantly improved using a distributed constellation of microsatellites. As a result, microsatellites are becoming more widely used around the world. China has launched several series of microsatellites for Earth observation, such as the “SJ” series, “Tsinghua-1”, “NS-2”, and “Beijing-1”, which have improved and enriched the Chinese satellite observation system.

SJ-9A and SJ-9B are a new generation of microsatellite launched in 2012. They are the first satellites in the “New-tech Civilian Experimental Satellite” series. SJ-9A is equipped with a high-resolution multispectral camera with a panchromatic resolution of 2.5 m and multispectral resolution of 10 m. SJ-9B carries longwave infrared focal plane components for optical imaging with a resolution of 73 m. As of August 2013, the “SJ” satellite series had developed up to SJ-11E and provided adequate services for China’s space science and technology experiments (Guo et al. 2013).

3.2.3.5 Remote Sensing from the Shenzhou Spacecraft

China has successfully developed and launched ten Shenzhou spacecraft, representing the country’s achievements and capability in space science and technology. A series of scientific experiments such as space measurement, environmental monitoring, and Earth observation have been carried out in space with the support of the Shenzhou spacecraft. The Shenzhou spacecraft have accelerated the development of Earth observation technology in China.

In 2011, China’s first space laboratory, Tiangong-1, was successfully launched. It was the starting point for Chinese space station development and signified that China had the ability to build short-term untended space stations. In the same year, Tiangong-1 successfully docked with the Shenzhou-8 unmanned spacecraft, revealing that China had achieved a series of key technologies such as space rendezvous and docking and operation of combined bodies. Shenzhou-9 and Shenzhou-10 were launched in 2012 and 2013, respectively. Shenzhou-11 was launched on October 17, 2016. For the first time, China realized space rendezvous and docking of manned spacecraft, and Chinese astronauts carried out teaching activities in space, marking an important step forward in China’s space laboratory development (Jiang 2013). Figure 3.9 shows the development timeline of the Shenzhou series of spacecraft.

3.2.3.6 Commercial Remote Sensing Satellites

China’s government is encouraging more participation from the private sector in commercial space programs to ensure the sustainable growth of the nation’s space industry, and some commercial remote sensing satellites and missions have been launched or are planned, including Jilin-1, Beijing-2, SuperView-1, and Lishui-1.

The Jilin-1 satellites are China’s first self-developed remote sensing satellites for commercial use and were launched from the Jiuquan Satellite Launch Center in northwestern China’s Gansu Province on Oct. 7, 2015. The system includes one optical remote sensing satellite, two satellites for video imaging and another for testing imaging techniques. Jilin Province is one of China’s oldest industrial bases and is developing its satellite industry as a new economic driver. The Jilin-1 GP 01 and 02 satellites for multispectral imaging were launched on a Long March 11 rocket from the Jiuquan Satellite Launch Center on January 21, 2019. By 2020, the plans

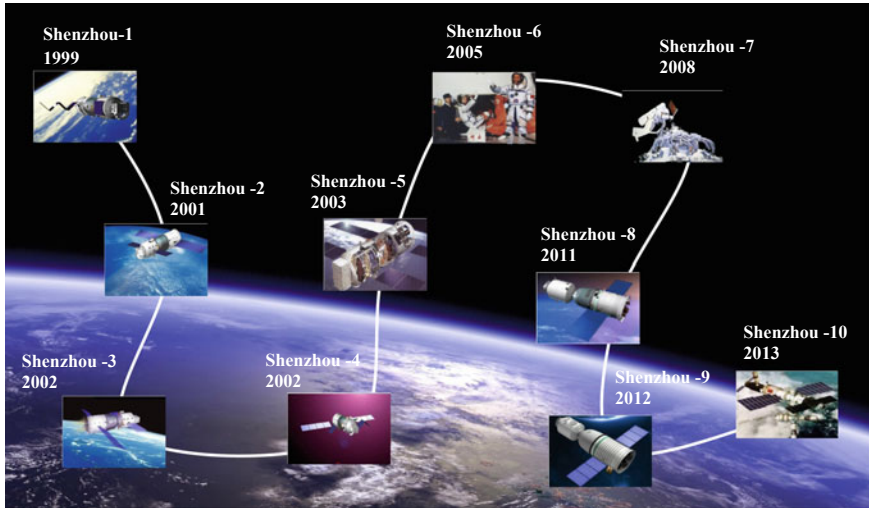


Fig. 3.9 Roadmap of the Shenzhou spacecraft program

indicate a 60-satellite orbital constellation capable of a 30-min update. From 2030, the Jilin constellation will have 138 satellites in orbit, forming a 24-h, all-weather, full-spectrum acquisition segment with the capability of observing any arbitrary point on the globe with a 10-min revisit capability, providing the world's highest spatial and temporal resolution space information products.

The Beijing-2 remote sensing satellite constellation comprises three identical optical EO satellites, which makes it possible to target any place on Earth once per day. The constellation provides less than 1-m high-resolution imagery products with a 23.4-km swath. The constellation was launched on July 10, 2015 from the Dhawan Space Centre in Sriharikota, India. The space and ground segments were designed to efficiently deliver timely information. The satellites were developed by the UK-headquartered Surrey Satellite Technology Ltd. (SSTL), which is the world's leading small satellite company and part of the Airbus Group. The Twenty First Century Aerospace Technology Company (21AT) will manage the satellites' operation, which includes observation and control, data reception and production, and related services. The satellites will provide the best combination of spatial resolution and temporal resolution to stimulate monitoring applications such as urban planning and intelligent management at a very high resolution. The main parameters of the constellation are shown in Table 3.15.

The SuperView-1 01 and 02 satellites were launched by one rocket on December 28, 2016, and two better performing satellites will be launched in the future to comprise four 0.5-m resolution satellites phased 90° from each other on the same orbit to provide services to global clients.

The Lishui-1 satellites, developed by the privately owned Zhejiang Lishui Electronic Technology Co Ltd, are commercial remote sensing satellites that were

Table 3.15 Parameters of the Beijing-2 satellite constellation

Feature	Parameter
Number of satellites	3
Satellite orbit	Sun-synchronous orbit Altitude: 651 km LTAN: 10:30
GSD	<1 m PAN <4 m MS
Bands	B/G/R/NIR
Swath width	23.4 km
MTF	PAN: 10% MS: 20%
Signal-to-noise	>100
Off-pointing capacity	$\pm 45^\circ$
Revisit	1 day
Lifetime	7 years

launched by an LM-11 solid-fuel rocket from the Jiuquan Satellite Launch Center in northwest China on November 10, 2016. The company plans to build a constellation of up to 80 to 120 commercial satellites to obtain images of the Earth and data to serve business purposes.

3.2.4 Other Land Observation Satellites

3.2.4.1 Japan's Satellites

In 1992, Japan's first Earth resource satellite, JERS-1, was launched into orbit. It carried next-generation SAR and optical sensors with a ground resolution of 18 m. During satellite operation, SAR transmits more than 1,500 microwave pulse signals per second to the surface and receives signals reflected from the ground with the same antenna. The optical sensor is composed of a VNIR radiometer and a shortwave infrared radiometer, and Earth observation is carried out in eight wavebands. Japan's Advanced Earth Observation Satellite (ADEOS), launched on August 17, 1996, was a next-generation large-scale Earth observation satellite that followed Japan's marine observation satellite, MOS, and Japan's Earth resource satellite, JERS-1.

On January 24, 2006, the Japan Space Agency launched the ALOS-1 satellite. ALOS-1 used advanced land observation technologies to obtain flexible, higher resolution Earth observation data that could be applied to mapping, regional observation, disaster monitoring, resource surveys, technical development, and other fields. The basic parameters of the ALOS-1 satellite are shown in Table 3.16.

The JAXA completed operation of ALOS-1 on May 12, 2011. The technologies acquired from ALOS-1 operation were succeeded by the second Advanced Land Observing Satellite (ALOS-2). The PALSAR-2 on board ALOS-2 is an L-band SAR

Table 3.16 ALOS-1 characteristics

Parameter	Value
Launch date	2006.01.24
Type of orbit	Sun-synchronous orbit
Repetition period (d)	46
Altitude (km)	691.65
Inclination (°)	98.16
Attitude control precision (°)	2.0×10^{-4} (in coordination with ground control point)
Positioning accuracy (m)	1.0
Data rate (Mbps)	240 (via data relay satellites)
Onboard data storage	Solid-state data recorder (90 GB)

sensor, a microwave sensor that emits L-band radio waves and receives their reflection from the ground to acquire information. The PALSAR-2 has three modes: (1) Spotlight mode—the most detailed observation mode with 1 by 3 m resolution (25 km observation width); (2) Strip Map mode—a high-resolution mode with the choice of 3, 6 or 10 m resolution (observation widths of 50 or 70 km); and (3) ScanSAR mode—a broad area observation mode with observation widths of 350 or 490 km and resolution of 100 or 60 m, respectively.

3.2.4.2 India's Satellites

Resourcesat is part of the Indian remote sensing satellite system. The first of the Resourcesat satellites, Resourcesat-01, was launched on October 17, 2003. This series is used for disaster forecasting, agriculture, water resources, forest and environment monitoring, infrastructure development, geological exploration, and mapping services.

The second satellite of this series, Resourcesat-02, was the 18th remote sensing satellite designed and developed by ISRO (Fig. 3.10). With a total mass of 1,206 kg, Resourcesat-02 adopts three-axis stabilization technology and was designed to work for five years. Its sensors and related subsystems were jointly developed by the ISRO Satellite Center (ISAC) and the Space Application Center (SAC). The Indian National Remote Sensing Center (NRSC) is responsible for receiving and preprocessing the satellite's image data as well as for production and distribution of products. Resourcesat-02 enhanced the Earth observation capability of the country's remote sensing satellite system to better serve India's economic development and national defense.

Resourcesat-02 replaced Resourcesat-01 after a series of on-orbit tests, and expanded ISRO's remote sensing data services. The Resourcesat-02 satellite's payload includes: linear imaging self-scanning sensors (LISS-3 and LISS-4), an

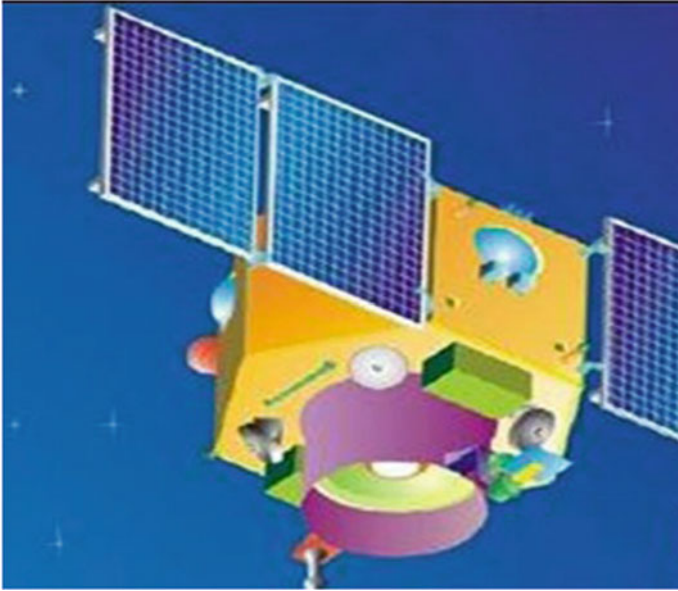


Fig. 3.10 The Resourcesat-02 satellite

advanced wide field-of-view sensor (AWIFS), three high-resolution multispectral cameras, and a marine automatic identification system (AIS). LISS-4 has a spatial resolution of 5.8 m and scanning width of 70 km, can work in the VNIR spectral range, and can obtain cross-track stereo images (Goward et al. 2012).

