

Development and Application of Space Dynamic Remote Sensing Technology

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Abstract

With the ever-growing social demand for Earth surface data, the service mode of space remote sensing is undergoing a profound transformation, and dynamic remote sensing with high temporal resolution will become the mainstream mode of future remote sensing observation. Compared with static remote sensing, dynamic remote sensing can acquire continuously updated data, thereby revealing the change patterns and development trends of ground objects and serving macro-level planning and management. Breakthroughs in technologies such as satellite constellation networking and fixed-point staring imaging have also brought about a substantial improvement in the temporal resolution of dynamic remote sensing. This paper discusses the technical approaches, development status and development trends of dynamic remote sensing. On the basis of analyzing the key technologies and data processing methods related to video satellites, the development and application prospects of video satellites are presented.

Keywords

Dynamic remote sensing; Temporal resolution; Video satellite; Fixed-point staring.

1. Introduction

In recent years, the global aerospace industry has been developing rapidly. With the development of Internet technology, big data analytics and artificial intelligence, the social requirements for space remote sensing data have been continuously increasing. In terms of image quality, remote sensing images are required not only to have high geometric quality but also high radiometric accuracy. In terms of spatial resolution, remote sensing instruments need to achieve meter-level or better resolution capability, and the spectral specifications have also expanded from traditional panchromatic to multispectral and even hyperspectral. In addition, in order to achieve dynamic monitoring of ground objects so as to better formulate macro-level planning and management schemes, the acquisition of remote sensing data also needs to evolve from periodic revisit toward real-time monitoring. Traditional static remote sensing can no longer satisfy modern, fast-paced and personalized commercial demands, and dynamic remote sensing with high temporal resolution will become the mainstream in the future commercial space remote sensing field [1-3].

Improving temporal resolution and realizing dynamic remote sensing is an important development direction for the popularization of satellite remote sensing technology. Modern society has abundant demand scenarios for dynamic remote sensing, such as dynamic surveillance of ground resource development and utilization, monitoring of the whole process of natural disasters, dynamic inversion of socioeconomic parameters, and support for military operations. Therefore, multiple dynamic remote sensing means need to cooperate with one another to satisfy the temporal resolution requirements of different application scenarios.

2. Technical Approaches to Dynamic Remote Sensing

The most critical indicator of dynamic remote sensing is temporal resolution, and different remote sensing means can be matched to different temporal resolution requirements. Traditional dynamic remote sensing refers to the acquisition of static image data at relatively long time intervals. By comparing the changes of the same location over long intervals, the evolution status and trend of that location can be obtained. Fig. 1 shows remote sensing images of Lake Powell in the United States over several years, released by NASA, in which (a), (b) and (c) are images acquired in 1999, 2002 and 2005, respectively. It can be seen that the lake had abundant water in the early stage; by 2002, the water volume had visibly decreased and a desertification trend had emerged; by 2005, the lake had dried up. In general, the temporal resolution of multi-orbit revisit by a single satellite ranges from several days to one month. For scenarios with such relatively long revisit cycles, a single satellite taking remote sensing images of the same scene through multi-orbit revisit can satisfy the detection requirements.

