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Thermal radiation stray light integration method of infrared camera in geostationary orbit

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Abstract: The space environment of the three-axis stabilized satellite in geosynchronous orbit is complex, and the background radiation of the instrument varies greatly. The traditional stray light analysis method can not simulate the non-uniform temperature field, and can not calculate the instrument background in real time. Also the simulation error is large. Thermal radiation stray light integration method was used to analyze instrument background radiation of in-orbit infrared camera. The background radiation of the instrument and the signal-to-clutter ratio of the camera on the detector was calculated by using the real-time temperature fields with temperature gradient and radiation transfer factor. Comparing the result of the thermal radiation stray light integration method and traditional stray light analysis method with the on-orbit measurement, the error of the thermal radiation stray light integration method was less than 17%, while the error of traditional stray light analysis method was up to 114%. The result shows that the thermal radiation stray light integration method is closer to the actual on-orbit situation, and the simulation efficiency and accuracy are higher.

Key words: thermal radiation stray light integration method; Monte-Carlo Method; radiation transfer factor; signal-to-clutter ratio

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地球同步轨道红外相机的热辐射杂散光集成法

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摘　要：地球同步轨道上的三轴稳定卫星所处的空间环境复杂，仪器背景辐射变化较大。传统杂散光分析法无法模拟非均匀温度场，且无法实时计算仪器背景，仿真误差较大。提出用热辐射杂散光集成法来分析在轨红外相机的仪器背景辐射，通过更趋于在轨真实温度的且具有温度梯度的实时温度场，结合辐射传递因子，计算探测器上的仪器背景辐射以及相机的信杂比。将热辐射杂散光集成法、传统杂光分析法计算信杂比与在轨实测信杂比进行对比，热辐射杂散光集成法误差小于 17%，而传统杂光分析法误差达 114%。表明热辐射杂散光集成法的仿真结果更趋近于在轨实际情况，仿真效率和仿真精度更高。

关键词：热辐射杂散光集成法；　蒙特卡罗法；　辐射传递因子；　信杂比

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0 Introduction

For the three-axis stabilized satellite in geosynchronous orbit, its space environment temperature is complex. The satellite temperature is affected by the sun, which not only changes with the season, but also varies greatly at different time of the same day. The temperature inside the camera determines the background radiation of the instrument and affects the dynamic range of the camera. Therefore, the simulation and calculation of the background radiation of the instrument becomes an important factor affecting the accuracy and quantification of the infrared camera in geosynchronous orbit.

For the analysis of stray light in instrument background, the traditional stray light analysis method (TSLAM) is based on Tracepro, Lighttools and other software, which greatly simplifies the temperature field of each component. Usually, the radiation analysis of uniform temperature field can not simulate the actual non-uniform temperature field in orbit, nor can the real-time calculation of the temperature field changing in one day being carried out[1−8], The simulation error is usually greater than 100%. However, because of the non-uniformity of the distribution of the external light source and the internal heat source, the temperature field of the camera components varies with time. Especially for geosynchronous orbit space camera, the temperature of each optical component varies dramatically with time in one day. The pointing mirror of the Geostationary Operational Environment Satellite system (GOES) is exposed to the outside, the maximum temperature difference can reach 7 K, and the temperature gradient on the surface of GOES ’s pointing mirror will change with the sun's relative orientation[9]. The temperature difference in different regions of the primary mirror of the James Webb Space Telescope (JWST) is as high as 14 K. If the average temperature field is used in stray light simulation, the error is large. Therefore, the method of subregional simulation is adopted[10].

It can be seen that the temperature field of geosynchronous orbit varies greatly with time. The background radiation of the instrument caused by the temperature field has become an important factor affecting the imaging quality of infrared cameras. Real-time analysis of the influence of stray light from instrument background radiation on camera detection ability caused by non-uniform temperature field in one day is a necessary step in optical system design. In this paper, the thermal radiation stray light integration method (TRSLIM) is proposed to analyze the instrument background radiation of on-orbit infrared camera. The temperature field of each optical component is directly simulated by thermal radiation stray light software. The temperature field is real-time and has temperature gradient, which tends to be more realistic. The background radiation of the instrument on the detector can be calculated by combining the temperature field of each node of the opto-mechanical element with the radiation transfer factor. The signal-to-clutter ratio (SCR) of the camera can be calculated by combining the radiation characteristics of the target.

