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Modeling the space-based optical imaging of complex space target based on the pixel method

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ABSTRACT

This paper aims at the visible light imaging detection of complex space targets (satellites) at close range, utilizes the pixel method based on OpenGL and 3ds target model, studies the basic space-based optical imaging process, which includes the link elements such as space environment, solar radiation, target, optical receiver system, image detector and relative motion and so on. By using the pixel method and Bi-directional Reflectance Distribution Function (BRDF), this paper models the target's scattering of solar radiation and analyzes the energy response characteristics, the spatial frequency transfer characteristics and the noise mathematic model of each link. At last this paper introduces the complex target's space-based optical imaging simulation method based on 3D programming tool OpenGL and 3ds target models, and gives some examples of simulated images. This research can provide references for the next research thinking and methods of imaging system simulation and evaluation.

1. Introduction

Space-based optical imaging system has the ability to track earth-bound satellites in order to know and predict their position, movement, and some physical features, and also can capture their images under suitable conditions to obtain the target geometry features and provide target recognition basis [1]. Compared with ground-based imaging system, the measurement scope and duration of space-based imaging are larger and longer, the restrictions are fewer and the imaging distance also may be closer so that the detail target information can be obtained. Space-based optical imaging system is a multi-technology integration of complex subsystems, but now we do not have actual experimental conditions in space, therefore to complete the imaging system load and platform testing work, imaging modeling and simulation under the ground laboratory environment is very necessary and important [2].

American researchers have already carried out the space-based optical imaging simulation study earlier and achieved remarkable achievements [3]. There are already some excellent engineering and commercial systematic simulation programs, such as AFRL's Time-domain Analysis Simulation Software for Advanced Tracking (TASAT) [4,5], Boeing's Satellite Visualization and Signature Tools (SVST) [6], Analytical Graphics Inc.'s STK EOIR [7], etc. These software applications have high cost and have already been applied to the space target tracking, monitoring and identification, and played important roles. Many other institutions and agencies also precede the deep researches accordingly [8–10].

However, these programs cannot be integrated with the electro optical simulation and analysis tools we normally use, because we do not control their source codes. We need our own tool to help provide an efficient user interface and simulation platform.

In addition, the actual space targets are complex, such as complicated geometry structure, the variety of target surface materials, and the different scattering characteristics of various materials [11,12]. In previous studies researchers usually regard the satellite surface as Lambert surface, and the target is usually simplified and considered to be a combination of simple geometry of the cuboids, cylinders and so on, and the type of target material is single [13]. These considerations are simple and convenient for calculation, but they are quite different to actual situation. Subsequently researchers utilize BRDF to specify the scattering characteristics of materials gradually [14]. This method is more accurate than the diffuse reflectance method, but it is not used in the simulation of optical imaging widely yet.

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Therefore we utilize the pixel method, which will be introduced in Section 2, to simulate the imaging of complex target. We use 3D software to construct the 3ds files of target models based on the size parameters, which contains different materials information, and adopt BRDF to describe the material's scattering characteristics. Then employ the spatial frequency of detector array as the benchmark of image's resolution, analyze the scattering of complex target surfaces, and research each correlative link's signal response, spatial frequency response and noise model. This method combines the optical scattering characteristics of complex targets with the imaging performance of visible imaging systems. The integral calculation of target curved surface, which cannot be calculated directly, is translated into the numerical calculation pixel by pixel. Therefore if the imaging system parameters and target model parameters are given, the dynamic imaging and detection performance of visible observation systems can be calculated. Compared with previous researches, the target satellite model and imaging performance model in this paper have more convenience to some degree, and can provide the method foundation for realization of imaging simulation effectively.

2. Imaging modeling method

The space-based optical imaging system studied in this paper mainly includes the optical receiver system, the digital sensor CCD (Charge Coupled Device) and signal processing circuit. According to the linear filtering theory, photoelectric imaging system can be regarded as a mix consists of series subsystems with a certain frequency (space or time) features [15]. Therefore, according to the basic process of visible light imaging of space target, this article uses the theory of linear filtering theory and optical imaging principle to set up the mathematical model of space-based optical imaging, and mainly research light intensity reflected by the target in each link of the situation, as well as the spatial frequency transfer characteristics of optical system, detector and relative motion [16].

The basic imaging process is shown in Fig. 1, which mainly includes the target satellite, solar radiation, space environment, motions of target and imaging platform, optical receiver system and digital sensor. The influences of space environment and motion on imaging quality are mainly embodied in the image degradation (blurring) and the stars background.