3.2.4.3 Russia's Satellites

The Resurs-F series of satellites are tasked with monitoring crop growth, ice cover, landforms, and other features. They also undertake scientific research missions. For example, the two Resurs-F1 satellites launched in May and July 1989 were passive atmospheric research satellites, 70 mm in diameter and 78 kg in mass, that were used to study the density of the upper atmosphere. The two satellites also carried scientific instruments from other countries for scientific experiments.

The first Resurs-F satellite was launched on September 5, 1979 from the Plesetsk Launch Site using an SL-4 rocket. The satellite was 7 m long, 2.4 m in diameter, 6,300 kg in mass and was composed of three compartments. The central part of the satellite was a 2.3-m diameter sphere that housed the imaging system, electronic control system, and recovery system. One side was connected to the 3 m long and 2 m wide propulsion module via a fixing mechanism that unlocked when the retarding rocket was ignited. The other side was 1.9 m long and the propulsion unit occupied up to 1.0 m. The propulsion unit was used for orbital adjustment and was cast off when the return capsule re-entered the atmosphere. The remaining 0.9 m of space was

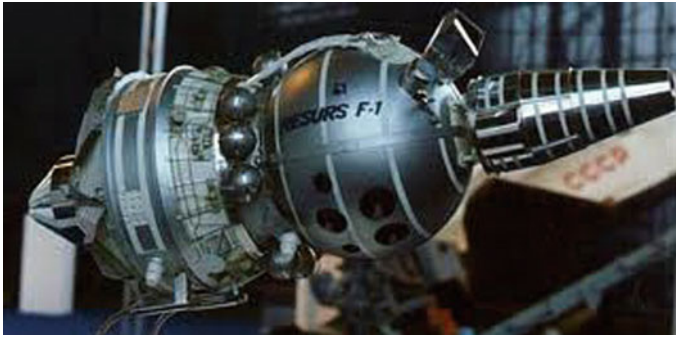


Fig. 3.11 The Resurs-F1 satellite

used to carry additional releasable secondary payloads of up to 30 kg or more. These secondary payloads could be placed inside or outside the return capsule and carried back to the ground. An overview of the Resurs-F1 satellite is shown in Fig. 3.11.

The imaging system on board the Resurs-F1 satellite included an SA-20M long-focus wide imaging system with a KFA-1000 camera and an SA-34 wide mapping and imaging system with a KATE-200 camera. Compared with Resurs-F1, the Resurs-F2 satellite's biggest improvement is the addition of two solar panels, which extended its service life to nearly one month. The first Resurs-F2 satellite, also known as Cosmos-1906, was launched into space in 1987. However, the launch was unsuccessful and the satellite was destroyed in orbit. Resurs-F2 satellites are operating in 170–240 km low Earth orbits and near-polar circular orbits with an orbital inclination of 82.3°. An outline of the Resurs-F2 satellite is shown in Fig. 3.12.

The Resurs-F2's imaging system is significantly different than that of Resurs-F1 and includes a KFA-1000 camera and a high-resolution MK-4 mapping camera. Equipped with a passive remote sensor, the MK-4 camera can record images on three separate pieces of film and perform imaging in any three of the following six spectral bands: 0.63–0.69 μm , 0.81–0.90 μm , 0.52–0.57 μm , 0.46–0.51 μm , 0.58–0.80 μm , and 0.40–0.70 μm . The camera's focal length is 300 m, the spatial resolution is greater than 10 m, the panchromatic spectral resolution is 8 m, and the ground width is 120–180 km. One scan can generate 2,700 images and the image size is 180 \times 180 mm with an overlap ratio of 60%. The satellite can be used for mapping, environmental monitoring, and geographic surveys.

The Resurs-O series of satellites were mainly used in geology, cartography, fire detection, ice detection, hydrology, and agriculture. They were designed and manufactured by the then National Institute of Electronics in the former Soviet Union.



Fig. 3.12 The Resurs-F2 satellite

3.3 Ocean Observation Satellites

Ocean satellites are the best tools for understanding Earth's oceans, and can be economically used for real-time, synchronous, and continuous monitoring of large areas. At present, ocean satellites are the primary means of marine environment monitoring, making their development a necessity. Ocean satellites can enhance scientists' capability for marine environment and disaster monitoring, forecasting, and early warning, and can provide efficient services for marine resource surveying, development, and management. These satellites can conduct global surveys of fisheries, scientifically estimate fishery potential, and provide a basis for the development of fishery policies. Furthermore, they can effectively and affordably measure the marine gravity field to provide an understanding of submarine tectonics and oil and gas reserves, and assist in developing offshore oil fields.

3.3.1 US Ocean Observation Satellites

3.3.1.1 Development Stages of US Ocean Satellites

The development of US ocean satellites has experienced four stages (Dong 2012): (1) preparation stage (before 1978); (2) experiment stage (1978–1985); (3) application research stage (1985–1999), and (4) comprehensive oceanographic observation stage (1999–present).

(1) Preparation stage

The first US meteorological satellite, TIROS-I, was launched by NASA in April 1960, followed by TIROS-II, which started sea surface temperature observation. In 1961, the United States began to implement the Mercury Program, making it possible for astronauts to observe the ocean from a high altitude. In 1969, NASA began to promote a marine observation plan; in 1975, GOES-3 was equipped with an altimeter for measuring the distance from the satellite to the sea surface. In 1973, the Skylab space station confirmed the potential of visible and infrared remote sensing in continuous Earth observation.

(2) Experiment stage

In this stage, marine remote sensors were mainly installed on US ocean satellites such as Seasat, Nimbus-7, TIROS-N, and GEOS. The main marine elements inversed in this stage included sea surface temperature, ocean color, and sea ice. In 1981, NOAA satellites began using the multichannel sea surface temperature (MCSST) algorithm to forecast sea surface temperature.

(3) Application research stage

The main ocean satellites launched in this stage were equipped with a variety of microwave monitoring instruments, infrared radiometers and ocean color imagers to monitor the sea surface, submarine topography, sea waves, sea wind, ocean currents, marine pollution, primary oceanic productivity, and other factors. In 1985, the United States launched an ocean topography satellite called Geosat, which was mainly used to measure significant wave height, wind velocity and meso-scale oceanic features. Over the years, Geosat provided a wide range of altimeter data. Other meteorological satellites were also involved in marine observation. For instance, NOAA meteorological satellites were used for sea surface temperature inversion, sea condition monitoring, and sea pollution research. In 1987, the SeaWiFS Working Group of NASA and the Earth Observation Satellite Company (EOSAT) jointly proposed a systematic plan for spaceborne wide-field-of-view marine observation. In August 1997, the United States launched an ocean satellite, SeaSTAR, (also called OrbView-2), which was later included in the EOS program as the first ocean color satellite of the program. Subsequently, the United States developed the navy remote ocean sensing system (NPOSS) and, in cooperation with France, NASA developed TOPEX/Poseidon for observing ocean topography.

(4) Comprehensive oceanographic observation stage

According to the research objectives of the EOS and ESE, the period from 1999 to the present is the comprehensive oceanographic observation stage in the development of ocean remote sensing. The first satellite of the next-generation international Earth observation satellite system, Terra (EOS-AM1), was launched on December 18, 1999, marking the beginning of a new era of human observation of Earth. The second polar-orbiting environmental remote sensing satellite, Aqua (EOS-PM1), was launched on May 4, 2002. Both Terra and Aqua are equipped with a Moderate Resolution Imaging Spectroradiometer (MODIS) that has 36 wavebands ranging from visible to thermal infrared light, nine of which can be used for ocean color remote sensing. Compared with SeaWiFS, MODIS is more advanced and is known as the third-generation ocean color (and meteorological element) sensor (DeVisser 2013). The Jason program was proposed to meet the requirements for establishing a global marine observation system and the demands of oceanic and climatological research. The Jason-2 ocean altimetry satellite (also used for accurate determination of ocean topography) was jointly developed by the Centre National d'Etudes Spatiales (CNES), EUMETSAT, NASA, and NOAA and launched on June 20, 2008. As a follow-up to TOPEX/Poseidon and Jason-1, it is an important observation platform for global oceanographic studies.

3.3.1.2 Typical US Ocean Satellite Systems

(1) Seasat-1

Launched on June 27, 1978, Seasat-1 operated on orbit for 105 days and stopped working on October 10, 1978, due to an electrical system fault. It was launched to demonstrate global monitoring technologies including the observation of oceanic dynamics and satellite orbit characteristics and to provide oceanographic data for the development and application of an operational ocean dynamics monitoring system.

Seasat-1 was the first ocean satellite to use synthetic aperture radar (SAR) for ocean observation by means of remote sensing (Fig. 3.13). Its purpose was to prove the feasibility of using satellites to monitor global oceanic phenomena and help determine the requirements of ocean remote sensing satellite systems. The goal was to collect data about ocean surface wind, sea surface temperature, atmospheric water, sea ice characteristics, ocean topography, and similar parameters. Seasat-1 could cover 95% of the world in a 36-h observation cycle.

(2) OrbView-2

Also called SeaStar, OrbView-2 was launched into a 705 km sun-synchronous orbit on August 1, 1997. The mass of the parent capsule was 155 kg, the mass of the instruments was 45.4 kg, and that of the satellite was 317 kg. The outer dimensions of the satellite were $1.15 \times 0.96 \times 1.6$ m, and the solar wing plate had a span of 3.5 m when unfolded (Fig. 3.14).



Fig. 3.13 Seasat-1

The satellite carried only one remote sensing instrument, SeaWiFS, which could monitor ocean color, generate multispectral images of the land and sea surface, and analyze the impacts of ocean color changes on the global environment, atmosphere, carbon cycle, and other ecological cycles. SeaWiFS consisted of optical remote sensors and an electronic module, and the satellite covered the global ocean area once every two days.

OrbView-2 was the world's first satellite that could generate color images of the Earth every day. The imager had eight spectral segments, six of which were visible and two of which were near infrared. With a spatial resolution of 1.1 km and a 2,800 km scanning width, OrbView-2 data could be used in the fishing industry, agriculture, scientific research, and environmental monitoring.

