An Approach to Space-Debris Optical Image Simulation Considering the Streak and Saturated Star-Background

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Abstract. In present, space-object optical image simulation study is very important to the area of space technology, because it can support the development of space-object detection algorithm before the optical platforms are launched to the space and supplement the information of unusual cases which is absent in the real optical images. Although there’re many simulation methods focus on different space-object and space-surveillance platforms, this paper mainly proposed an optical image simulation approach focus on the small field-of-view and high detection sensitivity spatial imaging system for detecting space-debris. The proposed simulation method focuses on two key features streak and saturated star-background in the space-debris optical images which caused by high angular speed of space-debris and bright star respectively. Firstly, for the purpose of simulating the saturated star-background, this paper introduces an accurate star radiation calculating model by using bolometric magnitude to replace common visual magnitude. Secondly, in order to simulate the streak, an energy accumulation based linear approximation method is proposed which is more sufficient than the original gauss distribution model when simulate the streak caused by fast moving space-debris. Finally, the experiment results show the efficiency of proposed method.

1. Introduction
For the purpose of collision avoidance and fragmentation analysis, space-debris is one of the most important space-objects need to be survey. In present, space-based optical systems are the main instruments to capture the information of space-debris, for example, the Space-based Visible (SBV) sensor [1-2] and the European Space Situational Awareness System (ESSAS)[3]. It is necessary to develop space-debris optical image simulation technology to help implement a space-based optical system when it is not ready to launch into the space, because space-debris optical simulating image can not only provide enough experiment data to help the engineers to design information process algorithm, but also can simulate the special situations on the images like valid streak and stray light which are unusually happened during the operating period on orbit.

Although the image simulating technology of space-based sensors has recently been a tremendous development, there still remain many problems, especially in the area of space-debris optical image simulation. In fact, the space-debris optical images can not only be influenced by the parameter of optical system, CCD/CMOS noises, exposure time, coordinate transformation, etc., but also be affected by the angular velocity of space-debris. Generally, space-debris move fast and lightless, it can only be detected when shined by solar-light in space. Thereby, space-debris represents as a streak constructed by sequential faint point target in the optical image and the space-based visible surveillance system need high detection sensitivity to find space-debris[4]. However, bright star will be
saturated in those optical images captured by space-based optical systems with high detection sensitivity. In summary, the streak and saturated star background simulation are the key problems need to solve.

As mentioned above, there’re two important problems of simulating space-debris optical images need to solve. One is how to simulate saturated stars which will commonly appear in the space-debris optical images. Another is how to simulate the streak caused by high velocity of space-debris. Therefore, the main purpose of this paper is trying to find a way to solve those two problems. There’re two contributions of this issue. Firstly, this paper theoretically derives the energy calculating equations of saturated stars in CCD/CMOS image plane by using bolometric magnitude instead of visual magnitude and conducts the approach of seeking table to find the spread size of saturated stars. Secondly, an Energy Accumulation based Linear Approximation method (EALA) is proposed to simulate the streak of rapid moving space-debris in optical images.

2. Saturated star background simulation process

In general, if a star is saturated, it means that the radiation from the star to the image plane of CMOS/CCD is larger than the full well capacity (FWC) of the CMOS/CCD. Although a method had been proposed in [5] to calculate electrons generated by star radiation on the image plane, the computing process directly use star visual magnitude to calculate the star radiation which will lead to the inaccurate results. Because the visual magnitude of stars is measured in visible spectrum, the accurate estimation results of star radiation should be on the basis of the bolometric magnitude which is measured in full-wave band. Thereby, the first part of this section proposes an accurate star radiation calculating model based on bolometric magnitude.

2.1. Star Radiation Estimation Model

For the purpose of using bolometric magnitude to replace visual magnitude during star radiation calculating, a correction coefficient BC is needed to modify the difference between them. BC can be represented as equation (1).

\[ BC = m_{bol} - m_{vis} \]  

Where \( m_{bol} \) represents bolometric magnitude, \( m_{vis} \) represents visual magnitude.

The BC can be computed due to the effective temperature on the surface of the star.

\[ BC(T_{eff}) = -42.54 + 10 \cdot \log(T_{eff}) + \left(29000K/T_{eff}\right) \]  

Where \( T_{eff} \) represents the effective temperature on the surface of the star.