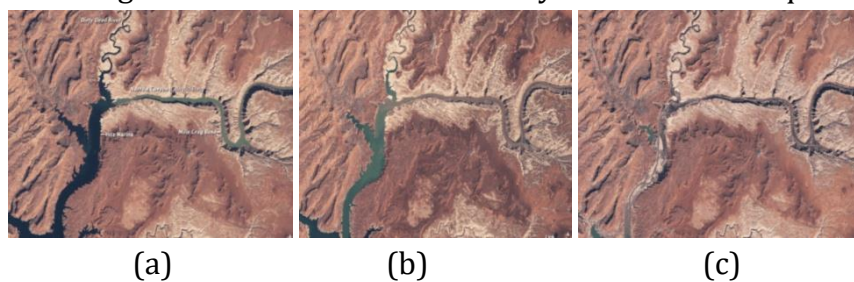


Fig. 1 Remote sensing images of Lake Powell: (a) 1999, (b) 2002, (c) 2005

The swath width and temporal resolution of a single satellite are constrained by its orbital altitude and satellite size. As shown in Fig. 2, compared with multi-orbit revisit by a single satellite, using multiple satellites flying in formation as a constellation to provide cross coverage of the observed ground objects can both expand the spatial coverage and improve the temporal resolution of remote sensing observation [4-6]. The Dove constellation designed and manufactured by the American company Planet Labs is currently the largest remote sensing satellite group in the world. At present, more than 170 Dove satellites are in orbit, at orbital altitudes above 400 km, with a spatial resolution of about 3 m. Through this distributed cluster working mode, the Dove constellation can acquire imagery of the entire global land surface within 24 hours. Its high temporal resolution enables the Dove constellation to play an important role in land survey, disaster monitoring, ship detection and many other applications [7,8]. As shown in Fig. 3, when a wildfire broke out in California, the Dove constellation rapidly captured the movement trend of the fire, providing important reference data for the disaster relief operations of government departments. In addition, the mass of a single Dove satellite is about 5 kg — only one thousandth of some large remote sensing satellites — and its cost is also far lower than that of large satellites. This characteristic allows Dove satellites to be replaced flexibly so as to guarantee the quality of the constellation's service. The advantages of low cost, wide coverage and high temporal resolution make multi-satellite constellation observation a future development trend.

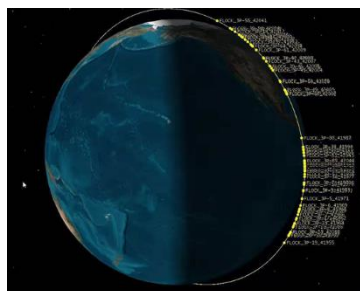


Fig. 2 Schematic diagram of micro/nano-satellite constellation observation



Fig. 3 Remote sensing image of the California wildfire

Traditional dynamic remote sensing plays an important role in application scenarios where the time unit is "year, month or day", such as macro-state analysis of large regions, change monitoring of natural ground objects, pre- and post-disaster analysis, and land use change detection. However, the temporal resolution of traditional remote sensing modes remains limited: they cannot determine the motion and change state of targets, i.e., they are hardly applicable to real-time surveillance and trend analysis scenarios. New types of dynamic remote sensing can achieve a temporal resolution of several seconds or even sub-seconds, and can be used to extract the velocity, direction and trajectory of moving targets and to perform real-time situation analysis and interpretation. New dynamic remote sensing includes two modes: in-orbit reciprocal push-broom scanning and fixed-point video staring.

As shown in Fig. 4, in-orbit reciprocal push-broom scanning refers to achieving multiple repeated observations of the same target through the agile attitude maneuvering of a satellite. The current world-leading level is represented by WorldView-1, which performs imaging 21 times in a single pass, with a pitch angle of less than 45° and an imaging interval of less than 7 s [9]. This detection mode requires extremely strong satellite maneuvering capability, and the reciprocal maneuvering process consumes considerable energy.

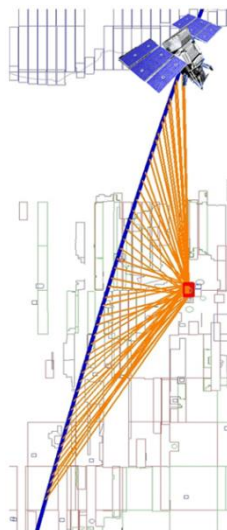


Fig. 4 Schematic diagram of in-orbit reciprocal push-broom scanning

Fixed-point video staring technology includes geostationary-orbit staring and low-Earth-orbit (LEO) staring [10,11]. This imaging mode conforms to the visual characteristics of the human eye and possesses a genuine time dimension. The geostationary orbit is the best way to realize staring imaging, but due to the constraint of orbital altitude, its spatial resolution is relatively low. China's GF-4 satellite has the highest geostationary-orbit resolution in the world, at 50 m [12]. To achieve a resolution of 1 m, the aperture of a geostationary camera would have to reach 30 m-4.6 times that of the world's most advanced JWST and 12.5 times that of the Hubble Space Telescope. Therefore, high spatial resolution in the geostationary orbit is difficult to achieve in the short term.