(3) Jason-1

As an ocean satellite, Jason-1 is used to study the relationship between the ocean and the atmosphere, monitor global ocean circulation, improve global weather prediction and forecasting, and monitor El Niño, ocean eddies, and other events (Chander et al. 2012). With a total weight of 500 kg and payload of 120 kg, Jason-1 was launched on December 7, 2001 (Fig. 3.15). It was the world's first satellite to use the French Alcatel PROTEUS multifunctional microplatform and carried five scientific instruments: one dual-frequency solid-state spaceborne radar altimeter (Poseidon-2), which was the main payload of Jason-1, one triple-channel microwave radiometer (JMR) used to measure atmospheric water vapor content and provide water vapor correction for the radar altimeter, and three other instruments for accurate orbit determination that comprise one Doppler orbitography by radio positioning integrated by satellite



Fig. 3.14 OrbView-2



Fig. 3.15 Jason-1 ocean satellite

(DORIS), one laser retro reflector array (LRA), and one turbo rogue space receiver (TRSR).

As the main payload of the Jason-1 satellite, Poseidon-2 was developed by the CNES as an improved model of the Poseidon-1 radar altimeter. In addition to inheriting all the advantages of its predecessor, Poseidon-2 used dual-frequency technology, with working frequencies of 13.575 GHz (Ku-band) and 5.3 GHz (C-band). Compared to other radar altimeters, Poseidon-2 was smaller in volume and lighter weight and had more efficient power consumption. It is mainly used to measure sea surface height, wind velocity, significant wave height, and ionospheric corrections. The main technical parameters of the Poseidon-2 radar altimeter are shown in Table 3.17.

Table 3.17 Main technical parameters of the Poseidon-2 radar altimeter

Satellite feature	Parameter
Operating frequency (GHz)	13.575 (Ku), 5.3 (C)
Pulse repetition frequency (PRF) (Hz)	2,060
Pulse duration (μ s)	105
Bandwidth (MHz)	320
Antenna diameter (m)	1.2
Antenna wave width ($^{\circ}$)	1.28 (Ku), 3.4 (C)
Power (W)	7

3.3.2 European Ocean Observation Satellites

The successful launch of the first meteorological satellite, *Meteosat*, in 1977 marked the beginning of the implementation of the European Earth Observation Program (EOP). The main task of *Meteosat* was to monitor the atmosphere over Europe and Africa. Implementation of the ERS missions in the early 1990s marked the EOP’s entry into a new stage. The launch of an *ENVISAT* satellite in 2002 sped up the pace of EOP implementation. The ESA proposed the Living Planet Programme (LPP) in 1998. Compared with the ERS and *ENVISAT* missions, the LPP used smaller satellites, was less costly and had better defined targets.

3.3.2.1 ERS-1/2

The ERS-1/2 satellites operated on a near-polar sun-synchronous orbit, with an average orbital altitude of 785 km and an orbital inclination of 98.50°. The local time when the satellite moved from north to south across the equator was 10:30 AM. The ERS-1 launch involved a number of adjustments to the orbital altitude instruments. The three months after launch, the satellite used a three-day period for trial operation at an orbital altitude of 785 km (reference orbit). The orbital adjustment period of the sun-synchronous satellite was 3–176 days, and the main working period was 35 days. The average orbital altitude for the three-day period was 785 km, the orbital altitude above the equator was 909 km, and the satellite circled Earth 43 times. The main parameters of ERS-1/2 are shown in Table 3.18.

The satellite platform carried the following seven instruments (Fig. 3.16): (1) an active microwave instrument (AMI) with an SAR that had a 100-km mapping swath; (2) a wind scatterometer that used three groups of antennas to measure the direction and velocity of sea surface winds; (3) a radar altimeter that was used to accurately measure sea surface topography and elevation, wave height, sea surface wind velocity, and characteristics of sea ice; (4) an orbit-tracking scanning radiometer and microwave sounder; (5) a precision ranging velocimeter that was used to accurately measure the satellite position, orbital characteristics, and the position of fixed ground stations; (6) a laser reflector that used laser beams emitted from the

Table 3.18 ERS-1/2 parameters

Satellite parameter	Value
Weight (kg)	2,400
Total length (m)	11.8
Solar cell array	Area: $11.7 \times 2.4 \text{ m}^2$; power: 1.8 KW; service life: 2 years
SAR antenna (m)	10×1
Scatterometer antenna (m^2)	Anterio-posterior direction: 3.6×0.25 ; middle direction: 2.3×0.35
Radar altimeter antenna diameter (m)	1.2
Communication frequency band	S-band
Orbit	800 km sun-synchronous orbit
Orbital period (d)	35



Fig. 3.16 ERS-1

ground station to measure the satellite orbit and position; and (7) an onboard data processing system.

3.3.2.2 ENVISAT Satellite

Launched on March 1, 2002, ENVISAT was a polar-orbiting Earth observation satellite and the largest Earth observation satellite built (Fig. 3.17). ENVISAT had ten



Fig. 3.17 ENVISAT satellite

Table 3.19 The working modes and characteristics of the ASAR sensor on the ENVISAT satellite

Feature	Image	Alternating Polarization	Wide Swath	Global Monitoring	Wave
Imaging swath width (km)	Max. 100	Max. 100	Approx. 400	Appr. 400	5
Downlink data rate (Mbps)	100	100	100	0.9	0.9
Polarization mode	VV or HH	VV/HH or VV/VH or HH/HV	VV or HH	VV or HH	VV or HH
Resolution (m)	30	30	150	1,000	10

instruments that constituted an observation system that captured lithosphere, hydrosphere, atmosphere, biosphere, and ice layer information.

At the time, the ASAR on board ENVISAT was the world’s most advanced spaceborne SAR sensor with new features including multipolarization, multiple modes, and multiple incident angles. The ground resolution of data reached 25 m, and the widest coverage was 400 km. The multipolarization SAR imaging system could acquire copolarization and cross-polarization information of ground objects and more accurately detect features of a target. The five working modes and characteristics of the ENVISAT satellite’s ASAR sensor are listed in Table 3.19.

3.3.2.3 The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)

The GOCE was a satellite that adopted new technologies to map the Earth's gravitational field (Fig. 3.18). The GOCE was launched on March 17, 2009 (Metzler and Pail 2005). The satellite started scientific observation activities on September 30, 2009 and carried out its functions during its service life. In October 2010, the first batch of GOCE satellite data was released freely to scientific researchers and noncommercial users across the world, opening up a new historical period for Earth gravity field research.

The GOCE moved on a low, nearly-circular, twilight sun-synchronous orbit. The orbital plane's eccentricity was less than 0.001 and its inclination was 96.7° , leaving a nonobservable area with a spherical radius of approximately 6.7° in the northern and southern polar regions. The satellite's working time was twenty months, including three months of commissioning and calibration followed by a period of scientific measurement and period of dormancy. Due to its energy supply, trial operation, gradiometer calibration, orbital adjustment and other reasons, the time period for scientific observation was only twelve months. Once the satellite's working time period had expired, it was decided to extend the GOCE's operational period based on the working state of all systems and the quality of data products obtained. The original plan was to extend the mission by ten months and increase the observation tasks accordingly (Floborghagen et al. 2011).

The goal of the GOCE mission was to provide a high-precision, high-resolution static Earth gravity model (Bouman et al. 2009). Such models can be obtained based



Fig. 3.18 GOCE

on the gravity gradient and GPS tracking data. The specific goals were to: determine global gravity anomalies with a precision of 1 mGal, determine the global geoid with a precision of 1–2 cm, and fulfil these goals with a spatial resolution above 100 km (half-wavelength) (Visser 2010; Gooding et al. 2007).

3.3.3 China’s Ocean Observation Satellites

China’s first independently developed ocean satellite, HY-1A, was launched on May 15, 2002. As an experimental satellite, HY-1A was used to monitor ocean color and temperature. HY-1B was launched on April 11, 2007, and was positioned for operation on September 3. HY-1B was the successor to HY-1A, with a design life of three years, and its technical indicators and functions were superior to those of HY-1A. The HY-2A satellite was launched on August 16, 2011. As a marine dynamic environment satellite, HY-2 worked to detect the sea surface wind field, temperature field, sea surface height, wave field, and flow field. It adopted the platform of the ZY-1 satellite. A roadmap of ocean satellite development is shown in Fig. 3.19.

(1) HY-1A

The ten-band Chinese ocean color and temperature scanner (COCTS) was used to detect ocean color environmental factors (concentration of chlorophyll, content of suspended sediments, and presence of soluble organic matter) and temperature field. The satellite had a nadir ground resolution of 1,100 m, 1,024 pixels per line,

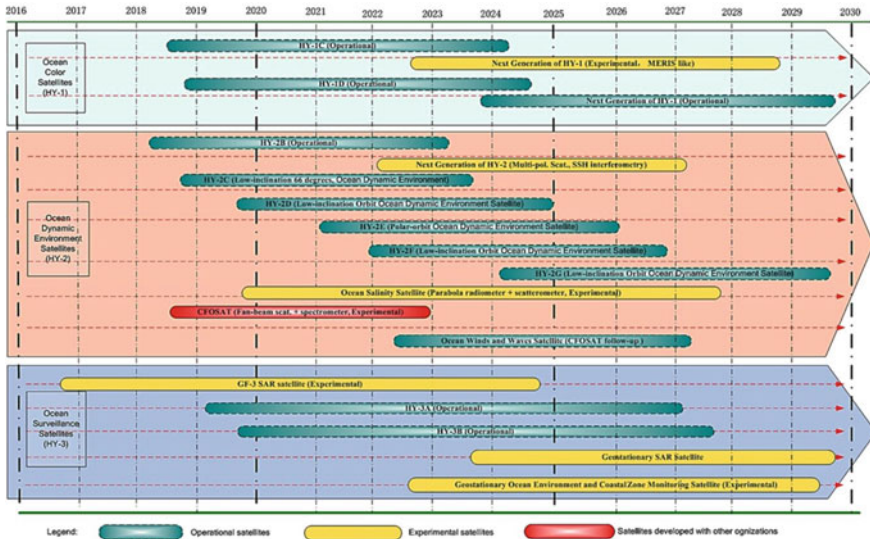


Fig. 3.19 Roadmap of ocean satellite development

Table 3.20 Ocean color and temperature scanner parameters

Parameter	Value
Spectral range (μm)	B1: 0.402–0.422, B2: 0.433–0.453 B3: 0.480–0.500, B4: 0.510–0.530 B5: 0.555–0.575, B6: 0.660–0.680 B7: 0.740–0.760, B8: 0.845–0.885 B9: 10.30–11.40, B10: 11.40–12.50
Band-center wavelength shift (nm)	$\leq 2(B1-B8)$
Nadir ground resolution (m)	≤ 1100
Number of pixels per line	1664
Quantization level (bit)	10
Radiometric precision	Visible light: Infrared: ± 1 K (when the onboard calibration accuracy is 300 K)

a quantization level of 10 bits, and a radiometric precision of 10% of the visible light. The four-band CCD imager was used to monitor coastal zone dynamics to obtain relatively high-resolution images of land-sea interaction areas. The imager had a nadir ground resolution of 250 m, 2,048 pixels per line, and $\leq 5\%$ degrees of polarization.

