Chapter 2
Fine Guidance Sensor Attitude Determination System of the High-Accuracy Satellite Mission

Jinsong Li, Dong Li, Shuang Liu, Yingquan Yang, Wen Chen, and Jinpei Yu

Abstract Fine guidance sensor is becoming a norm for future satellite missions. Missions requiring attitude stability better than sub-arcsec to milli-arcsec employ satellite specific Fine Guidance Sensor (FGS), which is an interferential instrument with complex research, as it forms extended field of view that focuses the optic signal from the telescope primary dish to provide high pointing stability information to the satellite for control. High precision and high stability pointing are hot issues in attitude determination research both in the past and now. First, this work introduces the FGS of foreign astronomical telescopes mission (Hubble and Kepler), cameras of TESS mission, and the FGS of the domestic mission astronomical telescope mission (SVOM). Secondly, the attitude estimation algorithms of SVOM and foreign high-precision satellites are compared. Finally, a closed-loop test of the SVOM system achieves a stability of 0.8 arcsec /100 s.

2.1 Introduction

Satellite attitude determination is the basis of satellite attitude control and the premise of satellite function realization. The Space Variable Objects Monitor (SVOM), a joint Space telescope project between China and France, is an astronomical satellite in which the main goal is to observe the characters of the most energetic phenomena in the universe, called gamma-ray bursts. The pointing stability of SVOM satellite is required to be less than 0.8 arcsec per 100 s [1]. As an important part of attitude determination system, the accuracy synthesis of attitude sensor and attitude determination algorithm determines the pointing accuracy of attitude determination system [2, 3]. Pointing accuracy of more than sub-arcsec has become a common requirement for future astronomical observation satellites.

Due to the relative motion of the spacecraft and the observation object, uneven gravity of orbit, the sun's radiation pressure caused by the spacecraft orbit perturbation, spacecraft attitude, such as pitch, yaw, and roll change, operation of spacecraft

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J. Li (✉) · D. Li · S. Liu · Y. Yang · W. Chen · J. Yu
Innovation Academy for Microsatellites of CAS, Shanghai 201210, China
e-mail: lijs@microsate.com

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moving parts and some space inside the platform operation and walking astronauts are likely to cause the vibration of a spacecraft platform. The image blur caused by the relative motion of the object and the detector during the exposure time of the imaging detector is called image shift. Image shift will blur the outline of the observed object. There is a certain gap between the target and the background. The transition region expands with the increase of image shift. When the transition region reaches a certain extent, the images of two adjacent targets overlap and even cannot be distinguished. Hence, the existence of image shift will seriously affect the resolution and imaging quality of the telescope.

This paper introduces the development and analysis of a high-precision attitude determination system which consists of a precise sensor and an optimal EKF. The next section briefly describes the FGS of well-known telescopes at home and abroad, and introduces the attitude pointing accuracy and pointing stability required by different space missions. Further, the selection of FGS, gyro and star sensors and the design of EKF estimation algorithms are described. Finally, the FGS-star tracker—Gyro-fusion was verified by the closed-loop test of the satellite system.

2.2 FGS Overview and Attitude Accuracy Requirements

2.2.1 Hubble Mission

Hubble's FGS measurement accuracy has been reached to 0.0028 arcsec, with a frequency of 40 Hz for feedback, the boresight axis can be kept within the range of 0.007arcsec within 10 min [4]. Three sets of FGS were applied to the Hubble in a 90-degree alignment around the main focal plane array. Two of them are used to point and lock the observational target of the telescope, and the other is used as an astrometric instrument to measure the position of a specific celestial body. Each FGS consists of two moveable Koester prism interferometers with a 60 arcmin^2 field of view to search and track stars and a 5.0 arcsec^2 instantaneous field of view to accurately locate stars. The two sets of FGs work together to determine the pointing position [5]. First one FGS searches for and locks on one guide star, then another FGS searches for and locks on the other. Once the two guides are locked, the image of the observed object is kept in the selected focal plane of the scientific instrument for a long period of time. The attitude pointing accuracy and pointing stability of the Hubble satellite is undoubtedly the best among launched and studied satellites (Fig. 2.1).