As shown in Fig. 5, LEO staring imaging refers to using the attitude maneuvering of a micro-satellite in a low Earth orbit to keep the optical axis always pointing at the same ground area and to perform area-array imaging of that area. LEO staring imaging has the advantages of high spatial resolution, a genuine time dimension and low technical cost, which make it the best engineering choice at present and the most closely watched technical approach in this field [13].

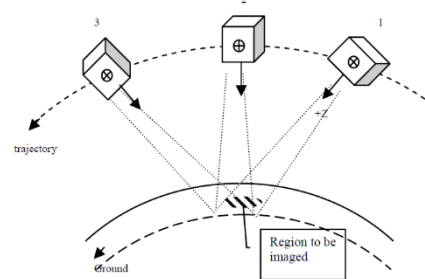


Fig. 5 Schematic diagram of LEO staring imaging

3. Staring Video Satellites

The world's first video satellite is LAPAN-TUBSAT, shown in Fig. 6, jointly developed by the Indonesian National Institute of Aeronautics and Space and the Technical University of Berlin, Germany. Launched on January 1, 2007, its main purpose was to observe natural resources in the Indonesian region and provide weather forecasting. LAPAN-TUBSAT is a micro-satellite with a mass of 54.7 kg, a volume of $450 \times 450 \times 275 \text{ mm}^3$, a spatial resolution of 6 m and an orbital altitude of 635 km [14,15].



Fig. 6 The LAPAN-TUBSAT satellite

The American SkySat series satellites are a group of sub-meter resolution Earth observation satellites owned by Planet Labs, operating in inclined polar circular orbits about 450 km above the Earth. SkySat-1, shown in Fig. 7, was the world's first commercial satellite of the 100 kg class with sub-meter resolution; its telescope adopts an R-C (Ritchey–Chrétien) two-mirror configuration, providing 0.8 m panchromatic resolution and 1.0 m multispectral resolution. SkySat-1 is capable of capturing 90-second high-definition video at 30 frames per second, and was launched on November 21, 2013. On July 8, 2014, the identical SkySat-2 was launched as a secondary payload. To date, seven satellites of the SkySat series have been launched.



Fig. 7 The SkySat-1 satellite

UrtheCast 1, developed by UrtheCast, a company based in Vancouver, Canada, is an Earth observation payload mounted on the International Space Station. As shown in Fig. 8, this payload consists of two camera systems: the Medium Resolution Camera (MRC) and the High Resolution Camera (HRC) [16]. The MRC points directly downward and continuously images the Earth over a range of about 50 km at a resolution of about 6 m. The HRC is a video camera mounted on a steerable platform, which enables it to perform fixed-point imaging of the Earth through attitude adjustment. The HRC has a spatial resolution of 1 m and can be used to capture detailed video.

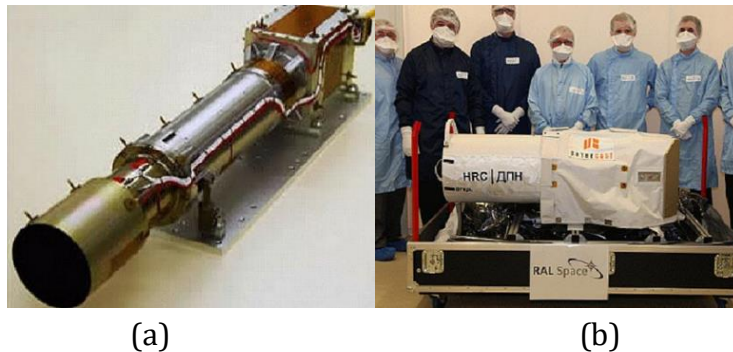


Fig. 8 (a) Medium Resolution Camera; (b) High Resolution Camera

China's first satellite with video capability is Tiantuo-2, launched in 2014 by the National University of Defense Technology. Tiantuo-2 has a mass of 67 kg and a volume of $515 \times 524 \times 685 \text{ mm}^3$. Its main mission is to observe and record moving targets by video imaging and transmit the data in real time. Fig. 9(a) shows the Tiantuo-2 video satellite, and (b) a video frame of ships in the South China Sea captured by it.



