Chapter 41
Research on Simulation of Space-Based Optical Space Debris Images

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Abstract A method for imaging simulation of space-based debris based on visible light is proposed. In response to the development needs of space-based space debris detection systems, by analyzing the imaging principles of space-based visible light space debris, the structure and flow of imaging simulation are designed, and the basic simulation of space-based space debris visible light imaging is realized. According to the imaging characteristics of CCD devices, the principle of the Smear tailing effect of super-bright stars is analyzed, and the Smear tailing effect of super-bright stars can be fully reflected in the image generated by the simulation. This method realized the visible light imaging simulation of any orbital platform, any field of view, any time, and any space debris.

41.1 Introduction

With the continuous exploration of space by mankind, increasing space activities have brought hundreds of millions of space debris. The huge number of space debris greatly increases the probability of space collisions. In order to cope with the increasingly severe problem of space debris, countries have developed space target surveillance and detection technologies.

According to the classification of detection methods, space target monitoring and detection technologies are mainly divided into photoelectric detection and radar detection. Compared with radar detection, photoelectric detection has the characteristics of long range and lower cost and has become an important method of space target

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monitoring and detection technology [1]. According to the location of the detection platform, photoelectric detection is divided into ground-based detection and space-based detection. Compared with ground-based detection, space-based detection has incomparable advantages such as being unaffected by the atmosphere, all-time, all-weather, and has become the preferred method of space target monitoring and detection technology. However, in the development process of the space-based space target detection system, it is difficult to obtain the required image data for relevant verification in a short time due to the high cost of the actual installation experiment. Therefore, it is of great significance to study the visible light imaging simulation method of space-based space targets. While providing a large amount of data, it can also verify the performance of the detection and tracking algorithm and reduce the cost in the development process.

Therefore, domestic and foreign scholars have carried out related research on the simulation of visible light imaging of space targets. Literature [2] discussed the visibility of space targets based on geosynchronous orbital observation platforms in combination with the geometrical positions of the sun, space-based observation platforms, and space targets. Literature [3] established a quantitative method for brightness simulation of space targets based on the scattering cross-sectional area and the bidirectional reflectance function. Literature [4] took the development and performance test requirements of real on-orbit optical cameras as the starting point, and designed and realized the imaging simulation software of space-based optical cameras. Literature [5] considered the target's background radiation environment, surface material properties, geometric structure size, orbital elements, etc., through finite element analysis and vector coordinate transformation, using the bidirectional reflection distribution function to establish a mathematical model of the target's optical scattering characteristics. Literature [6] designed a distributed simulation system for space-based surveillance of space targets based on HLA and the extensive application of HLA in the field of aerospace system simulation.

It can be seen from the existing literature that the analysis of the whole process of the simulation of visible light imaging of space targets is relatively weak, and the simulation of the Smear tail phenomenon of super-bright stars is not involved. This paper studies the imaging simulation of space-based debris. The simulation process is divided into three parts. By analyzing the formation mechanism of the super-bright star Smear phenomenon, the super-bright star Smear phenomenon is simulated, forming a complete high fidelity simulation image forming method. The simulation imaging method has a great effect on the development of a space-based space target detection system.

41.2 Simulation Structure and Process Design

The imaging simulation of space debris realized by this method is based on a CCD optical sensor, so the imaging process can be represented by the following figure (Fig. 41.1):

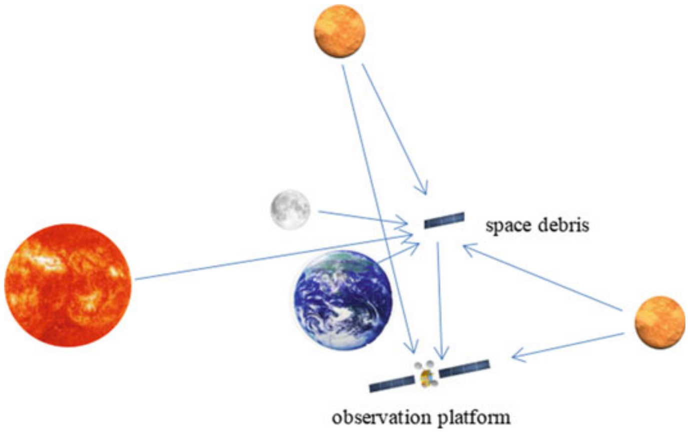

Fig. 41.1 Schematic diagram of space debris imaging process

Space debris is illuminated by space light sources such as sunlight, moonlight, starlight, and diffuse reflected light from the earth. The light reflected on its surface reaches the CCD sensor mounted on the observation platform, and the light from the stars on the starry sky background also reaches the CCD sensor. Because the space debris target and the star are far away from the observation platform, it can be considered as a point light source. It performs photoelectric conversion through the CCD photosensitive unit array and then forms the actual observation image on the CCD imaging plane.