1 Optical structure of camera and illumination analysis of target

The optical model of the space camera is an off-axis three-mirror structure. The optical path diagram is shown in Fig.1. After the parallel light is reflected by the pointing mirror, the primary mirror, the secondary mirror and the third mirror are illuminated successively through the aperture stop. The field stop is set at the convergence point between the secondary mirror and the third mirror. The back light path adopts the way of splitting by splitters, and achieves the splitting of channel 1, channel 2 and channel 3 by setting splitter 1 and splitter 2.

For channel 3 (infrared channel), the radiation flux of the point target received by the camera on the focal plane device is as follows:

$$P_0 = J \cdot \frac{\pi D_0^2}{4l^2} \cdot \tau_a \cdot \tau_0 \cdot Enc \tag{1}$$

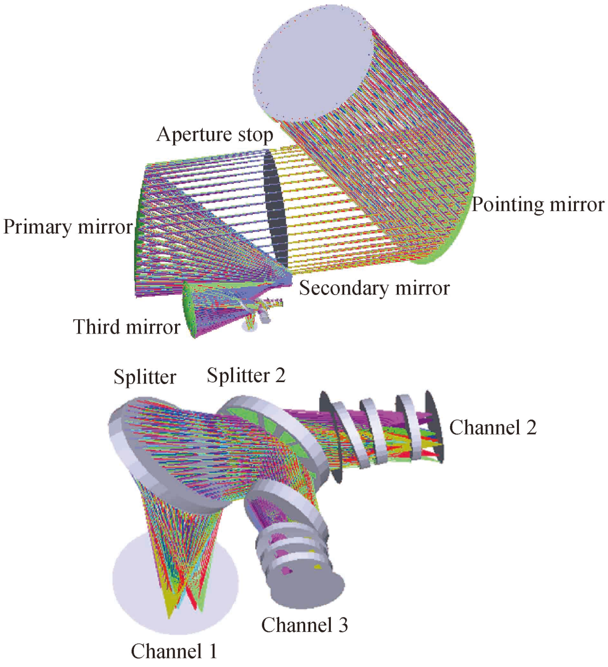

Fig.1 Schematic diagram of light path

The irradiance of the point target received on the focal plane is as follows:

$$H_0 = J \cdot \frac{\pi D_0^2}{4I^2 a^2} \cdot \tau_a \cdot \tau_0 \cdot Enc \tag{2}$$

Among them, J is the radiation intensity of the point target; I is the detection distance of the point target; τ_a is the atmospheric transmittance in infrared band, the value is 0.65; τ_0 is the optical transmittance in the channel 3 of the camera, the value is 0.48; Enc is the concentration of diffraction energy in one pixel of the channel 3 of the camera, the value is 70%; D_0 is the optical aperture of the optical system, and a is the pixel size. Finally, the irradiance of the point target on the detector of channel 3 is calculated to be 1.887×10^{-3} W/m^2.

2 Thermal radiation stray light integration method (TRSLIM)

2.1 Radiation transfer factor

In recent years, the commercial software Structural/Thermal/Optics Performance (STOP) for optical-mechanical thermal integration analysis has been gradually integrated into the engineering application[11−12]. It can complete the simulation analysis of the image quality change of the camera under the influence of temperature field change and stress release on the orbit, but it can not complete the simulation analysis of the stray light change of the camera when it works on the orbit. In terms of the nature of light, both heat and light are electromagnetic waves, which are only the differences of manifestations. Thermal simulation analysis software and stray light simulation analysis software have common features. The most prominent point is that the two analysis software adopts MCM, a relatively mature method.

At present, TracePro and Lighttools are mainly used to analyze instrument background radiation. These software uses mature Monte-Carlo Method (MCM) for ray tracing. However, the stray light software itself can not analyze the orbital parameters of the space camera and the periodic variation of the temperature field of the instrument, so the non-real-time and uniform temperature field is often used for approximate analysis. Thermal analysis software such as Thermal Desktop, TMG and so on, also uses MCM calculation method, but can obtain real-time instrument temperature field with temperature gradient. The radiation transfer factor is introduced into the thermal software, which includes the energy exchange between the opto-mechanical elements and the focal plane, which is concerned by stray light analysis. The radiation transfer factor remains unchanged in the process of solving the energy transfer problem. Finally, the instrument background radiation can be calculated by the instrument temperature field and the radiation transfer factor.

Therefore, it is feasible to use thermal analysis software for stray light analysis.