(2) HY-1B

As the successor of HY-1A, the HY-1B ocean satellite was launched on April 11, 2007, and had a design life of three years. Its payload parameters are shown in Table 3.20 (National Satellite Ocean Application Service 2007, 2011). HY-1B monitors the Bohai Sea, the Yellow Sea, the East China Sea, the South China Sea, and their coastal zones to detect chlorophyll, suspended sediments, soluble organic matter, and sea surface temperature.

(3) HY-2A

The HY-2A ocean satellite was China's first marine dynamic environment satellite to integrate active and passive microwave remote sensors and is capable of high-precision orbital measurement and determination, and all-weather, 24-h global detection. Its mission is to monitor and investigate marine environments and obtain dynamic ocean environment parameters including sea surface wind, wave height, ocean current, and sea surface temperature. HY-2A also provides data for the pre-warning and forecasting of disastrous sea conditions, and offers supportive services for the prevention and mitigation of marine disasters, protection of marine rights and interests, development of marine resources, protection of the marine environment, marine scientific research, and national defense. HY-2A was launched at 06:57 on August 16, 2011 from the Taiyuan Satellite Launch Center using a CZ-4B rocket.

The satellite is equipped with a scanning microwave radiometer, a radar altimeter, a microwave scatterometer, a calibrated microwave radiometer, DORIS, dual-frequency GPS, and a laser range finder. The parameters of the radar altimeter are shown in Table 3.21.

Table 3.21 Technical parameters of the HY-2 radar altimeter

Parameter	Value
Operating frequency (GHz)	13.58, 5.25
Pulse limited footprint (km)	≤2
Altitude measurement precision (cm)	<4
Effective wave height measurement range (m)	0.5–20

3.3.4 Other Ocean Observation Satellites

In addition to the United States and the ESA, Russia, Japan, Canada, and India have launched various ocean satellites into space. Generally, modern ocean satellites have an accurately determined sun-synchronous orbit, use a variety of remote sensors for measurement, and adopt a comprehensive remote sensing platform.

3.3.4.1 Japan’s Satellites

On February 19, 1987, Japan launched its first ocean observation satellite, MOS-1, on an N-1 rocket from the Tanegashima Space Center (Fig. 3.20).

MOS-1 was loaded with two optical remote sensors: a multispectral electronic self-scanning radiometer (MESSR) and a visible thermal infrared radiometer (VTIR). Other payloads included a microwave scanning radiometer (MSR), a data collection system (DCS), and a visible thermal infrared repeater. The MESSR is an electronic scanning optical observation remote sensor that uses a CCD to capture land and ocean information. Wavelengths ranging from visible light to near infrared are divided into four spectral bands (see Table 3.22). On board the satellite were two identical devices

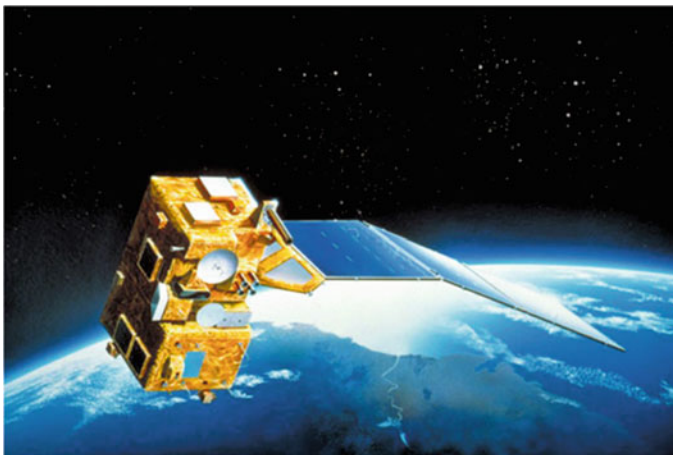


Fig. 3.20 MOS-1

Table 3.22 MOS-1 sensor characteristics

	MESSR	VTIR		MSR
Observation purpose	Ocean color, land use, etc.	Sea surface temperature, etc.		Water vapor, ice, snow, etc.
Observed wavelength (μm)	0.51–0.59	0.5–0.7	6–7	
	0.61–0.69			
	0.72–0.80		10.5–11.5	
	0.80–1.1		11.5–12.5	
Instantaneous field of view (km)	0.05	0.9	2.7	32, 23
Radio wave resolution	39–15 dB	55 dB	0.5 K	<1.5 K
Observation width (km)	100	1500		317
Scanning mode	Electronic scanning	Mechanical scanning		Mechanical scanning

with a land observation width of 100 km, coordinated coverage of 185 km, and ground resolution of 50 m.

3.3.4.2 India’s Satellites

OceanSat-1 was launched for the study of marine physics and marine biology on May 26, 1999 using a PSLV-C2 rocket (Dash et al. 2012). It was equipped with an ocean color monitor (OCM) and a multifrequency scanning microwave radiometer (MSMR) (Fig. 3.21). The OCM was used to collect data and worked at 402–422 nm, 433–453 nm, 480–500 nm, 500–520 nm, 545–565 nm, 660–689 nm, 745–785 nm, and 845–885 nm with a spatial resolution of 360 m and width of 1,420 km.

OceanSat-2 was launched on September 23, 2009 using a PSLV-C14 rocket. It functions on a circular near-polar sun-synchronous orbit 720 km above Earth, and continuously provides effective IRS-P4 services (Gohil et al. 2013; Sathiyamoorthy et al. 2012). The observation data from OceanSat-2 are applied to new areas of ocean research such as tornado trajectory prediction, coastal area mapping, and atmospheric research. The OCM and ROSA provide several geophysical parameters such as suspended sediment, yellow matter, phytoplankton, sea surface temperature (SST), sea wind, sea conditions, significant wave height, and atmospheric profiles derived from GPS radio occultation.



Fig. 3.21 OceanSat-1

3.3.4.3 Russia’s Satellites

Since 1979, the Soviet Union/Russian Federation has launched a series of ocean color satellites known as the Okean-O1 series of satellites for marine and polar ice observation (Fig. 3.22). Twelve Okean-O1 satellites were launched (including one launch failure) by the end of August 1995 and four satellites were launched between May 1988 and October 1994, referred to as Okean-1 to Okean-4. The satellite payloads included an X-band side-looking radar with 350/1,500 m resolution and 1,380/1,930 km scanning width, and a microwave radiometer with an 8 mm working



Fig. 3.22 Okean-O1 Satellite

frequency and a 550 km scanning width. The Okean-O1 series of satellites functioned at an orbital altitude of 650 km and an inclination of 82.5°. Each satellite weighed 1.95 t and had a design life ranging from six months to a year. In 1999, Russia launched a new type of ocean satellite, Okean-O, whose design life and weight were increased to three years and 6.5 t, respectively. The Okean-O series of satellites adopted a sun-synchronous orbit with an altitude and inclination of 670 km and 98°, respectively. Each satellite was equipped with nine remote sensors, leading to improved optical resolution (25–200 m for visible light and 100–600 m for infrared).

3.3.4.4 Canada's Satellites

RADARSAT is a joint research project conducted by Canada (Canadian Space Agency/Canada Centre for Remote Sensing) and the United States (NASA). The radar is designed to provide detailed information for sea ice, land ice, and climate studies, and the radar images can be used in fields such as oceanography, agriculture, forestry, hydrology, geology, and geography and to provide real-time ice surveillance of the Arctic ocean.

RADARSAT-1 was launched by Canada on November 4, 1995 (Fig. 3.23). Satellite-borne SAR is an active remote sensing device. Because it actively emits electromagnetic waves to obtain information, it can penetrate clouds and fog and overcome night barriers and is capable of all-weather, 24-h observation. It can observe the surface on a regular basis and obtain real-time observation data. The SAR on board RADARSAT-1 was a C-band multiangle sensor with an HH polarization mode and



Fig. 3.23 RADARSAT-1

seven working modes used for coastal zone observation, sea ice monitoring, topographic surveys, and other uses.

RADARSAT-2 was launched in December 2007 as Canada's next-generation commercial radar satellite offering powerful technical advancements for mapping in Canada and around the world. This satellite is a follow-up to RADARSAT-1. It has the same orbit and is separated by half an orbit period (~50 min) from RADARSAT-1 (in terms of the ground track, this represents ~12 days of separation). RADARSAT-2 is a C-band imaging radar system, with a nominal imaging swath from 20 to 500 km, incidence angles from 10° to 60°, and fully polarimetric imaging capability; it is an indispensable tool for managing natural resources and monitoring the environment in the twenty-first century. It fills a wide variety of roles, including in sea ice mapping and ship routing, iceberg detection, agricultural crop monitoring, marine surveillance for ship and pollution detection, terrestrial defense surveillance and target identification, geological mapping, land use mapping, wetlands mapping, and topographic mapping.

3.4 Meteorological Observation Satellites

Meteorological satellites have become an indispensable part of the basic and strategic resources for national economic and social development in countries across the world. As the problems of environmental pollution, resource shortages, and natural disasters become increasingly worse, the role of meteorological satellites in weather forecasting, environmental monitoring, and disaster mitigation and prevention has become more important than ever.

3.4.1 US Meteorological Observation Satellites

Since the launch of its first meteorological satellite in April 1960, the United States has developed two series of meteorological satellites: geostationary meteorological satellites and polar-orbiting meteorological satellites. The former is the Geostationary Operational Environmental Satellite (GOES) series and the latter comprises NOAA satellites in the Defense Meteorological Satellite Program (DMSP).

3.4.1.1 The DMSP Satellite System

DMSP satellites operate on sun-synchronous orbits. Some of the orbital parameters are listed in Table 3.23.

The DMSP satellite series adopts a double-satellite operation system. One satellite operates on a 06:00 AM orbit and the other on a 10:30 AM orbit, both with a repeat observation cycle of twelve hours and seven payloads, which are shown in Table 3.24.