Fig. 9 (a) The Tiantuo-2 satellite; (b) a video frame captured by Tiantuo-2

China's first satellite capable of capturing meter-level color video is the Jilin-1 video satellite produced by Chang Guang Satellite Technology Co., Ltd. The optical systems of the Video 01 and 02 satellites adopt a Cassegrain two-mirror configuration (Fig. 10(a)) [17]. The video satellites have a spatial resolution of 1.13 m, an orbital altitude of 650 km, a ground coverage of $4.6 \text{ km} \times 3.4 \text{ km}$ and a maximum off-nadir pointing angle of $\pm 45^\circ$. The Video 03 satellite shown in Fig. 10(b) has a spatial resolution of 0.91 m and a ground coverage of $11 \text{ km} \times 4.5 \text{ km}$; its imaging modes include staring video, semi-staring mode, push-broom mode, nightlight mode and space target imaging. Fig. 10(c) shows Madrid Airport in Spain captured by a Jilin-1 video satellite.

To achieve better detection performance and richer functions, video satellites need to be compatible with the functions of traditional satellites, i.e., while acquiring video, they should also support the wide-area acquisition and multispectral capabilities of traditional push-broom satellites. In addition, most moving targets on the ground are man-made targets of limited spatial extent; to interpret the information better, video satellites need to further improve their resolution so as to represent targets with more pixels. Since information on dynamic targets is time-sensitive, on-board fast information processing will also become a research hotspot in the field of video satellites.

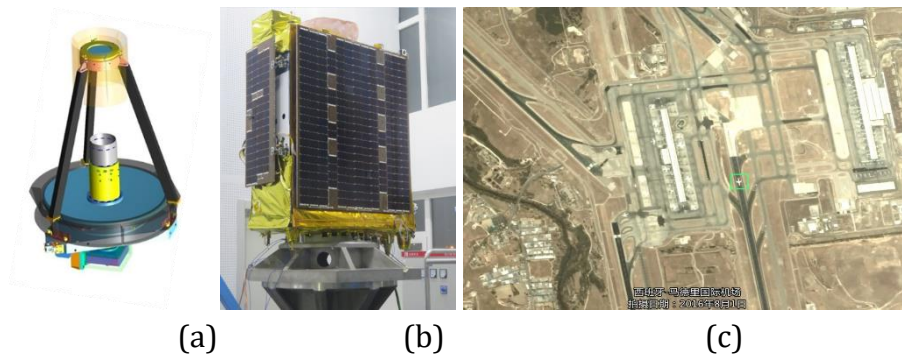


Fig. 10 (a) Optical system of the Video 01/02 satellites; (b) the Video 03 satellite; (c) a remote sensing image captured by the video satellite

A low-Earth-orbit satellite achieves fixed-point staring through attitude maneuvering, but the staring can only last about 2 minutes. Therefore, large-scale constellation networking is required to achieve multiple observations within a short time. Constellation technology requires determining the payload specifications according to application requirements, on the basis of which platform design and orbit selection are carried out; finally, the constellation characteristics are analyzed to judge whether they satisfy the application specifications.

During the attitude maneuvering of a satellite for fixed-point staring, the magnitude of the satellite's angular velocity is large and varies continuously and nonlinearly, imposing extremely high requirements on the attitude angle, angular velocity and angular acceleration. Moreover, during the maneuvering process, the disturbance torques input by the actuators are considerable and are accompanied by the influence of other flexible components, which affects high-resolution imaging. Therefore, precisely controlling the pitch-angle tracking accuracy through fast maneuvering stability control technology is the key to sharp imaging by video satellites [18].