The radiation transfer factor B_{ij} is defined as the percentage of the energy directly projected from surface 1 to surface 2 to the radiation energy of surface 1. The definition can be written as:[13]

$$B_{ij} = \frac{Q_{12}}{Q_1} \tag{3}$$

Among them, Q_1 is the effective radiation of surface 1 and Q_{12} is the projection radiation of surface 1 to surface 2.

If the number of volume V_i and panel S_j in the thermal radiation system is N and M, the energy equation of volume V_i is

$$4\sigma\kappa_i V_i T_i^4 = \sum\nolimits_{j=1}^{N} 4\sigma\kappa_j V_j T_j^4 B_{ji} + \sum\nolimits_{k=1}^{M} S_k\sigma\varepsilon_k T_k^4 B_{ki} \quad (4)$$

The energy equation of panel S_i is

$$S_i\varepsilon_i\sigma T_i^4 = \sum\nolimits_{j=1}^{N} 4\sigma\kappa_j V_j T_j^4 B_{ji} + \sum\nolimits_{k=1}^{M} S_k\sigma\varepsilon_k T_k^4 B_{ki} \quad (5)$$

The radiation transfer factor emitted by volume V_i and absorbed by panel S_j is as follows:

$$B(V_i,S_j) = \frac{N_j(S_j)}{N_i(V_i)} \quad (6)$$

Among them, $N_i(V_i)$ is the total number of energy beams emitted by volume V_i and $N_j(S_j)$ is the total number of energy beams absorbed by panel S_j.

2.2 Calculation Principle of TRSLIM

The method of calculating instrument background radiation for thermal radiation stray light integrated analysis is based on the orbital model and the radiation characteristics of the camera itself. The thermal analysis of the camera is carried out, and the non-uniform temperature field of each optical component of the camera is obtained. For the element of interest, the node temperature and the specific emissivity of the element with time are taken and calculated according to Planck's law of radiation. The radiation illumination of the element node with time varying in the spectrum of interest is as follows:

$$M_{i\lambda} = \varepsilon\frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{ch/\lambda kT_i}-1} \quad (7)$$

Through the thermal radiation module of the thermal radiation stray light integrated analysis software, the radiation transfer factor B_{ij} between each element node and detector node is calculated, and then the instrument background irradiance of each element on the detector which changes with time is calculated. The calculation formula is as follows:

$$E = \frac{\sum_j\sum_i\int_{\lambda_1}^{\lambda_2} M_{i\lambda} d_\lambda \cdot B_{ij}}{\sum^j} \quad (8)$$

Then, the total instrument background irradiance on the detector is obtained by adding the instrument background irradiance of each component. According to the calculation results of the irradiance of the point target on the detector in the last section, the SCR caused by the instrument background radiation with time is calculated. The calculation process is shown in Fig.2.

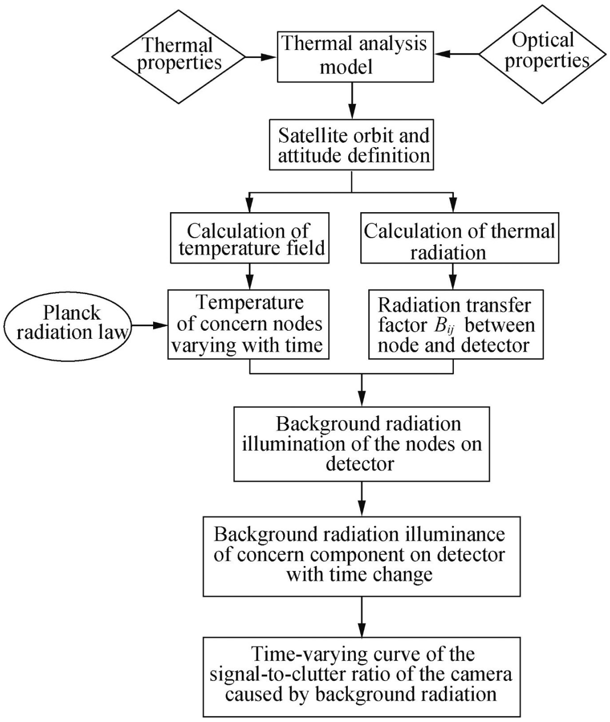

Fig.2 Calculating process of instrument background radiation stray light for TRSLIM