The integral radiation energy density outside the stellar atmosphere is shown in equation (3) and (4):

\[ S_{m_{bol}} = 2.512 \cdot m_{bol} S_0 \]  
\[ S_{0: \infty} = 2.512 \cdot \left(m_{vis} + BC\right) S_0 \]  

Where \( S_0 = 2.48 \times 10^{-12} \text{ W cm}^{-2} \).

Equation (4) gives the star radiation in full-wave band, but the optical sensors can’t receive the whole energy of stars. So the calculation of star radiation in a small bandwidth should be considered. Equation (5) shows the solutions as below.

\[ M(\lambda, m_{vis}, T_{eff}) = 2.512 \cdot \left(m_{vis} + BC\right) \cdot S_0 \cdot \frac{M(\lambda, T_{eff})}{M_s} \]  

\( M(\lambda, T_{eff}) \) represents the star radiation in a specific wave-band when Stellar emission rate \( \varepsilon \) is set to 1.
Where $K$ is Boltzmann constant, $h$ is Planck’s constant, $c$ is speed of light. $M_s$ represents the star radiation in all wave-band.

$$M_s = \int_{0}^{\lambda_{\text{max}}} M(\lambda, T_{\text{eff}}) d\lambda = \int_{0}^{\lambda_{\text{max}}} \frac{2\pi h c^2}{\lambda^5} \frac{1}{(e^{h\nu/k_{\text{B}}T_{\text{eff}}} - 1)} d\lambda = \sigma T_{\text{eff}}$$

Therefore, the atmospheric external radiation of stars among a wave range can be calculated as below:

$$M = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} M_s d\lambda$$

As mentioned above, the single star flux in a specific integration time on the imaging detector can be calculated as below:

$$N_e = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} M_s \cdot A \cdot QE \cdot t \cdot d\lambda$$

Where $N_e$ represents the electron numbers on the imaging detector, $A$ represents the pupil area, $t$ represents the integration time, $QE$ represents the quantum efficiency, $\tau_0$ represents the transmissivity of optical systems.

2.2. Star energy distribution model

After star electrons being calculated, the star energy distribution model needs to be determined. Generally, in ideal imaging condition, star energy diffusion model is subjected to two-dimensional gauss distribution.

$$f(x, y) = \frac{N_e}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(x - x_0)^2 + (y - y_0)^2}{2\sigma^2}\right\}$$

Where $(x_0, y_0)$ represents the center coordinate value of gauss function, $\sigma$ is the size of gauss function.

For space-debris detection visible sensor, bright star will be saturated. As described in many researches, under ideal imaging condition, the pixel size of saturated star will become much bigger than unsaturated star[4]. Therefore, how to confirm the pixel size value is the key point in saturated star simulation. This section proposes a theoretically simple but efficient and fast method based on table-checking to quickly acquire the pixel size value of saturated star in image plane. The process diagram is shown as below. The main contents in the comparison table are the relationships between the value of pixel size and $\sigma$. The process diagram is shown in Figure 1.
3. Streak Simulation Method

In the image plane of space-debris visible sensor, fast moving space-objects will generate a line of streak which is the key feature to separate space-object from star background. Therefore, the streak simulation is the most important aspect need to be concern.

This paper proposes an energy accumulation based linear approximation method which is built up on the basis of that the space-debris is moving at a constant speed. Firstly, we assume that the angular moving speed of space-debris on the image plane is $V$, the velocity components in $X$ and $Y$ coordinate direction are $v_x$ and $v_y$, respectively, so among a specific integration time $t$, the moving pixels of space-debris on the image plane are $M_x$ and $M_y$.

$$M_x = V_x \cdot t / P$$

$$M_y = V_y \cdot t / P$$

(11)

(12)

Where, $P$ represents the viewing angle of single pixel on the image plane.

The process of proposed method is shown as below:

Step 1: Build a local image of streak as shown in Figure 2.

