Design of Hainan Satellite Constellation and Applications for Ocean Observations

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Abstract. The one belt and one road initiative, an international tourism island construction and the sustainable development of the Hainan province in China, requires the global Earth observation information obtained via satellite remote sensing. However, the unique geographical location of the Hainan province and its cloudy and rainy climate causes several challenges for the acquisition of high-quality satellite remote sensing images. To address this issue, the proposed Hainan satellite constellation is aimed at building a remote sensing satellite system equipped with optical, hyperspectral, and radar payloads as well as a payload for ship automatic identification system, considering specific business requirements. The application will focus on ship detection and islands and marine environment observations. Once the complete operation of the Hainan satellite constellation is established, it will supply high-frequency and coverage observations in low-latitude regions, covering major portions of the maritime silk road areas. This will facilitate marine environment protection and services, and marine resources exploration. This paper introduces the design of the Hainan satellite constellation, including its architecture, characteristics and innovations, and potential applications for ocean observations.

1. Introduction

Earth observation data is a national strategic resource because, using space and aviation observational platforms, humans can continuously monitor the Earth, quickly reproduce and objectively reflect the status, phenomena, processes, and spatial distribution of the Earth's surface through information processing, serving economic construction, and social development. Since the 21st century, space information technology, with Earth observation technology as its core, has become a comprehensive reflection of the scientific and technological progress of a country and its economic strength. As the Hainan province is located at the southern China, the one belt and one road initiative, an international tourism island construction and the sustainable development of the Hainan province, requires comprehensive global Earth observation information obtained via satellite remote sensing. However, the unique geographical location and the cloudy and rainy climate of the Hainan province results in several difficulties during the acquisition of high-quality satellite remote sensing images.

To serve the needs of the national strategy and the regional application of satellite remote sensing data in the Hainan province, a remote sensing satellite ground station was built in Sanya city, Hainan province, in 2010. Thus far, five receiving antennas have been built, and these antennas are
responsible for receiving the tasks of more than 20 satellites in China and other countries, including resources, environment, and high-resolution satellite series. On June 25, 2016, the Long March No. 7 launch vehicle was successfully launched from the Wenchang Space Launch Site in the Hainan province. This proves that Wenchang in Hainan has emerged as another space launch base in China. Since then, the Hainan province has been closely linked with the space science and technology fields of China. In less than ten years, Hainan has established its essential position in the field of space science and technology due to its advantages arising from its unique location. It has the foundation and advantages to establish a new space satellite and remote sensing industry pattern in Hainan, termed as "Satellite Launching in WenChang in the North and Satellite Application in Sanya in the South", to develop the commercial space of Hainan and build a robust aerospace province.

As the Hainan province is located in a low-latitude region, the observation coverage is insufficient due to the effects of cloudy and rainy climate, even though several remote satellites are in operation. This significantly decreases the effective acquisition ability of remote sensing satellites in low-latitude regions. Low-latitude satellites play an important role for Earth observations and regional social-economic development. Therefore, the development of the Hainan satellite constellation for Hainan's special geographical location and climatic conditions is essential to meet the needs of national strategy and Hainan regional applications for multi-source satellite remote sensing.

Due to the rapid development of remote sensing satellites in China and worldwide, a series of remote sensing satellite systems for meteorology, ocean, and Earth observations have been built [1, 2, 3, 4, 5]. Among these, there have been considerable developments in the remote sensing satellites for ocean observations [6]. Previous studies have also reviewed the progress of the developments of remote sensing platforms and sensors technologies [7, 8]. In recent years, commercial space, marked by private investment in space activities and products, and the commercial applications of space services are undergoing rapid developments and have steadily occupied the core leading position in the world space economy. As a significant contributor to the development of space services, commercial space is expected to play an important role in promoting economic development and scientific and technological progress, and it is also expected to become a significant driving force for establishing a reliable space power. Since 2015, a few Chinese commercial remote sensing satellite constellations, such as Jilin-1 satellite and OVS-1 satellite, have made progress in remote sensing applications. However, the development of commercial remote sensing satellite constellation mainly for low-latitude regions has not been established thus far.

This paper introduces the design of the Hainan satellite constellation, including its architecture, characteristics and innovations, and potential applications for ocean observations.