2.3 Modeling and input conditions

2.3.1 Establishment of model

Because of the complex thermal characteristics of space camera in orbit, it is necessary to simplify the geometric model, the external heat flow and the thermal characteristics of nodes before building the model. The simplification is mainly based on the technical status and heat transfer characteristics of the space camera. In the process of building thermal model, the partition of nodes and grids is also an important step. If the main thermal characteristics of space camera can be embodied, the number of nodes will be reduced as much as possible. If the optical-mechanical element is isothermal, it can be regarded as a node. If the temperature gradient of the optical-mechanical element is large, the node should be subdivided. In addition, the space camera is divided into several different components, including the main frame component, the pointing mechanism component, the main optical component, the rear light path component and the refrigerator Dewar component. The thermal contact relationship between the components is defined separately and connected through the grid assembly relationship. The final thermal analysis model of space camera is as shown in Fig.3:

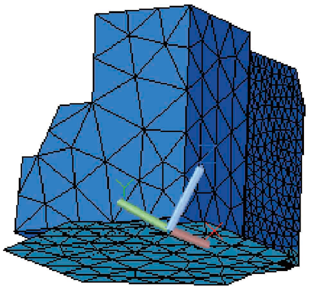

Fig.3 Thermal network model

2.3.2 Selection of calculating conditions

The orbit of the space camera is geosynchronous. Figure 4 shows the external heat flow of the camera in orbit around 4 hours of midnight under five working conditions of + 8.8 °, - 8.8 °, spring and autumn equinox, winter solstice and summer solstice. It can be seen from the picture that the external heat flow into the camera is different around midnight in different seasons. At + 8.8 °, the external heat flow into the camera is the most, at the winter solstice the least, and at the spring and autumn equinoxes there is a 72 min shadow period. Because of the most external heat flow and the most drastic change of camera temperature field in +8.8 ° working condition, we choose the solar altitude angle +8.8 ° working condition to calculate the temperature field inside the camera, and then analyses the influence of the corresponding instrument background radiation.

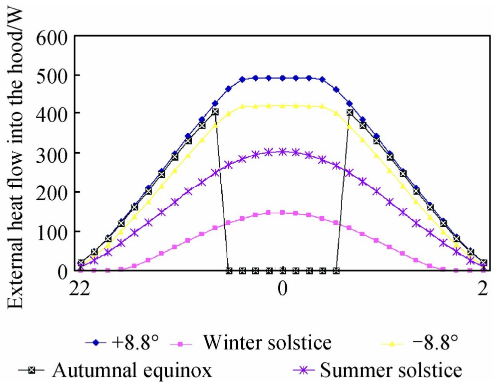

Fig.4 External heat flow into the hood

2.4 Calculation results

The TRSLIM is carried out for the infrared channel of channel 3. Firstly, the background irradiance of each optical-mechanical element should be calculated.

The temperature change curve and temperature gradient change curve of each optical-mechanical element in one day were obtained by thermal model and orbit parameters. Take the primary mirror as an example, Fig.5 and Fig.6 are the temperature change curve and the temperature gradient curve of the primary mirror in one day, respectively. The temperature of the primary mirror at 12:00, 20:00 and 6:00 is used to calculate the radiation in the infrared band. Table 1 calculates the average