Fig. 2.1 Hubble Space Telescope

2.2.2 *Kepler Mission*

The Kepler mission is a space telescope designed by NASA to find planets in the habitable zone [6]. A 0.95 m Schmitt telescope provides the 96 megapixel Kepler focal plane array with a field of about 13°, allowing continuous monitoring of more than 100,000 stars in the field. Four FGS CCD modules are mounted on the corners of invar substrate to collect additional pointing information for the attitude control system to achieve the required 2.5 milli-pixel (0.01”) pointing accuracy. The FGS module contains an E2V-made backlight, 3-phase, 3 MHz pixel readout rate operation FGS module, allowing a 10 Hz frame rate. The FGS module is located on the same mechanical surface as the science module and is subject to the same opto-thermo mechanical effects. The pointing precision required of the attitude determination and control system is 0.009 arcsec at 3σ on timescales of 15 min and longer.

The focal plane array assembly consists of 21 Science CCD and 4 FGS CCD modules, all located on a curved invar substrate located at the telescope image surface [7] (Fig. 2.2).

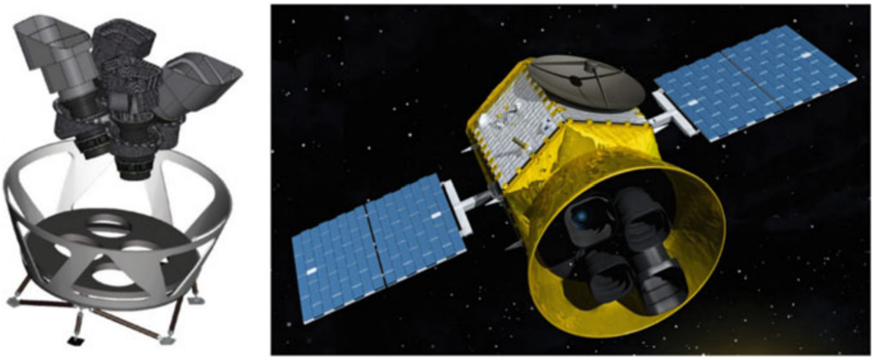


Fig. 2.2 Science CCD and FGS CCD modules

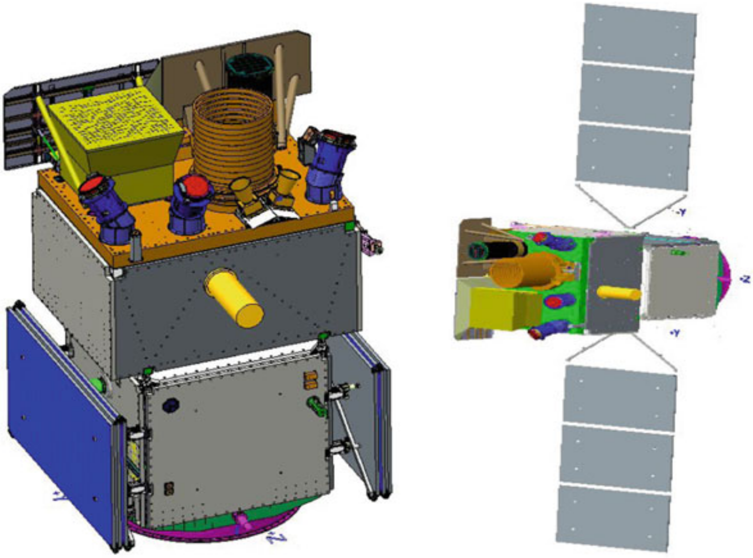


Fig. 2.3 TESS Cameras and spacecraft

2.2.3 TESS Mission

The Transiting Exoplanet Survey Satellite (TESS) is a two-year all-sky survey mission designed to look for transiting exoplanets around bright and nearby stars [8]. The TESS instrument consists of four superposed wide-angle cameras that provide a combined field of view of approximately 24 degrees by 96 degrees from the ecliptic plane to the ecliptic pole. The attitude determination errors of the four cameras are less than 5.2 arcsec. Equivalent Angle requirements of precision noise of instrument camera under nominal precision condition < 0.6 arcsec (3σ) in the cross-boresight axes and < 4.2 arcsec (3σ) in the roll axis. Pointing stability of the system during scientific operation is less than 0.06 (3σ) arcsec per hour and less than 2(3σ) arcsec per minute [9] (Fig. 2.3).