Table 3.23 Orbits of the current DMSP system satellites

Satellite code	Orbital altitude (km)	Orbital period (min)	Orbital inclination (°)	Launch time	Orbiting direction
DMSP 5D 3/F14	833	101	98.7	20:29	Clockwise
DMSP 5D 3/F15	833	101	98.9	20:29	Clockwise
DMSP 5D 3/F16	833	101	98.9	21:32	Clockwise
DMSP 5D 3/F17	850	101	98.7	17:31	Clockwise
DMSP 5D 3/F18	850	101	98.7	17:31	Clockwise

Table 3.24 Payloads of the DMSP system satellites in orbit

Satellite code	Payloads
DMSP 5D 3/F14	OLS, SSB/X-2, SSI/ES-2, SSJ/4, SSM, SSM/I, SSM/T-1, SSM/T-2
DMSP 5D 3/F15	OLS, SSI/ES-2, SSJ/4, SSM, SSM/I, SSM/T-1, SSM/T-2
DMSP 5D 3/F16	OLS, SSI/ES-3, SSJ/5, SSM, SSM/IS, SSULI, SSUSI
DMSP 5D 3/F17	OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI
DMSP 5D 3/F18	OLS, SSI/ES-3, SSM, SSM/IS, SSULI, SSUSI

The DMSP satellite series uses two data transmission modes: direct reading mode and storage mode. The former can transmit data to the ground station in real time and the latter transmits the data stored in the satellite-borne magnetic tape unit to the ground station when the satellite is flying over it. These ground stations include the Fairchild Air Force Base in the state of Washington, the Loring Air Force Base in Maine, and the Ka’ena Point Satellite Tracking Station in Hawaii. Then, the ground stations transmit the data, via relay satellites, to the Air Force Global Weather Center (AFG-WC) at the Offutt Air Force Base in Nebraska and the Fleet Numerical Oceanographic Center (FNOC) in Monterey, California.

3.4.1.2 The NOAA Satellite System (POES)

Satellites of the Polar-orbiting Operational Environmental Satellite (POES) system operate on sun-synchronous orbits. The NOAA satellite system adopts a double-satellite operation system. The local time of the orbit descending node of one of the satellites is in the morning, and that of the other is in the afternoon. Currently, the POES system satellites carry six kinds of payloads, which are shown in Table 3.25.

Table 3.25 Payloads of the POES system satellites

Satellite	Payloads
NOAA- K	AMSU-A, AMSU-B, ARGOS, ATOVS (HIRS/3 + AMSU + AVHRR/3), AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA)
NOAA- L	AMSU-A, AMSU-B, ARGOS, ATOVS (HIRS/3 + AMSU + AVHRR/3), AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- M	AMSU-A, AMSU-B, ARGOS, AVHRR/3, HIRS/3, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- N	AMSU-A, ARGOS, AVHRR/3, HIRS/4, MHS, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)
NOAA- N'	A-DCS4, ARGOS, AVHRR/3, HIRS/4, LRIT, MHS, NOAA Comms, S&R (NOAA), SBUV/2, SEM (POES)

In these payloads, AVHRR/3 is used to detect clouds, and cloud-top, sea surface and land surface temperatures. Its channel characteristics are shown in Table 3.26.

HIRS/3 is used to sound the vertical profiles of atmospheric temperature and humidity on cloudless or partly cloudy days. With a quantization level of 13 bits, the instrument has 20 channels and a resolution of 17.4 km.

AMSU consists of AMSU-A and AMSU-B. AMSU can sound temperature and humidity on cloudy days, sound precipitation on the land and sea, recognize sea ice and determine its scope, and sound soil moisture to a certain degree.

SEM is used to measure solar protons, alpha particles, electron flux density, the energy spectrum, and the total particle energy distribution in the satellite orbit to study the satellite's physical environment in space, predict proton events, and ensure the safe operation of spacecraft working in orbit.

ERBS is used to observe incident solar shortwave radiation, solar shortwave radiation reflected to outer space, and longwave radiation transmitted from the Earth-atmosphere system. SBUV is used to measure the total amount and vertical distribution of ozone. The instrument detects the 160–400 nm band and measures two aspects: the ultraviolet backscatter of the atmosphere in the O₃ absorption band and the ultraviolet radiation of the Sun.

Table 3.26 Channel characteristics and applications of AVHRR/3

Channel	Wavelength (μm)	Resolution (km)	Typical application
1	0.58–0.68	1.09	Daytime cloud imaging
2	0.725–1.00	1.09	Ice and snow monitoring
3A	1.58–1.64	1.09	Aerosol, snow, and ice monitoring
3B	3.55–3.93	1.09	Fire and nighttime cloud imaging
4	10.30–11.30	1.09	Daytime and nighttime cloud imaging, land surface and sea surface temperature sensing
5	11.50–12.50	1.09	Daytime and nighttime cloud imaging, land surface and sea surface temperature sensing

Table 3.27 Payloads of third-generation GOES satellites in orbit

Satellite code	Payloads
GOES-12	DCS (NOAA), GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI, WEFAX
GOES-13	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI
GOES-14	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder
GOES-15	A-DCS4, GOES Comms, Imager, LRIT, S&R (GOES), SEM (GOES), Sounder, SXI

3.4.1.3 The GOES Satellite System

The United States is now using the third generation of geostationary meteorological satellites. These satellites adopt a three-axis stabilization mode and a satellite-borne vertical sounder, and the imager can perform sounding separately at the same time. There are four main kinds of payloads. The orbital information and payloads of the Geostationary Operational Environmental Satellite (GOES) satellites currently in operation are shown in Table 3.27.

3.4.2 European Meteorological Observation Satellites

The European meteorological satellite program began in 1972. The initial goals of the program were to meet European countries' need for weather analysis and forecasting and meet the demand for global atmospheric monitoring and research in accordance with the WMO's World Weather Watch (WWW) program and the Global Atmospheric Research Program (GARP).

3.4.2.1 Typical Geostationary Meteorological Satellites of Europe

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) has launched ten Meteosat satellites since the first geostationary meteorological Meteosat satellite was launched in November 1977. The European geostationary meteorological satellites are the Meteosat series of satellites launched by EUMETSAT; Meteosat-7 belongs to the first generation (Fig. 3.24) and Meteosat-8, Meteosat-9 and Meteosat-10 belong to the second generation.

The main instrument installed on the first generation of Meteosat operational satellites is a three-channel imager, MVIRI. The parameters of each channel are listed in Table 3.28. The satellites' main tasks are to (1) provide 48 full-disk images of Earth daily; (2) transmit near-real time digital and analog images to primary data user stations and secondary data user stations; (3) relay image data transmitted from



Fig. 3.24 First-generation Meteosat system

Table 3.28 Features of first-generation Meteosat operational satellites

Channel	Spectrum (μm)	Pixel \times scan line
Visible (VIS)	0.5–0.9	5000 \times 5000
Infrared (IR)	10.5–12.5	2500 \times 2500
Water vapor (WV)	5.7–7.1	2500 \times 2500

other meteorological satellites; (4) collect data transmitted from the data acquisition platform; (5) send meteorological products to users; and (6) perform meteorological data distribution (MDD), which is mainly intended to improve the transmission of African meteorological data.

The second-generation Meteosat satellites entered Phase A (system design phase) before 1993 and entered Phase B (sample satellite development phase) soon after. Phase C was developed as the launch and implementation phase, and Phase D was the postlaunch application and improvement phase.

MSG is a spin-stabilized satellite (Fig. 3.25), similar to the first generation of meteorological satellites. Its design was improved in many aspects. For instance, the satellite-borne radiometer SEVIRI has much higher performance, the spectral channels were increased from three to twelve, the resolution was greatly improved (1 km in the wideband high-resolution visible light channel), and the scanning time was halved from thirty minutes to fifteen minutes. The data transmission system was also improved, making data transmission and broadcast much faster (3.2 Mbps and 1 Mbps, respectively).

Fig. 3.25 MSG satellite

3.4.2.2 Polar-Orbiting Meteorological Satellite System

The European Union's polar-orbiting meteorological satellite system, MetOp, and EUMETSAT teams are working closely together to develop a European polar-orbiting meteorological satellite system and launch the MetOp series of satellites which, starting in 2002, began replacing older meteorological satellites (TIROS series) launched earlier by NOAA. Satellites owned and operated by EUMETSAT will be part of an American-European three-satellite operating system, in which one US satellite will appear at dawn, MetOp will appear in the morning and another US satellite will appear in the early afternoon.

MetOp is being designed to carry instruments provided by the ESA, EUMETSAT, NOAA, and CNES. These satellites have a larger carrying capacity, improved payload, and better performance than the NOAA system. The MetOp series consists of three satellites; the first, MetOp-A (Fig. 3.26), was launched on October 19, 2006, with a design life of five years and the second, MetOp-B (Fig. 3.27), was launched on September 1, 2012.

The EUMETSAT polar-orbiting satellite system is an integral part of the global observing system (GOS) that is designed to provide long-term global observation



Fig. 3.26 MetOp-A



Fig. 3.27 MetOp-B

data in conjunction with NOAA satellites. The operational instruments on board the EUMETSAT polar-orbiting system are designed to be the same as those on board NOAA satellites to ensure the consistency of observation data. The first one or two satellites are large-capacity, nonoperational polar-orbiting platforms (EPOP/POEM), and subsequent satellites are smaller MetOp satellites.

3.4.3 China’s Meteorological Observation Satellites

China’s polar-orbiting meteorological satellites (FY-1 and FY-3 satellite series) are also referred to as sun-synchronous orbiting meteorological satellites, those whose orbital plane is usually 98° – 99° from the equatorial plane and whose orbit crosses the north and south poles. Geostationary meteorological satellites (FY-2 satellite series) move at the same speed as Earth’s rotation at an altitude of 36,000 km above the equator. Information on the FY satellite series is shown in Fig. 3.28 (National Satellite Meteorological Center, China Meteorological Administration 2013a).

3.4.3.1 Polar-Orbiting Satellites

(1) FY-1A/1B

FY-1A was launched on September 7, 1988, as an experimental meteorological satellite. Although it only worked in orbit for 39 days due to a control system failure, the successful launch of FY-1A was considered a milestone in China’s development of meteorological satellites. The satellite was equipped with an infrared and visible light scanning radiometer, a data collection system, a space environment detector, and other instruments. Technical parameters of the multispectral infrared and visible light scanning radiometer are shown in Table 3.29 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

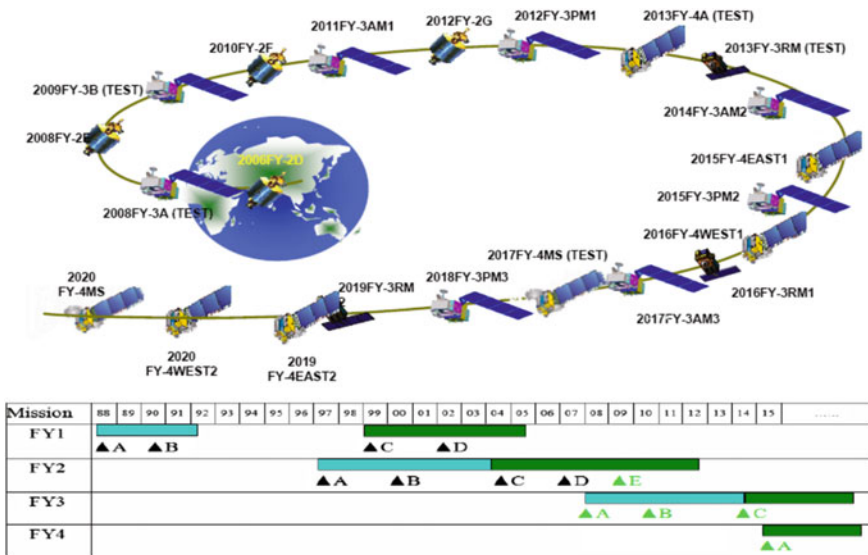


Fig. 3.28 FY satellite series (CMA)