In this paper we use the pixel element method to analyze the scattering characteristic of the target and imaging effects, and integrate the surface small elements of target surface with the image pixels of the target captured by digital sensor.

Fig. 2 illustrates the general geometric relationship among the sun, the imaging system and target. We consider that the target surfaces are composing by a large number of tiny flat surfaces. The surface element S_{mn} is imaged by optical receiver system and is corresponding to the CCD detector element D_{mn}, as well as the single pixel P_{mn} of the target image, where m and n means the row index and column index of the image, respectively.

Fig. 3 shows the lighting geometric of the surface element S_{mn}. The average BRDF of the element S_{mn} in visible wavebands is f_r, the unit normal vector of S_{mn} is $\vec{n}$, the unit vector from S_{mn} to the sun is $\vec{L}$, and the unit vector from S_{mn} to the detector is $\vec{S}$, and the angle between $\vec{n}$ and $\vec{L}$ is θ_{imn}, the angle between $\vec{n}$ and $\vec{S}$ is θ_{rmn}.

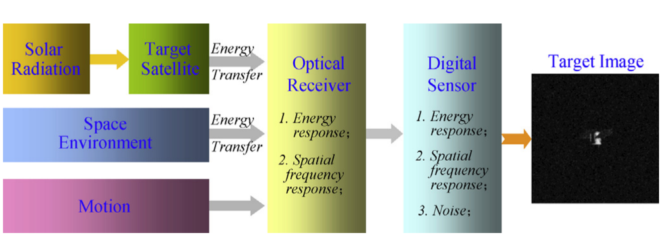

Fig. 1. Optical imaging process is categorized into six key elements.

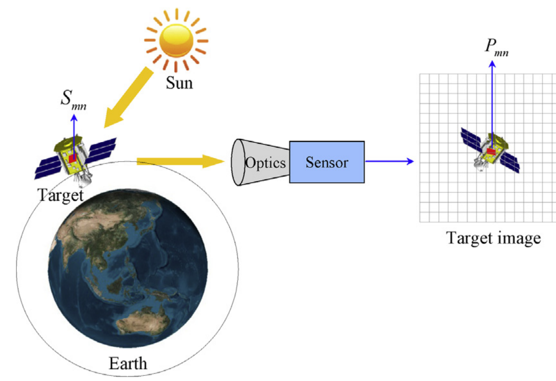

Fig. 2. The geometric relationship between the sun, the imaging system and target.

2.1. Sun radiation and target satellite

The solar spectrum radiation is closer to the radiation of the blackbody with the temperature 5900 K, and the sun can be considered as a parallel light source, whose visual field angle is about 0.5°. While space-based optical imaging system is working on orbit, the areas lightened by sun directly should be avoided. In addition, to detect the near-earth space target, the influence of the stray light in the atmosphere also should be considered. As the density of the earth's atmosphere at 120 km height is nearly close to zero, the area above the earth from zero to 120 km should be escaped to guarantee earth's atmospheric background cannot enter into the field of view (FOV) of imaging system [17].

In the spectrum scope of the visible light wavebands (between 380 nm and 780 nm), the solar irradiance near the target is shown as follows:

$$E_{sun} = \frac{M_{sun} R_{sun}^2}{R_0^2} \tag{1}$$

where M_{sun} is the solar radiation remittance of visible bands, R_{sun} is the radius of the sun (6.6599×10^8 m), and R_0 can be regarded as the average distance between the earth and sun (1.495×10^{11} m).

The sunlight irradiance received by the surface element S_{mn} is given by:

$$E_{imn} = E_{sun} \cos \ \theta_{imn} \tag{2}$$

Based on the definition expression of BRDF, we conclude that the radiance of S_{mn} in the direction of $\vec{S}$ is:

$$L_{mn} = E_{sun} f_{rmn} \left(\theta_{imn}, \theta_{rmn}\right) \cos \theta_{imn} \tag{3}$$

According to the actual situation of the sun lighting, we transform the Phong lighting model [18] to make it comply with BRDF

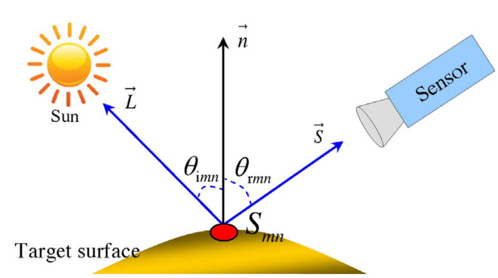

Fig. 3. The lighting geometric of target surface element S_{mn}.