By analyzing the characteristics of the above imaging process, this method divides the imaging process into three parts: space target motion modeling, space debris, and background star optical modeling, and CCD device imaging modeling. The above three parts are interdependent with each other. The overall structure of imaging simulation is as follows (Fig. 41.2):

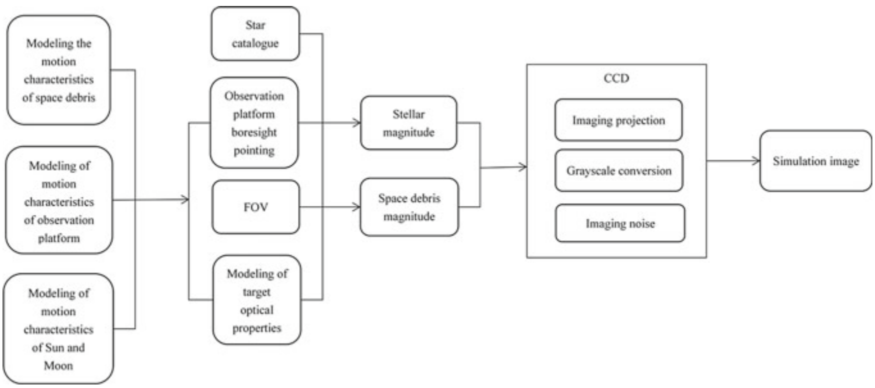

Fig. 41.2 The overall structure of imaging simulation

41.2.1 Modeling of Spatial Target Motion Characteristics

The modeling of the motion characteristics of space targets is mainly based on the relevant information to calculate the position and velocity information of space debris, observation platforms, stellar targets, and solar and moon near-Earth objects in the Earth's inertial coordinate system at any time.

For the modeling of the motion characteristics of space debris, in order to make the simulation results meet the imaging characteristics of space debris under real conditions, this method uses the SGP4 model developed by the North American Joint Air Defense Command (NORAD) to analyze TLE orbital elements issued by it to calculate the position and velocity information of the space debris [7].

For the modeling of the motion characteristics of the observation platform, this method assumes that its attitude is oriented to the ground, and the Kepler orbit elements are used to calculate its position and velocity information.

For the modeling of the motion characteristics of the stellar target, the star catalog selected in this method is the Tycho-2 catalog, which contains information such as the star's right ascension, declination, and right ascension, and the coordinate system used is the earth inertial coordinate system [8]. Taking into account the influence of the star proper motion, precession, and nutation, relevant corrections are made to the star catalog data, and the position information is calculated.

For the modeling of the motion characteristics of the sun and moon celestial bodies, this method uses the JPL DE430 ephemeris issued by the Jet Propulsion Laboratory (JPL) to calculate [9].

41.2.2 Modeling of Optical Properties of Space Debris and Background Stars

The optical property modeling of space debris and background stars is divided into optical property modeling of space debris and optical property modeling of background stars. For background stars, the magnitude information can be obtained from the star catalog.

For the modeling of the optical characteristics of space debris, the magnitude of space debris is mainly affected by ranging (distance between space debris and observation platform), phase angle (the angle between the sun, space debris, and observation platform), and the geometric and material properties of space debris targets. For the space observation platform, the light received by it is mainly diffuse reflected light of space debris, so the magnitude of the space debris can be calculated by the following formula [10]:

$$m = 1.4 - 2.5\log\gamma - 5\log D + 5\log\rho - 2.5\lg[\sin\sigma + (\pi - \sigma)\cos\sigma)] \quad (41.1)$$

In the above formula, γ is the diffuse reflection coefficient of the debris surface, D is the diameter of the space debris, ρ is the slant distance from the space debris to the observation platform, and σ is the angle between the sun, space debris, and the observation platform.