2. System design

The Hainan satellite constellation is aimed at building a remote sensing satellite system with optical, hyperspectral and radar payloads and ship automatic identification system (AIS) payload; hence, it has precise business requirements. Once the Hainan satellite constellation is fully operational, it will supply high-frequency coverage observations for low-latitude regions, covering major portions of the maritime silk road areas. This will facilitate marine environment protection and services, and marine resources exploration. Furthermore, it will also enable the research and development of satellites, assembly, measurement, and control capabilities, in the Hainan province.

The Hainan satellite constellation consists of six micro-optical satellites (Hainan-1), two micro-hyperspectral satellites, and two medium-size synthetic aperture radars (SAR) satellites (Figure 1). The satellite constellation aims to frequently acquire space observation data in low-latitude regions. The characteristics and innovations of this constellation are as follows: (i) it is the first low-latitude remote sensing satellite constellation; (ii) it incorporates the design concept of remote sensing satellite with coverage priority; (iii) it is lightweight, consumes low power, and has a wide coverage imaging technology; and (iv) it employs the sensor combination of optical, hyperspectral, and radar and ship AIS.
(1) Design and development of the first low-latitude remote sensing satellite constellation

Currently, a majority of remote sensing satellites focus their observation on the medium and high latitudes (Europe, North America, East Asia, and Russia), where human economic activity is the most active. Large inclination and polar-orbiting satellites that are suitable for repeated observation are often used in these regions, which results in a significant inadequacy of observation coverage in low-latitude regions. However, the Hainan province is located in low-latitude regions and has very distinct dynamic characteristics. Thus, the bottleneck of satellite remote sensing for the development of the Hainan province is the limitation in acquiring high-frequency and wide coverage remote sensing data.

The low-latitude regional dynamic remote sensing satellite constellation adopts the design of a small inclination orbit, and its observation range is mostly limited between the Tropic of Cancer and the Tropic of Capricorn. This ensures full coverage observation of low-latitude regions. By launching several remote sensing satellites to form a constellation, the revisiting frequency increases significantly, and the first Earth observation satellite constellation that specializes in high-frequency observations at low-latitude regions can be built.

(2) The advancement of Remote Sensing Satellite Concept: satellite system design with coverage priority

Currently, operating remote sensing satellites generally involves the adoption of the spatial-resolution-first or revisiting-ability-first priority strategies, which cannot guarantee the required area coverage for a certain period of time in actual business applications. However, the Hainan remote sensing satellite constellation employs a coverage priority design concept. The orbital parameters, swaying capability, energy security, swath width, observable time per orbit, data format, downlink speed, and receiving station distribution are all designed considering coverage priority to ensure that the Hainan satellite constellation is capable of supplying high frequency and coverage observation.

(3) Development of a light, low power, and wide coverage imaging technology

As a commercial remote sensing satellite constellation, the technical specifications of the camera system include a spatial resolution of 5 m under an orbit altitude of 500 km, a swath width of 100 km, and a weight of 5 kg. New innovative design methods for the structure and the optical and electronic system need to be developed to implement the above mentioned technical specifications.

Figure 1. Architecture of Hainan satellite constellation.
To meet the 100-km ground swath width requirement, the field of view angle of the optical system should exceed 12°; however, the off-axis three-mirror optical system of the secondary aspheric surface cannot meet the abovementioned requirement. A camera with an off-axis tri-inversion optical system with a high aspheric coefficient was innovatively proposed to enlarge the field of view angle of the optical system, thereby meeting the technical requirements of wide coverage areas.

Furthermore, to meet the 100-km ground swath width requirement, the length of the pixel array spliced by the focal plane should have a minimum value of 20K, which results in a significantly large focal plane of the camera system and enlarges the total weight of the camera. However, this is not feasible as the total weight of the camera should be less than 5 kg. To solve this problem, an optimal method to design an imaging circuit system based on the Time Delay Integration (TDI) Complementary Metal Oxide Semiconductor (CMOS) detector is proposed for the implementation of a light, low-power, and wide coverage electronic system.