In Figure 2, each square represents a pixel, black square represents space-debris reside in the pixel in a very short time $\Delta t$ in which the space-debris can be seen as stationary object.
Step 2: The energy distribution model described in section 2 is used to calculate the electron number $N$ of space-debris on the image plane in $\Delta t$. If $N$ is larger than the full well capacity of image sensor, we can check the comparison table to determine the value of $\sigma$. Otherwise, a normal gauss distribution model can be used to simulate the stationary object in the black square. Therefore, a serial overlapped Gaussian diffusion models can be generated as shown in Figure 3. And Figure 4 shows the overlapped energy region between ① and ② which are the stationary points in a streak.

![Figure 4 Diagram of energy overlapped region](image)

Figure 5 shows the overlapped energy region between ① and ② which are the stationary points in a streak.

Step 3: By accumulating the energy overlapped region of neighbouring black squares, the simulated streak can be generated as shown in Figure 5.

4. Experiment
This section introduces a detailed implementation of space-debris optical image simulating experiment based on a specific CMOS imaging sensor CIS2521F. Firstly, the parameters of optical system is described in Table 1 and the parameters of CMOS imaging sensor can be found in[6].

| Parameter of optical system | Value         |
|-----------------------------|---------------|
| 1 Optical transmissivity    | 0.85          |
| 2 Lens caliber              | $A$ (cm)      |
| 3 Integration time          | $T$ (s)       |
| 4 Field of View             | $2^\circ \times 1.4^\circ$ |

In Table 1, the lens caliber and integration time is adjustable which will directly influence the computing results of star radiation energy. Secondly, according to the parameters in Table 1, we can use the calculation equation (9) in section 2 to compute the electron numbers of different magnitude stars. Thirdly, we use the approach mentioned in [7] to calculate the image noise of CIS2521F. The calculation equation is introduced as below.
\[ n_{\text{CB2352W}} = \sqrt{N_s^2 + n_{\text{DCSN}}^2 + n_{\text{DCNU}}^2 + n_{\text{PRNU}}^2 + n_{\text{RN}}^2} \]  (13)

\( N_s \) is the electron numbers of star radiation energy on the image plane, \( n_{\text{DCSN}} \) is the root mean square of dark current noise, \( n_{\text{DCNU}} \) is the root mean square of Dark current non-uniformity noise, \( n_{\text{PRNU}} \) is the root mean square of PRNU, \( n_{\text{RN}} \) is the root mean square of read noise. Fourthly, other imaging parameters are introduced as below: (1) the orbit parameters of space-debris are initialized by Satellite Tool Kit (STK) software which is developed by Analytical Graphics Corporation. (2) Four star catalogs are used to simulate the star background such as SKY2000, SAO, Tycho II and UCAC4. The UCAC4 star catalog which includes approximate a hundred million stars, compared to the commonly used star catalogs, indicates more detailed stars between 8th magnitude and 16th magnitude. (3) Space-debris do not give off light of their own, which can only be detected by space-based optical imaging sensor when they are shined by the sunlight. And the proposed method in [8] and [9] can calculate the space-debris energy on the image plane. (4) The stars position on the CMOS image plane can be calculated by using the approach mentioned in [10], while the space-debris position is computed by the aid of coordinate transform theory and SKT software. (5) The Matlab2014 is used as implementing software, and the experiments are conducted on the PC with Intel i5 core and 4G memory. Finally, the simulating experiment results are shown from Figure 6 to Figure 7 which contains streak, star background and image noise. It can be seen that saturated stars have bigger area than unsaturated stars, detected space-debris have clear and continuous streak.

5. Conclusion
This paper conducts the research of space-debris optical image simulation technology and proposes three suggestions for improvement: (1) we use bolometric magnitude instead of visual magnitude to calculate the star radiation, for the reason of acquiring precise electron numbers; (2) we propose a method of seeking table to fast determine the spread area size of saturated star; (3) we introduce an energy accumulation based linear approximation method to simulate the streak on the optical images to avoid error streak. The experiment results show that the proposed image simulation method can imitate the key features of space-debris optical image such as saturated star background and streak.

Figure 6. Simulated image when \( T=1s, A=15cm \)  
Figure 7. Simulated image when \( T=1.6s, A=15cm \)

Acknowledgment
This research was supported by the National Natural Science Foundation of China (Grant No: 61503410)

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