41.2.3 CCD Imaging Modeling

The imaging sensor simulated by this method is CCD, and its imaging mechanism is that light is irradiated to the CCD pixel, and photons are injected into the photosensitive unit array for photoelectric conversion to form an actual observation image on the imaging plane. When the CCD performs photoelectric conversion, while generating signal charges, noise signals are inevitably introduced. Therefore, CCD imaging modeling is mainly divided into imaging projection modeling, constellation and image gray conversion modeling, and imaging noise modeling.

For imaging projection modeling, it is mainly divided into space debris imaging projection modeling and background star imaging projection modeling. Space debris imaging projection modeling can be calculated according to the relative position of the space debris and the observation platform and the conversion matrix of the relevant coordinate system. Suppose the position vector of the observation platform in the earth inertial coordinate system at a certain moment is $\boldsymbol{R}_O$, the position vector of space debris in the earth inertial coordinate system is $\boldsymbol{R}_T$, and R_1^* is the rotation matrix from the satellite body coordinate system to the optical camera coordinate system, R_2^* is the rotation matrix from the satellite orbit coordinate system to the satellite body coordinate system, R_3^* is the rotation matrix from the earth inertial coordinate system to the satellite orbit coordinate system, then the position vector P_a of the space debris in the optical camera coordinate system is

$$\boldsymbol{P_a} = R_1^* \cdot R_2^* \cdot R_3^* \cdot (\boldsymbol{R_T} - \boldsymbol{R_O}) \tag{41.2}$$

For the background star imaging projection modeling, in the spatial target motion characteristic modeling part, the rectangular coordinate vector **I** in the earth inertial coordinate system is obtained, then the position vector $\boldsymbol{P}_b$ of the star in the optical camera coordinate system is

$$\boldsymbol{P_b} = R_1^* \cdot R_2^* \cdot R_3^* \cdot \mathbf{I} \tag{41.3}$$

Furthermore, according to the principle of small hole imaging, the position vector of the space debris and the background star in the optical camera coordinate system is projected into the imaging plane, and the imaging position in the image is calculated.

For the modeling of magnitude and image grayscale conversion, this method is based on the imaging principle of the CCD optical system to estimate the number of photons received by the CCD, thereby calculating the gray value of the corresponding magnitude [11]. Then the gray value A of the space debris target is

$$A = P/G \tag{41.4}$$

In the above formula, P is the number of photons received by the CDD, and G is the CDD gain parameter. Due to the non-ideal nature of CCD imaging, the imaging point on the image plane will have a diffusion effect. Therefore, this method uses a two-dimensional Gaussian distribution function as the point spread function to process the imaging point for the diffusion effect.

For imaging noise modeling, there are many noise sources for scientific CCD devices. Considering the actual simulation performance requirements, the following three types of noise are mainly considered: photon noise, dark current noise, and readout noise.

41.2.4 Smear Tailing Phenomenon

Through the analysis of the measured images, it is found that in addition to the above-mentioned modeling process, the Smear tailing phenomenon as an inherent characteristic of the CCD image sensor is often ignored. It refers to the phenomenon that striped white bright lines are formed on the image when the CCD is shooting a high-brightness point light source (Fig. 41.3).

For the stellar target, since its position on the imaging plane basically does not change during the exposure time and the readout time, the Smear tail phenomenon of the stellar target always presents the shape of a vertical bright band. Its impact on imaging quality is relatively large, so it is easy to cause the inundation of space

Fig. 41.3 The Smear tail phenomenon of the star in the measured image

debris, and increase the difficulty of detecting space debris, thus it is necessary to simulate it.

The CCD sensor is generally composed of three parts: photosensitive area, imaging area, and register [12]. Take a four-line CCD sensor as an example to analyze the mechanism of the Smear tail phenomenon of stars. Assume that the third row of the CCD sensor is illuminated by a star target. In Figure 41.4, the gray square in the imaging area represents the pixel being imaged, t_1–t_5 is an integration period, and t_6-t_{10} is an integration period. At time t_1, the third row of the CCD sensor generates signal charges. From t_2 to t_5, the signal charge is transferred to the register. As the photosensitive area is continuously exposed during the transfer process, additional charges are continuously generated in the illuminated area. When these charges are transferred to the register, the pixel positions in the first to third rows are occupied by additional charges. At time t_6, the third row of the CCD sensor generates signal charges. After the integration period is over, the signal and the additional charge generated by the charge readout time are transferred to the shift register in order to wait for output and write the image. In this way, the stellar Smear tail phenomenon occurs.