(4) The sensor combination of multi-spectral, hyperspectral, and radar and ship AIS
The sensor combination of optical, hyperspectral, radar, and ship AIS on a universal micro-satellite platform is proposed to realize integrated ocean applications. Using the sensor combination of optical, hyperspectral, and SAR, the Hainan satellite constellation can observe marine environments, marine ecology, reefs, and coastal zones. Moreover, using the optical, hyperspectral, SAR, and AIS sensor combination, the Hainan satellite constellation can realize the detection, identification, and dynamic information acquisition of ships.

Through simulations and calculations, it was found that using an inclination of 30° and an orbit height of 500 km, a constellation consisting of three satellites can achieve full-coverage observations once a day, for the entire Hainan province and several times a day in key areas. With the help of the Sanya remote sensing ground station, a dynamic observation and application system can be built quickly. If the number of satellites in the constellation increases to 10, it can achieve daily, full coverage observations of the tropical and marine areas in low-latitude regions, thereby covering major portions of the maritime silk road areas. This will facilitate marine environmental protection and services, and marine resources exploration. Considering the cloudy and rainy climate, the payload can include optical, hyperspectral, and SAR sensors and employ the assistance of oversea ground stations to provide seamless observation and reception capabilities in low-latitude regions.

3. Applications on Ocean Observation
The Hainan satellite constellation focuses on ship detection as well as islands and marine environmental monitoring. For the Hainan-1 satellite, the optical payloads are specially designed for ocean observation, particularly ship detection, as the ship AIS payload and the optical payload are onboard.

The implementation of ship detection using the Hainan-1 satellite includes two steps: first, the selection of spectral bands, and the second part involves the imaging of the dual-line array. Through a simulation of the geometric characteristics of the target, it can be found that the radiation characteristics of the ships in the visible and infrared bands are in significant contrast with the background seawater. Furthermore, the radiation characteristics of the bubble wake in the visible and near-infrared bands are also in significant contrast with the background seawater when the ship is sailing. Through an analysis of the spectral characteristics of ships, it is found that the background of near-infrared spectrum images is more homogeneous than other bands, and the seawater reflectivity is lower, which facilitates target detection. Through an analysis of the ship motion characteristics, it is found that the red and near-infrared spectral bands information has a higher contrast and is more useful for target detection. It is easy to detect ships and other moving targets with movement tracks in two different images by using information such as time difference among the two images. The selection of near-infrared and red spectral bands is therefore useful for the detection of ships, as well as for the observation of ports and coastal zones and is sensitive to vegetation information.

Considering that ships are mainly affected by ocean waves and clouds (cloud shape, the adhesion of clouds with ships, etc.) in remote sensing images, the optical payload is designed as a dual-line
array push-sweep imaging mode based on the off-axis triple-reflection optical system, to create two remote sensing images with time dimension, thereby improving target recognition ability. In other words, the double linear array push-sweep mode is used to realize the observation effect of staggered time to the Earth, according to the location relationship of the detector (the scanning time interval of the double linear array is 3–5 s). Automatic detection and the surveillance and recognition of ships from the satellite images are completed by comparing two images acquired by the same camera at different times. Important parameters such as type, number, position, movement track, and speed of ships can be obtained by combining AIS information. Additionally, image matching is realized using the relative location relationships of multiple ships, which can be used as control points for image geometric correction and the improvement of image positioning accuracy.

Based on simulation data (5m spatial resolution remote sensing images), the accuracy rate of moving ships detection by dual-line array push-sweep imaging mode was evaluated and it was found that the accurate rate for 20m*10m size ships was around 90% and for 30m*15m size ships was around 95%.

4. Conclusions
As the Hainan province is located in a low-latitude region, the observation coverage is insufficient due to the impacts of cloudy and rainy climate, even though several remote sensing satellites are in operation. This significantly decreases the effective acquisition ability of remote sensing satellites in low-latitude regions. To address this issue, the low-latitude orbit design of the Hainan satellite constellation aimed at the special geographical location of Hainan can increase observation coverage. Moreover, the selection of near-infrared and red spectral bands of the optical payload and the design of dual-linear array push-broom imaging mode can facilitate on-board image automatic detection and ship surveillance and identification, combined with AIS data to obtain other important parameters. The Hainan satellite constellation is expected to meet the requirements for multi-source remote sensing satellites for the national strategy and applications in the Hainan province.

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