2.2.4 SVOM Mission

The attitude and orbit control system (AOCS) of SVOM satellite is responsible for the required spacecraft attitude during all mission phases and in particular for high pointing accuracy during science observation [10]. The major tasks are stabilization of the spacecraft after separation from the launcher, autonomous attitude acquisition and determination, stabilization and control of the attitude in 3 axes with very demanding fine pointing requirements, and attitude maneuvers to allow for scanning

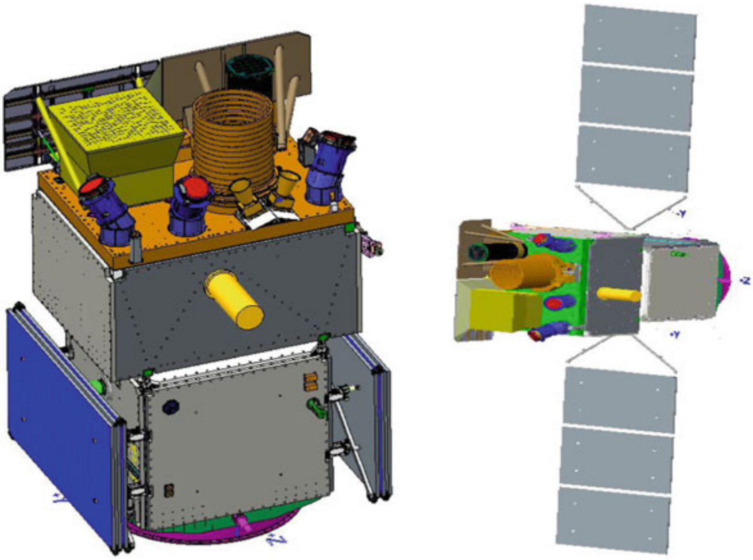


Fig. 2.4 SVOM satellite schematic

the extragalactic sky according to the gamma ray burst(GRB)observation strategy (step and stare).The stability requirement based on the FGS as considered for the following AOCS analysis is 0.8 arcsec/100 s (Ys, Zs axis, 0-peak) (Fig. 2.4).

2.3 Mission High Stability Pointing Mode

2.3.1 Sensor Requirements

The Sun Sensor part includes six analog sun sensors (ASS), two 01 sun sensors (01-SS), and one electronic box. The quantity of the earth magnetic field vector in orbit, which determines the attitude information of the spacecraft (S/C), is provided by Magnetometer. The absolute inertial attitude reference is provided by star trackers (STRs). There are three STR on S/C, in which vertical optical axis measurement accuracy is better than 3.5 arcsec. The Fine Guidance Sensor is used for SVOM to provide accurate attitude measurements during the scientific observations. Two following requirements on FGS are derived from the S/C system design. First is to provide the signal in a frequency of not less than 1 Hz. Second to provide the relative attitude measurement with a precision of not bigger than 0.2 arcsec in the whole FOV of visible telescope (VT). The Gyro Unit is used as rate measurement unit. Two fiber optic gyroscopes (FOGs) are foreseen for redundancy. Absolute error of output

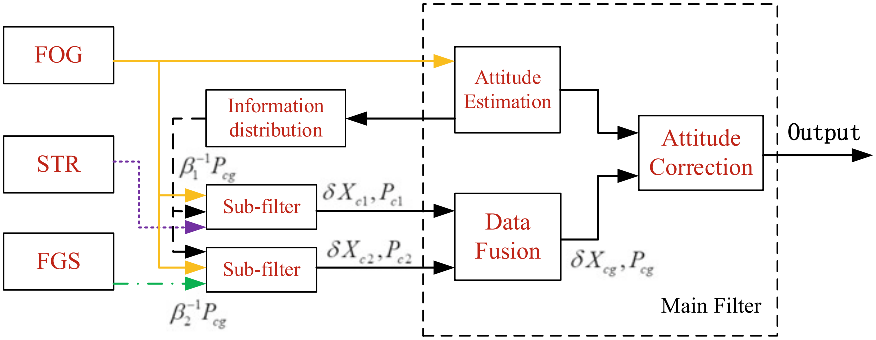


Fig. 2.5 Multi-sensor information fusion algorithm

precision of angle rate of FOGs is better than 3×10^{-5}°/s when angle rate is less than 0.1°/s.