Table 3.29 Technical parameters of FY-1A's visible and infrared scanning radiometer

Component	Parameter
Sensor	Multispectral infrared and visible light scanning radiometer
Tasks	To acquire day-and-night visible light, infrared cloud imagery, snow and ice cover, vegetation, ocean color, sea surface temperature, etc.
Scan rate	6 scanning lines/second
Earth-scanning angle (°)	±55.4
Nadir ground resolution (km)	1.1
Data quantization level (bit)	10
Calibration accuracy	Visible and near infrared channels 10% (reflectance); infrared channels 1 K (300 K)
Wavelength (μm)	0.58–0.68, 0.725–1.1, 0.48–0.53, 0.53–0.58, and 10.5–12.5
Data transmission	For high-resolution picture transmission (HRPT), the bit rate is 0.6654 Mbps and the operating frequency is 1,670–1,710 MHz. In low-resolution image transmission (APT), delay picture transmission (DPT), high-resolution picture transmission (APT) and DPT are analog signals

The FY-1B satellite was successfully launched on September 3, 1990. As China's second experimental meteorological satellite, FY-1B was an improvement over FY-1A. Compared with FY-1A, FY-1B's attitude control system was improved and its visible cloud images were clearer. The performance of the satellite's sensors and the main functions of the satellite were similar to those of the United States' third-generation polar-orbit meteorological satellites. The satellite's performance was at a level similar to that of commercial applications, its visible channel image quality was high, and its signal-to-noise ratio was above the design requirement. However, the satellite's system lacked reliability.

(2) *FY-1C*

FY-1C was successfully launched from the Taiyuan Satellite Launch Centre on May 10, 1999. Compared with FY-1A/B, the FY-1C satellite had significantly improved performance, with increased detection channels and accuracy. Its design life was two years. A series of technical measures were taken that led to improvements in the product quality, adaptability to space environments, and system reliability. FY-1C functioned stably in orbit until June 24, 2004, when the reception of FY-1C cloud images ceased.

The satellite was equipped with a space particle composition detector and a multichannel visible infrared scanning radiometer (MVISR). The number of MVISR channels for FY-1C was increased from five (FY-1A) to ten, and included four visible light channels, one shortwave infrared channel, and two longwave infrared channels. Table 3.30 lists the wavelength and use of each channel. The field of view was 1.2 microradians, the nadir resolution was 1.1 km, and the scanning speed was six scan lines per second, with each line containing 20,480 pixel points. The calibration

Table 3.30 Technical parameters of FY-1C's multispectral infrared and visible scanning radiometer

Channel no.	Wavelength (μm)	Main purpose
1	0.58–0.68	Daytime clouds, ice, snow, vegetation
2	0.84–0.89	Daytime clouds, vegetation, water
3	3.55–3.93	Heat sources, nighttime clouds
4	10.3–11.3	Sea surface temperature, day/nighttime clouds
5	11.5–12.5	Sea surface temperature, day/nighttime clouds
6	1.58–1.64	Soil moisture, ice and snow recognition
7	0.43–0.48	Ocean color
8	0.48–0.53	Ocean color
9	0.53–0.58	Ocean color
10	0.90–0.965	Water vapor

accuracy of the visible and near infrared channels reached 10%, and the infrared radiometric calibration accuracy reached 1 K, as technically required. The spatial resolution of the HRPT and GDPT images was greater than 1.1 km and 4 km, respectively. The Chinese high-resolution picture transmission (CHRPT) had a frequency of 1,700 MHz, a bit rate of 1.3308 Mbps, and real-time reception from anywhere in the world. The delay picture transmission (DPT) had a frequency of 1,708 MHz and a bit rate of 1.3308 Mbps and was divided into two types: GDPT and LDPT (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(3) *FY-1D*

Design of the FY-1D flight model began in 2000 based on FY-1C technology and previous experience. Fourteen technical improvements were made that led to improved stability. The 950 kg satellite was launched from the Taiyuan Satellite Launch Center on May 15, 2002, using an LM-4B rocket. FY-1D functioned normally for ten years, exceeding its design life and completing all tasks. It is no longer in operation.

FY-1D's main onboard sensor was a multichannel visible infrared scanning radiometer (MVISR), whose main technical parameters are listed in Table 3.31. Data were transmitted using two methods: HRPT and DPT. The HRPT's bit rate was 1.3308 Mbps, and the carrier frequency was 1,700.4 MHz. The DPT's bit rate was 1.3308 Mbps, and the carrier frequency was 1,708.46 MHz. Global meteorological data could be acquired through four channels (Channels 1, 2, 4 and 5), with a spatial resolution of 3.3 km (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(4) *FY-3A*

The FY-3 satellites (FY-3) were China's second-generation polar-orbiting meteorological satellites used for weather forecasting, climate prediction, and environmental monitoring. The FY-3 series comprised two satellites: FY-3A and FY-3B. The satellites were used to conduct 3D atmospheric detection, greatly improved China's ability

Table 3.31 Technical parameters of FY-1D's multispectral infrared and visible scanning radiometer

Component	Parameter
Sensor	Multispectral infrared and visible light scanning radiometer
Tasks	To acquire day-and-night visible light, infrared cloud imagery, snow and ice cover, vegetation, ocean color, sea surface temperature, etc.
Scan rate	6 scanning lines/second
Earth-scanning angle (°)	±55.4
Nadir ground resolution (km)	1.1
Data quantization level (bit)	10
Calibration accuracy	Visible and near infrared channels 10% (reflectance); infrared channels 1 K (300 K)
Wavelength (μm)	0.58–0.68, 0.84–0.89, 3.55–3.93, 10.3–11.3, 11.5–12.5, 1.58–1.64, 0.43–0.46, 0.48–0.53, 0.53–0.58, and 0.900–0.965
Data transmission	For high-resolution picture transmission (HRPT), the bit rate is 0.6654 Mbps and the operating frequency is 1,670–1,710 MHz. In low-resolution image transmission (APT), delay picture transmission (DPT), high-resolution picture transmission (APT) and DPT are analog signals

to acquire global information and further enhanced its cloud area and surface feature remote sensing capabilities. These features enabled the country to obtain global, all-weather, three-dimensional, quantitative, multispectral data on atmospheric, land surface, and sea surface characteristics.

FY-3A was the first FY-3 meteorological satellite launched using an LM-4C rocket from the Taiyuan Satellite Launch Center at 11:02 on May 27, 2008. Although it was developed based on the FY-1 meteorological satellites, FY-3A was substantially superior in both technology and function. The satellite was capable of three-dimensional atmospheric detection, greatly improving the capability for global information acquisition and cloud area and surface feature remote sensing.

(5) *FY-3B*

FY-3B is the second satellite in the FY-3 meteorological satellite series. It was launched from the Taiyuan Satellite Launch Center in the early morning of November 5, 2010, using an LM-4C rocket. FY-3B is China's first afternoon-orbit meteorological satellite, making it the first polar-orbiting meteorological satellite to conduct observations at this time. FY-3B is useful for accurate monitoring and numerical forecasting of rainstorms in southern China that usually occur in the afternoon. Working in conjunction, FY-3B and FY-3A increased the global scan frequency from twice a day to four times a day. Thus, China's ability to monitor disastrous weather events such as typhoons and thunderstorms was enhanced markedly. The satellite had a design life of three years but is still operating in orbit.

FY-3B is equipped with eleven advanced remote sensing instruments and 99 spectral detection channels, five of which have a resolution of 250 m. FY-3B is similar

to FY-3A in terms of the satellite platform, payload configuration, and main performance parameters. However, as the first next-generation, polar-orbiting meteorological satellite, FY-3A showed weak operation of some onboard instruments. FY-3B was developed by meteorological satellite experts based on their experience acquired from the development of the FY-3A satellite. As a result, FY-3B demonstrated improved performance for the infrared spectrometer, microwave radiation imager, and solar backscatter ultraviolet sounder.

(6) *FY-3C/3D*

FY-3C is a sun-synchronous orbit satellite launched on September 23, 2013 by the carrier rocket Chinese Long March 4C from the Taiyuan Satellite Launch Center in Shanxi province. The FY-3C orbital satellite joins its predecessors FY-3A and FY-3B. It replaced FY-3A to operate, after undergoing tests, in a morning orbit with FY-2B, which is in an afternoon orbit, to provide temporal resolution of global observation data of up to six hours.

The FY-3C missions primarily include Earth surface imaging and atmospheric sounding, and its observational data will be used in weather forecasting, and in monitoring of natural disasters and ecological and environmental factors. Compared with FY-3A and FY-3B, the payload on board FY-3C features 12 sensing instruments, including a visible infrared radiometer, a microwave scanning radiometer, a microwave temperature sounder (MWTS), a microwave humidity sounder (MWS), a microwave imager, and a medium resolution imaging spectrometer. It also includes a UV-O-zone sounder, a total O-zone UV detector, a solar radiation and Earth radiation detector, space environmental monitoring suits, and GNSS occultation detectors.

FY-3D was launched on November 14, 2017 as China's fourth second-generation polar-orbiting meteorological satellite and will replace the orbiting FY-3B satellite. The satellite is designed to provide weather forecasts in medium- and long-range numerical weather prediction (NWP) models, enabling high-impact weather forecasting up to a week in advance, and alleviate the impacts of natural disasters on the economy and society and improve livelihood.

Equipped with greenhouse gas probing capacity, FY-3D was also developed to help tackle climate change, in addition to serving ecological, civilization, and construction needs and the 'Belt and Road' initiative. FY-3D features ten instruments, including a microwave temperature sounder (MWTS), a microwave humidity sounder (MHS), a microwave radiation imager (MWRI), a space environment monitor (SEM), and a global navigation satellite system occultation sounder (GNOS).

3.4.3.2 Geostationary Orbit Satellites

(1) *FY-2A/2B*

The FY-2A satellite was the first experimental satellite in China's first-generation geostationary meteorological satellite series, FY-2, and was launched on June 10, 1997. FY-2A had a three-channel scanning radiometer and a design life of three

years at a stable spinning altitude. The satellite began to have issues after working for three months and then worked intermittently, only operating for six to eight hours each day. Ultimately, FY-2A failed to meet the requirements for commercial meteorological services.

The main payload of FY-2A was a visible and infrared spin-scan radiometer (VISSR), whose technical parameters are shown in Table 3.32 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

The FY-2B satellite was the second experimental satellite in China’s first-generation geostationary meteorological satellite FY-2 series. FY-2B was launched on June 25, 2000 from the Xichang Satellite Launch Center using an LM-3 rocket. The first original cloud image was received on July 6. FY-2B only had a three-channel scanning radiometer and a design life of three years in a stable spinning altitude. It functioned in orbit for less than eight months before a problem occurred with one of the components on board the satellite; from then onward, the signals it sent back were too weak to receive. Ultimately, FY-2B failed to meet the requirements for commercial meteorological services. However, FY-2B’s operation provided valuable experience for the development of subsequent FY-2 meteorological satellites.