For the Smear tail phenomenon of stars, according to related research, the gray value h is only related to the integration time t_1, the read-out time t_2, the total number of imaging image rows m, and the sum of the gray values of all pixels in the current column [13].

$$h = t_2 \cdot \mathrm{sum}/m/(t_1 + t_2) \tag{41.5}$$

The process of visible light imaging of space-based space debris has been discussed above, and the simulation of visible light imaging of space-based space debris has been realized.

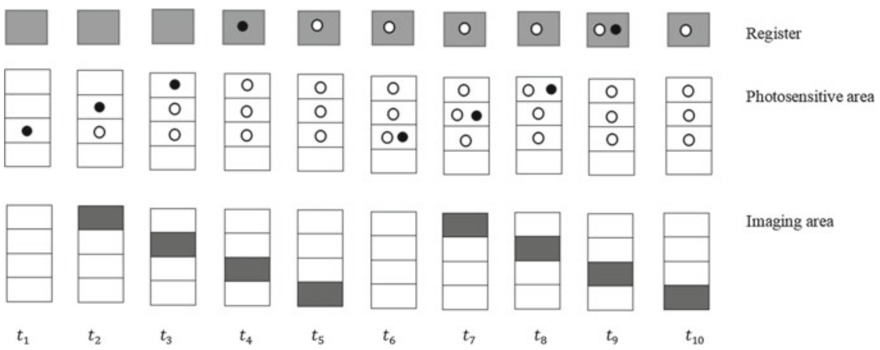

Fig. 41.4 Smear tailing phenomenon generation process

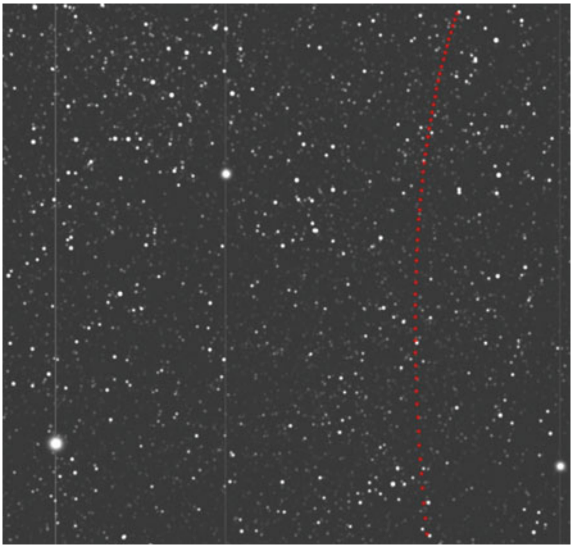

Fig. 41.5 Simulation imaging diagram

41.3 Analysis of Simulation Results

Assuming that the observation platform passes through the ascending node at zero time in the simulation, the space debris orbit is determined by TLE orbital elements. Using a certain model of sensor-related parameters, the number of pixels is 1024 × 1024, and the exposure time is 0.4 s. According to the survey results, the reflectivity is taken as 0.3. For other parameters, suppose the diameter of the space debris is 1 m. The simulation result of a certain frame is as shown in Fig. 41.5, and the space debris track calculated in the following 30 frames is marked in this frame.

Observing Fig. 41.5, we can find that the simulated image truly reflects the imaging characteristics of space debris, and the imaging points of different gray values also reflect the difference in imaging area size. The Smear tailing effect of super-bright stars is naturally obvious. The space debris trajectory appears as a curve with a certain arc, which fits the actual situation. In summary, the simulated image of this method conforms to the imaging characteristics of the real image and reaches the expected simulation result.

41.4 Conclusion

This method divides the imaging process into three parts: modeling of the motion characteristics of space targets, modeling of optical characteristics of space debris and background stars, and modeling of CCD device imaging. Furthermore, the imaging characteristics of the CCD device were analyzed, and the Smear tail phenomenon of super-bright stars was simulated, and the simulation image of space-based debris was obtained. Using this method, an observation simulation image can be obtained at any time, any observation platform, any direction of the visual axis, and any size of the field of view. It is of great significance for the research of space-based space target detection methods and the development of space-based space target detection systems.

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