Video satellites have high requirements for resolution, which inevitably leads to a smaller instantaneous field of view, increased environmental sensitivity, and a larger camera aperture and mass [19]. Lightweighting measures need to be taken under the premise of guaranteeing image quality. Lightweight, high-stiffness payload technology is a key technology for improving the performance of video satellites, in which the influence of the main parameters of the mirror support components on the thermal characteristics of the mirror will become the focus of optimization.

The attitude measurement accuracy during satellite imaging determines the geometric quality of remote sensing data. Unlike traditional push-broom satellites, which image under a three-axis stabilized attitude, video satellites undergo large-angle maneuvers during imaging, and the attitude measurement accuracy inevitably degrades; therefore, the attitude measurement components are required to have high dynamic characteristics. Generally, high-dynamic star trackers and high-precision fiber-optic gyroscopes can be used jointly for attitude determination to guarantee attitude measurement accuracy.

Staring video imaging generates a huge amount of data, while the resources of on-board components are limited. It is therefore necessary to resolve the contradiction among the large data volume, complex computation and the energy consumption of on-board components. Breakthroughs in high-speed real-time data processing and information extraction technology are mainly based on the following three points: (1) automatic searching based on target recognition results; (2) automatic AOI cropping; (3) automatic image stabilization. On-board information processing can be performed by the embedded multi-core DSP computer shown in Fig. 11.

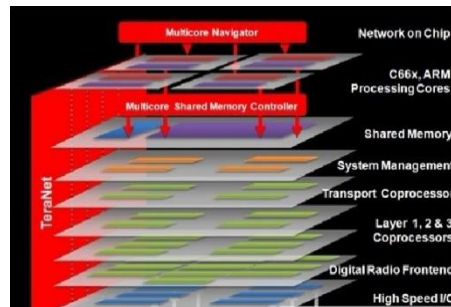


Fig. 11 Embedded multi-core DSP computer composed of multiple DSPs and an FPGA

4. Ground Processing of Spaceborne Video

Satellite staring remote sensing ultimately serves the ground; therefore, ground processing of the video plays an important role. The processing flow of remote sensing video is as follows: (1) decryption and decompression of the transmitted data; (2) radiometric correction of the staring video; (3) geometric correction of the staring video; (4) image stabilization of the remote sensing imagery to obtain standard products; (5) advanced processing of the remote sensing imagery, such as moving target extraction and super-resolution reconstruction.

Unlike traditional space remote sensing satellites, LEO video satellites are constrained by their imaging mode, which affects the remote sensing imagery. During satellite staring, the remote sensing observation angle varies continuously. As shown in Fig. 12, this variation causes the relative positions of ground objects to change across different frames of the satellite video, so inter-frame position correction must be performed afterwards. According to the satellite imaging mode, a high-precision geometric positioning model is established by combining the satellite orbit, attitude, time and other parameters, to realize the transformation between the image and ground coordinates. Differences in the observation angle also lead to differences in the inter-frame radiometric response. As shown in Fig. 13, for the same ground object, the radiometric characteristics of different frames differ considerably, and this inter-frame radiometric difference needs to be corrected. The internal distortion of the video area-array camera will seriously degrade the internal accuracy of the imagery and restrict the inter-frame registration accuracy; the remote sensing imagery needs to be resampled into distortion-free imagery to guarantee the accuracy of the subsequent satellite image stabilization. In addition, the motion of the staring satellite platform and the rotation of the optical axis cause the object-image relationship in the imaging model to vary with time; platform micro-vibration and other factors make the imaging frame jitter; and elevation parallax motion brings difficulties to moving target extraction. All of these require high-precision ground post-processing.