The technical parameters of the FY-2B and FY-2A satellites were identical. The cloud images sent from FY-2B played an important role in monitoring typhoons and marine weather, forecasting rainstorms, preventing floods, analyzing the weather system above the Qinghai-Tibetan Plateau, providing meteorological support for aviation, and predicting climate change.

(2) *FY-2C/2D/2E/2F/2G/2H*

FY-2C was the first commercial-use satellite in the FY-2 meteorological satellite series. After a successful launch on October 19, 2004, FY-2C was positioned at an altitude of 36,000 km above the equator at 105° east longitude on October 24.

Table 3.32 Technical parameters of FY-2A’s visible and infrared light spin-scan radiometer (VISSR)

Channel	Visible light	Infrared	Water vapor
Wavelength (μm)	0.55–1.05	10.5–12.5	6.2–7.6
Resolution (km)	1.25	5	5
Field of view (μrad)	35	140	140
Scan line	2,500 × 4	2,500	2,500
Detector	Si-photo-diode	HgCdTe	HgCdTe
Noise resolution	S/N = 6.5 (Albedo = 2.5%) S/N = 43 (Albedo = 95%)	NEDT = 0.5–0.65 k (300°K)	NEDT = 1 K (300°K)
Quantitative byte (bit)	6	8	8
Scanning step	140 μrad (N-S scanning)		

FY-2C occupied FY-2B's former position to monitor weather conditions in the Asia Pacific Region. Four days after it was positioned, adjustments were made to the ground application system to technically coordinate it with the satellite. The satellite's service monitoring, data transmission, and forwarding channels were opened, and the scanning radiometer was switched on. FY-2C could observe changes in sea surface temperature, and one of its channels was designed for measuring 3.5–4 μm light waves to observe high-temperature heat sources on the ground. It was possible to use spectral channels to observe ground heat sources to promptly discover forest fires in remote and desolate places, monitor their situation, and predict their development trends.

FY-2D was the fourth satellite in the FY-2 meteorological satellite series. FY-2D was also the country's second application-oriented geostationary-orbiting meteorological satellite. It was launched using an LM-3A rocket at 08:53 on December 8, 2006. After 1,421 s of flying, it successfully separated from the rocket, entering into a large elliptical transfer orbit with a perigee altitude of 202 km, apogee altitude of 36,525 km, and inclination of 24.97° . At 01:24 on December 9, the apogee engine was ignited for orbital transfer, and secondary separation was successfully completed. After four batches of orbit trimming, the satellite was positioned at an altitude of 36,000 km above the equator at 86.5° E longitude at 17:00 on December 13. It is currently no longer in operation.

On December 23, 2008, and January 13, 2012, China's third and fourth service-oriented geostationary meteorological satellites, FY-2E and FY-2F, respectively, were launched from the Xichang Satellite Launch Center using LM-3A rockets. The two satellites were of great significance for the continuous and stable operation of China's geostationary meteorological satellite observation services. FY-2F boasted flexible capability for scanning specific regions with a high temporal resolution and could monitor disastrous weather conditions such as typhoons and severe convections. FY-2F played an important role in China's meteorological disaster monitoring, early warning, prevention, and mitigation. The space environment monitor continuously monitored solar X-rays and the flow of high-energy protons, electrons, and heavy particles, and the data were used for space weather monitoring, forecasting, and early warning services.

The geostationary meteorological satellites FY-2C, FY-2D, FY-2E, and FY-2F working in orbit formed a "double-satellite observation with mutual backup" service pattern. These satellites helped modernize China's comprehensive meteorological observation system. During flood season, the double-satellite observation mode allowed for spinning the satellite, enabling it to provide a cloud picture every fifteen minutes. This intensified observation mode played a key role in monitoring disastrous weather systems such as typhoons, rainstorms, thunderstorms, and small- and medium-scale local convective systems. The FY-2 meteorological satellite series played a crucial role in combating heavy rain, freezing snow, and other extreme weather events. The satellites also provided assistance in the Wenchuan earthquake relief operations and in providing meteorological services for the Beijing Olympics and Paralympics.

The FY-2G satellite was launched on December 31, 2014 from the Xichang Satellite Launch Center. Based on the technology of FY-2 F satellite, the FY-2G satellite was improved by reducing infrared stray radiation, uplifting the observation frequency for the blackbody, and improving the telemetry resolution of optical components. These improvements increase the retrieval accuracy of FY-2G satellite quantitative products and enhance the quantitative application of satellite data products.

FY-2H was launched on June 5, 2018. It is positioned over the Indian Ocean and has realized the sustained observation of one-third of the Earth's territories from Oceania to central Africa. It can provide favorable observation perspectives and custom-made high-frequency subregional observation for countries and regions such as western Asia, central Asia, Africa, and Europe. Equipped with a scanning radiometer and a space environment monitor, FY-2H can supply data for dozens of remote sensing products such as cloud images, clear sky atmospheric radiation, sand and dust, and cloud motion wind (CMW) for weather prediction, disaster warning, and environmental monitoring, enriching the data sources for global NWP models.

The main payload of FY-2C/2D/2E/2F was a visible and infrared spin-scan radiometer (VISSR), whose technical parameters are shown in Table 3.33 (National Satellite Meteorological Center, China Meteorological Administration 2013b).

(3) FY-4A

FY-4A was launched on December 11, 2016, as the first Chinese second-generation geostationary meteorological satellite. FY-4A is China's first quantitative remote sensing satellite with a three-axis stabilization structure on a geostationary orbit. Four new instruments are on board the latest independently developed weather satellite, namely, an advanced geosynchronous radiation imager (AGRI), a geosynchronous interferometric infrared sounder (GIIRS), a lightning mapping imager (LMI) and a space environment package (SEP).

FY-4A is the first satellite in China that can capture lightning. The onboard Lightning Mapping Imager enables this function. It is the first geostationary optical remote sensing instrument in China and has filled the gap in terms of lightning observation and satellite-borne detection. FY-4A can detect lightning over China and neighboring areas and take 500 lightning pictures per second. By real-time and consecutive observation of lightning, it can aid in observation and tracking of severe convective weather and provide early warning for lightning disasters.

Table 3.33 Technical parameters of the radiometer on board FY-2C/2D/2E/2F

Channel	Waveband (μm)	Resolution (km)
Visible light	0.55–0.90	1.25
Infrared 1	10.3–11.3	5
Infrared 2	11.5–12.5	5
Infrared 3	6.3–7.6	5
Infrared 4	3.5–4.0	5

3.4.4 Other Meteorological Observation Satellites

3.4.4.1 Japan's Satellites

Since Japan launched its first geostationary meteorological satellite, GMS-1, in 1977, it has put five geostationary meteorological satellites into orbit. The GMS-4 satellite is positioned at 140°E above the equator and is equipped with visible and infrared scanning radiometers that observe a fourth of Earth to monitor cloud distribution, height and dynamics. The satellite can obtain information about winds below and above clouds, and detect sea surface temperature distribution.

Similar to other GMS satellites, GMS-5 is a spin-stabilized satellite. Its total mass is 756 kg, the design life is five years, and the main onboard instrument is a visible and infrared light spin-scan radiometer (VISSR). The VISSR was significantly improved by building upon the radiometer on board GMS-4. One 6.5–7 μm WV channel was added to observe water vapor radiation in the middle layer of the troposphere. The original 10.5–12.5 μm infrared window area was split into a 10.5–11.5 μm channel and an 11.5–12.5 μm channel to observe radiation from Earth's surface and the atmosphere. The nadir spatial resolution of GMS-5 is 1.25 km for the visible light channel and 5 km for the WV channel. The main parameters of the VISSR on board GMS-5 is listed in Table 3.34.

After GMS-5 was launched, Japan suspended the development of single-function meteorological satellite systems. The Japan Meteorological Agency and Japan Civil Aviation Administration jointly developed a new large, multifunctional, integrated satellite system called MTSAT. MTSAT-1, the first satellite of this system, was scheduled to be launched on November 15, 1999. However, the launch was unsuccessful due a fault with the rocket and both the satellite and rocket were destroyed. Japan manufactured another MTSAT satellite named MTSAT-1R (Kim et al. 2011). The satellite was not launched until February 26, 2005 due to the time required to remove the fault and improve the rocket. The satellite began to broadcast images two to three months after launch. It was followed by MTSAT-2, which was launched on December 26, 2006 (Fig. 3.29). The MTSAT satellites are equipped with VISSR, cloud image broadcasting, DCS, aviation communication, and other subsystems mainly used for meteorological exploration and aviation communication and are the largest geostationary satellites with meteorological sounding functions (Crespi et al. 2012).

Table 3.34 VISSR parameters of the GMS-5 satellite (Huang et al. 2004)

Channel	Wavelength (μm)	Quantization level (bit)	Spatial resolution (nadir) (km)
Visible light	0.55–0.90	8	1.25
Water Vapor (WV)	6.5–7.0	8	5
Infrared window area	10.5–11.5	8	5
Infrared window area	11.5–12.5	8	5

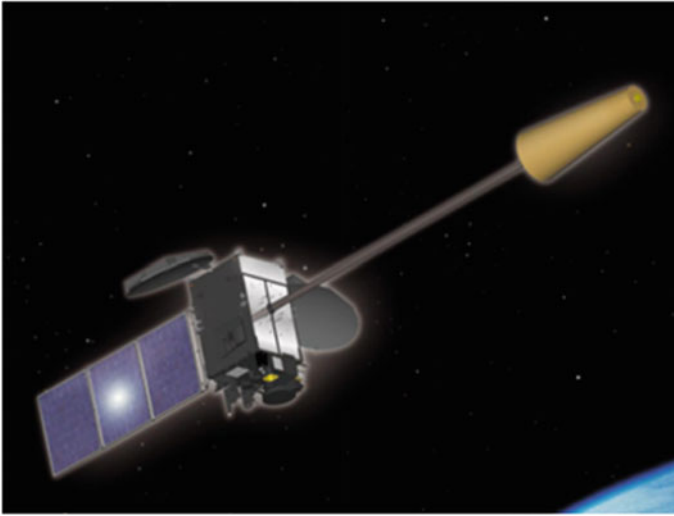


Fig. 3.29 The MTSAT-2 satellite

3.4.4.2 India's Satellites

INSAT is a multiagent multitarget satellite system and is one of the largest satellite systems in Asia. The INSAT satellite system has played an increasingly important role in the Indian aerospace industry with the continuous development and improvement of the INSAT-1, INSAT-2, and INSAT-3 series of satellites.

INSAT provides services such as domestic long-distance communication, meteorological and Earth observation data relay, augmented television receiver national direct satellite broadcasting, TV education, rural communications, meteorology, and disaster alarms.