2.3.2 *Data fusion*

The federated Kalman filter is used as the basic information fusion structure of the satellite attitude determination system. FOG is used as the common reference system, and the other sensors are combined with the gyro to form two subsystems: FOG/star tracker and FOG/FGS. The measurement information is fed into the corresponding sub-filter and processed. The attitude parameter error of gyro output is taken as the common state of each sub-filter. Each sub-filter uses the measurement information of its own sensor to give local estimation of the public state and input it to the main filter. The local estimation of the sub-filter is fused by the main filter to obtain the global estimation of the gyro attitude error, and then the attitude parameters obtained by the gyro are corrected to obtain the satellite three-axis attitude information. In the figure below, $\delta \overset{\rightharpoonup}{X}$ is the estimate of the error state variable, $\overset{\rightharpoonup}{P}$ is the estimated mean square error matrix, and β is the information distribution coefficient. The subscript g means the filtering result based on all measurements, that is the global estimate. i(i = 1,2) is the sub-filter and c is the common reference system gyro (Fig. 2.5).

2.3.3 *System Test Result*

The SVOM satellite is currently in phase C and is about to enter phase D. It is scheduled to launch in 2023. Joint tests of the satellite system, ground system, and application system are under way. Under the working mode of high precision and high stability, the stability of Y-axis and Z-axis is mainly assessed through FGS

Fig. 2.6 Y-axis stability

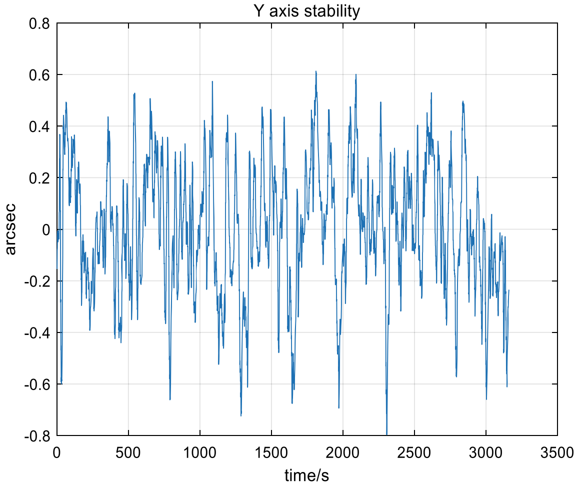
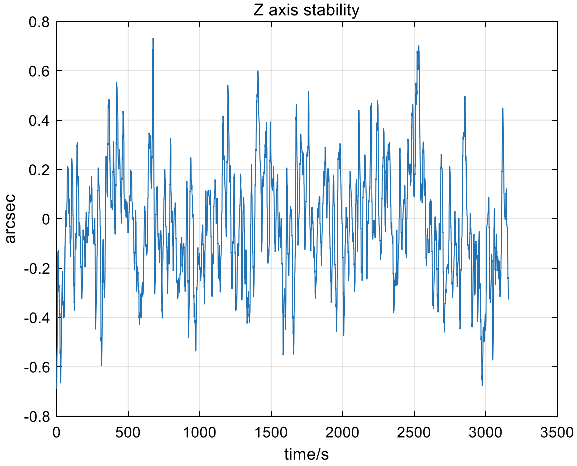


Fig. 2.7 Z-axis stability



attitude determination and PID wheel control. The test data shows that the index of pointing stability is better than 0.8 arcsec/100 s in this mode (Figs. 2.6 and 2.7).

2.4 Conclusions

In this paper, we design and develop a high-precision attitude determination system, which includes an EKF algorithm, three high-precision star tracker, and two gyros. Accurate pointing also requires sensor calibration prior to scientific observation to counteract the effects of launch shocks, in-orbit thermal fluctuations, and exhaust effects. The filtering method of SVOM satellite is extended Kalman filtering. Closed-loop test of the SVOM system achieves a stability of 0.8 arcsec/100 s.

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