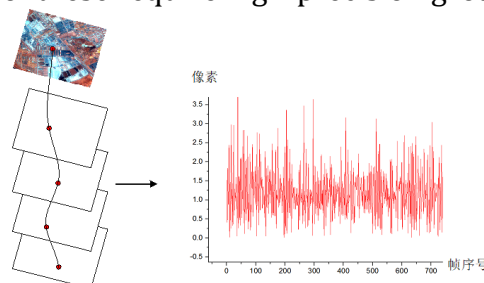


Fig. 12 Position changes of the same ground object across different satellite frames



Fig. 13 Radiometric differences of the same ground object across different satellite frames

To serve advanced applications, the staring video also needs higher-level processing. For example, to provide more detailed information, super-resolution reconstruction, shown in Fig. 14, can be applied to the required remote sensing images. Under the staring imaging mode, multiple frames of the same area can be obtained, and high-resolution images can be reconstructed by utilizing the complementary information among the multiple frames. At present, the super-resolution methods commonly used for remote sensing images include non-uniform interpolation, projection onto convex sets, adaptive filtering, and Markov random field methods [20-22].

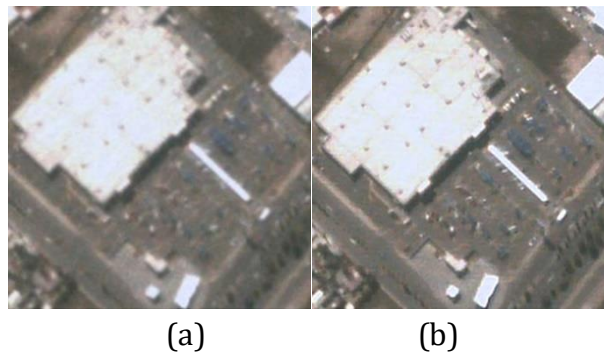


Fig. 14 Super-resolution reconstruction: (a) original image; (b) super-resolved image

As shown in Fig. 15, the continuous imaging of an area of interest by a video satellite can be used to detect and continuously track moving targets and to extract them [23]. Classical target tracking and extraction methods mainly include algorithms based on moving target detection, algorithms based on feature matching, algorithms based on kernel methods, and algorithms based on the Bayesian framework [24,25].

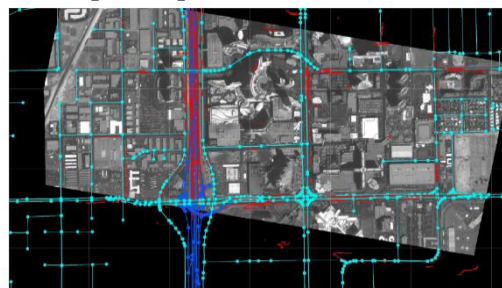


Fig. 15 Fusion of vehicle tracking trajectories in video imagery with the actual road

A staring satellite can continuously observe ground objects from different angles and can therefore obtain three-dimensional information about the targets. This characteristic can be exploited to perform three-dimensional reconstruction of ground objects. As shown in Fig. 16, the three-dimensional reconstruction image of a city clearly presents the protruding state of the buildings.

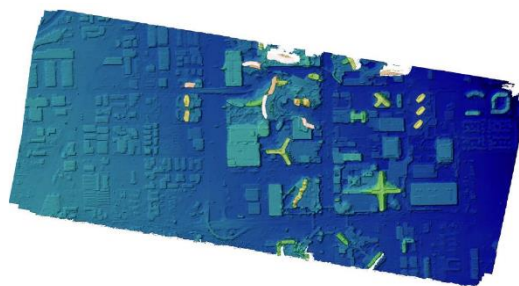


Fig. 16 Digital three-dimensional map of the urban surface

5. Conclusion

Against the background of the vigorous development of commercial aerospace at home and abroad, video dynamic remote sensing technology has the advantages of high spatial resolution, low technical cost and a genuine time dimension, laying the foundation for the transition of remote sensing technology "from static to dynamic" and enjoying broad application prospects. This paper has introduced the technical approaches, development status, trends and key technologies of dynamic remote sensing, as well as the ground processing and advanced applications of the imagery. At present, China is basically on a par with the world's advanced level in the field of video satellite manufacturing; even greater efforts should be devoted to in-depth research on back-end processing and operational applications, so that satellite remote sensing technology can better serve the general public at an early date.

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