The first-generation INSAT satellites, the INSAT-1 series, were manufactured by Ford Motor Co. in the United States and comprised four satellites: INSAT-1A, INSAT-1B, INSAT-1G, and INSAT-1D. The second-generation INSAT satellites, INSAT-2, were independently developed by India to meet the needs of the 1990s. The INSAT-2 series consisted of five satellites: INSAT-2A, INSAT-2B, INSAT-2C, INSAT-2D, and INSAT-2E. In addition to normal C-band transponders, the INSAT-2 satellites also adopted the high-frequency section of the C-band, or the extended C-band. The third-generation INSAT satellites, INSAT-3, were also made by the Indian Space Research Organization (ISRO) and comprise five satellites: INSAT-3A, INSAT-3B, INSAT-3C, INSAT-3DR, and INSAT-3DS.

INSAT-3A is a multipurpose satellite launched on April 10, 2003 using an Ariane rocket. The satellite is fixed at 93.50° E and has the following payloads (Fig. 3.30). Of the twelve C-band transponders, nine provide coverage that extends from the Middle East to southeast Asia with an EIRP of 38 dBW, and three provide coverage of India with an EIRP of 36 dBW. The six extended C-band transponders provide



Fig. 3.30 The INSAT-3A satellite

Indian coverage, with an EIRP of 36 dBW. The six Ku-band transponders also provide coverage of India, with an EIRP of 48 dBW. The one very high-resolution radiometer (VHRR) can perform imaging in the visible light channel (0.55–0.75 μm), thermal infrared channel (10.5–12.5 μm), and water vapor channel (5.7–7.1 μm) with ground resolutions of 2×2 km, 8×8 km, and 8×8 km, respectively. The CCD camera has a ground resolution of 1×1 km in the visible (0.63–0.69 μm), near infrared (0.77–0.86 μm), and SWIR (1.55–1.70 μm) channels.

3.4.4.3 Russia's Satellites

(1) *Russia's polar-orbiting meteorological satellites*

The “Meteor” series of polar-orbiting meteorological satellites was developed by the Soviet Union/Russian Federation and has gone through four generations. Most of the previous three generations of satellites do not function in sun-synchronous orbit. However, the fourth-generation of satellites is known to work in a sun-synchronous orbit.

As early as 1962–1969, the Soviet Union had launched more than 20 COSMOS satellites for meteorological observation. In March 1969, it launched its first-generation polar-orbiting meteorological satellite: Meteor-1. The first generation consisted of 31 satellites (Meteor-1-31) launched from 1969 to 1981, most of which had an orbital inclination of 81.2° . The second generation (Meteor-2) comprised 24 satellites launched after 1975. In most cases, two or three satellites were simultaneously operating on orbit, with an orbital inclination of 82.0° and orbital altitude of 950 km. The third-generation (Meteor-3) polar-orbiting meteorological satellites were launched in 1984. The third generation was composed of eight satellites, which had an orbital inclination of 82° and orbital altitude of 1,200 km.

Meteor-3 M N1, the first satellite of the fourth generation of Russian meteorological satellites, (the Meteor-3 M series) was launched on December 10, 2001 (Fig. 3.31).

Major changes in the Meteor-3 M series of satellites include: 99.6° orbital inclination, 1,024 km sun-synchronous orbit, and a broadcast data format that is compatible with NOAA's high-resolution picture transmission (HRPT).

(2) *Russia's geostationary orbit meteorological satellites*

Russia's first geostationary orbit meteorological satellite (GOMS) was successfully launched in November 1994. It is a three-axis stabilized satellite positioned at 76°E . A problem occurred with the attitude control after launch, but the satellite resumed working after some remedial measures were taken. Unfortunately, its scanning radiometer's visible light channel has been unable to acquire any images due to an optical design error; thus, the satellite can only capture infrared images.

On January 20, 2011, Russia launched the geostationary hydrological and meteorological satellite Elektro-L from the Baikonur Launch Center in Kazakhstan (Fig. 3.32). Fixed at a position 36,000 km above Earth, the satellite is used to monitor climate change in Russia's Asian region. The visible light and infrared photographic devices installed on the satellite can capture 1-km and 4-km resolution ground images, respectively. Under normal circumstances, the satellite takes a photo once every 30 min. The shooting frequency can be increased to once every 10–15 min in the event of a natural disaster. The satellite is also responsible for forwarding and exchanging weather information as well as receiving and forwarding signals from the international search and rescue satellite COSPAS-SARSAT. GOMS has a life span of ten years and the data distribution mode is HRPT/LRPT. Its mission is to observe



Fig. 3.31 The Meteor-3 M satellite

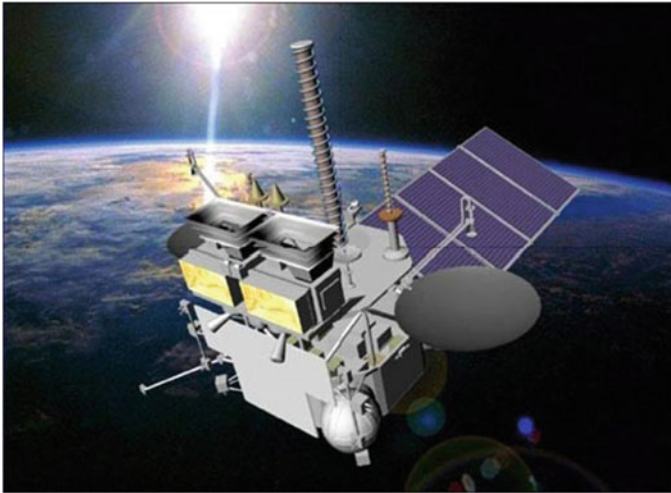


Fig. 3.32 The Electro-L satellite

Earth's surface and atmosphere, perform solar-geophysical measurement, and support the data collection system and COSPAS-SARSAT services. The satellite's main payload is an optical imaging radiometer, MSU-GS, which provides imaging data in three VNIR channels and seven infrared channels. Its nadir spatial resolution (sampling distance) is approximately 1 km (for visible light) and 4 km (for VNIR and infrared), with a new Earth image provided once every 30 min.

3.5 Trends in Remote Sensing for Digital Earth

Looking back on the past five decades of spaceborne remote sensing, every step along the way has been based on the national backgrounds and political and economic conditions of each country. During this period of development, the purpose of Earth observation shifted from single-field surveying toward serving the demands of the overall development of human society (Guo 2014). Since entering the period of globalization, remote sensing technologies have developed into a complete system (Guo et al. 2013), which will provide more abundant data for Digital Earth.

Countries and regions with leading Earth observation technologies, such as the United States and Europe, have formulated Earth observation plans for long-term development. In 2013, the United States and European organizations were expected to launch 34 Earth observation satellites, and India and China planned to launch 25 and 26 satellites, respectively. Russia, Japan, and Canada also had plans for over ten launch missions (Fig. 3.33). Russia will remain a major contributor to satellite launches in Europe, but European organizations will launch significantly more, and there will be a greater emphasis on cooperation and coordination between European

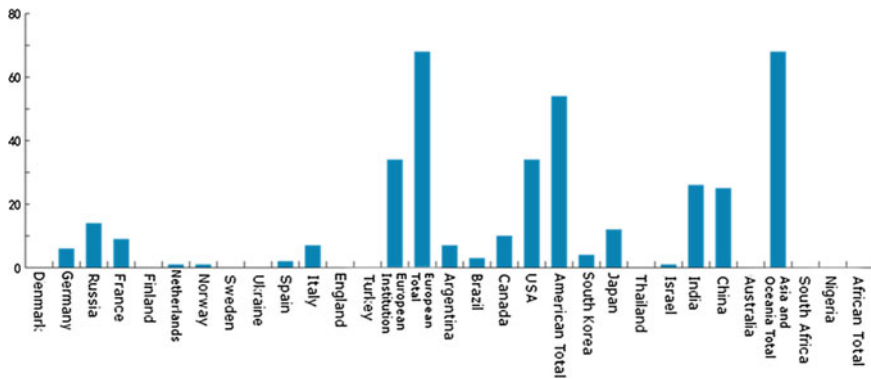


Fig. 3.33 Global launch plans for Earth observation satellites by 2035

countries. In America, the United States will remain a leading force, and Canada will occupy a secondary role. In Asia, the existing trend will continue, with China, India, Japan, and South Korea continuing to be major contributors. Currently, no African countries have plans to launch new satellites.

All of the aforementioned satellite programs have clearly defined services. For example, the United States' Earth observation program for 2016–2020 focuses on measuring global ozone conditions and other relevant gases (GACM program), atmospheric pollution monitoring (3D-Winds), geological disasters (LIST), weather forecasts (PATH), and water resource utilization (GRACE-II/SCLP) (Neeck et al. 2008). The European GMES program covers the six service fields of land, ocean, emergency management, security, atmosphere, and climate change (Veeffkind et al. 2012). In addition, Russia, Japan, India, and some other countries have issued strategic plans for Earth observation, forming systems with their own characteristics. The Russian Federal Space Agency (Roscosmos) intends to form a satellite system consisting of geostationary meteorological satellites (Elektro series), polar-orbiting meteorological satellites (METEOR series), and resource/environment satellites (KANOPUS-V and Resurs-P series) by 2020. The Japan Aerospace Exploration Agency (JAXA) proposed the GOSAT program for greenhouse gas monitoring and the GCOM program for global change monitoring in addition to its ongoing efforts to build the ALOS program of high spatial resolution satellites carrying L-band SAR and hyperspectral sensors. Additionally, JAXA has plans to continue with its navigation experiment satellite program (QZS). The Indian Space Research Organization (ISRO) and the Indian National Remote Sensing Agency (NRSA) aim to improve the spatial resolution of the Resourcesat series and develop SAR-carrying satellites and environment satellites (Environment Sat) of their own (RISAT series).

In addition, some companies such as DigitalGlobe are planning to deploy new high-resolution satellites and trying to enter the microsatellite field. The planned satellites have also been extended from optical to meteorological and radar satellites. However, at present, there are few companies in the commercial satellite market; for example, DigitalGlobe provides high-resolution optical images, and the European

Airbus Defence and Space division can provide high-resolution optical and radar data. China is also planning a series of microsatellites for commercial service. Shenzhen-1 is its first microsatellite constellation and will realize 0.5 m resolution with a revisit period of less than 1 day. Furthermore, the Zhuhai-1, Beijing-1 and Beijing-2 microsatellites will be launched successively and networked. These commercial microsatellites aim to provide real time information for Digital Earth.

Future Earth satellite observation programs will focus on program continuity, development potential, and the capacity for comprehensive and coordinated applications. Therefore, long-term observation programs will be proposed and the development of aircraft-carried and satellite-carried sensors will continue with improved coordination. Relevant Earth observation programs will emphasize the coordinated use of Earth observation platforms and data to better meet the requirements of various fields that may benefit from observation efforts, as well as the nuanced strategic goals of countries and regions (Guo 2018).

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