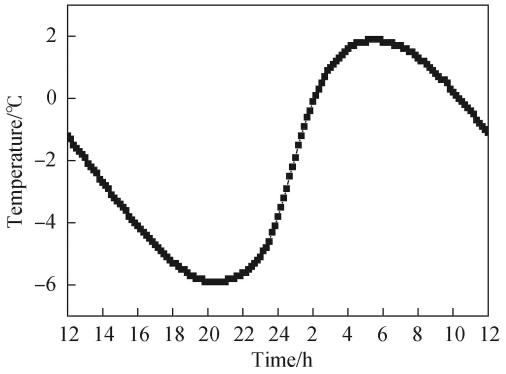

Fig.5 Temperature curve of primary mirror in one day

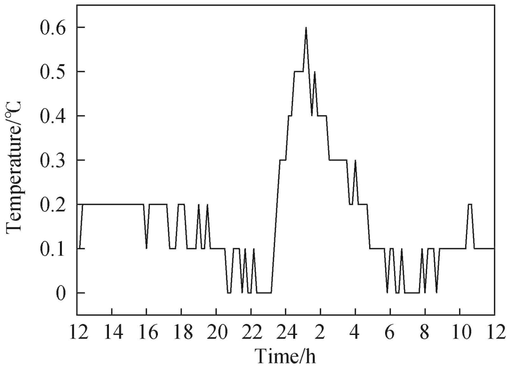

Fig.6 Temperature gradient curve of primary mirror in one day

irradiance of the primary mirror $M_{i\lambda}$ in the required infrared band. Table 2 calculates the radiation transfer factor B_{ij} between the primary mirror nodes and the infrared detector nodes by TRSLIM, in which the primary mirror nodes are Node1 and the infrared detector nodes are Node2. Based on the actual irradiance and B_{ij} of the primary mirror nodes in the infrared band, the average background radiation of the primary mirror on the infrared detector at 12:00, 20:00 and 6:00 can be calculated, as shown in Tab.3-Tab.5. The irradiance of the primary

Tab.1 Radiation calculation of primary mirror at different time in infrared band

Time	Temperature/°C	Emissivity	$M_{i\lambda}$/(W/m^2)
12:00	−1.3	0.04	0.049 0
20:00	−5.6	0.04	0.040 5
6:00	2.3	0.04	0.057 2

Tab.2 Energy transfer factor B_{ij} of nodes of primary mirror to detector

Cond_id	Node 1	Node 2	Area*e*B_{ij}	B_{ij}	B_{ji}
1	COMET.9284	COMET.6790	2.728 026e-05	0.018 532	0.012 89
2	COMET.9284	COMET.6791	5.640 484e-07	0.003 455 921	0.002 322 2
3	COMET.9284	COMET.7308	1.156 538e-06	0.013 559 96	0.001 076
4	COMET.9284	COMET.7309	1.401 487e-06	0.007 363 961	0.003 127 9
……					
N-3	COMET.9310	COMET.7309	6.087 829E-08	5.18E-05	0.001 187
N-2	COMET.9310	COMET.7310	1.103 783E-06	0.009 397 84	0.004 149
N-1	COMET.9310	COMET.7311	6.306 837E-07	0.005 369 77	0.001 819
N	COMET.9310	COMET.7312	2.469 422E-06	0.002 102 518	0.007 124

Tab.3 Radiation calculation of nodes of primary mirror on detector at 12:00

Cond_id	Node 1	Node 2	B_{ij}	E_j/(W/m^2)	E/(W/m^2)
1	COMET.9284	COMET.6779	0.005 853 2	0.000 726	
2	COMET.9284	COMET.6780	0.000 345 592 1	0.000 135	
3	COMET.9284	COMET.7270	0.003 559 96	0.000 532	
4	COMET.9284	COMET.7271	0.001 363 961	0.000 289	
……					3.712E-04
N-3	COMET.9310	COMET.7271	5.18E-05	2.03E-06	
N-2	COMET.9310	COMET.7272	0.009 397 84	0.000 368	
N-1	COMET.9310	COMET.7273	0.000 536 977	0.000 21	
N	COMET.9310	COMET.7274	0.002 102 518	8.24E-05	

Tab.4 Radiation calculation of nodes of primary mirror on detector at 20:00

Cond_id	Node 1	Node 2	B_{ij}	E_j/(W/m^2)	E/(W/m^2)
1	COMET.9284	COMET.6779	0.005 853 2	0.000 595	
2	COMET.9284	COMET.6780	0.000 345 592 1	0.000 111	
3	COMET.9284	COMET.7270	0.003 559 96	0.000 435	
4	COMET.9284	COMET.7271	0.001 363 961	0.000 236	
……					1.820E-04
N-3	COMET.9310	COMET.7271	5.18E-05	1.66E-06	
N-2	COMET.9310	COMET.7272	0.009 397 84	0.000 302	
N-1	COMET.9310	COMET.7273	0.000 536 977	0.000 172	
N	COMET.9310	COMET.7274	0.002 102 518	6.75E-05	

mirror on the infrared detector in one day can be calculated by calculating the irradiance of the three points of time mentioned above, as shown in Fig.7. Use this method, the background irradiance of other optical-mechanical elements can be calculated. The total background irradiance of the instrument can be obtained by adding the background irradiance of all optical-mechanical elements on the infrared detector, as shown in Fig.8. According to the irradiance of the point target on channel 3 detector in section 2, which is 1.887×10^{-3} W/m^2, the SCR curve formed by instrument background radiation of channel 3 is calculated, as shown in Fig.9.

Tab.5 Radiation calculation of nodes of primary mirror on detector at 6:00

Cond_id	Node 1	Node 2	B_{ij}	E_{ji}/(W/m^2)	E/(W/m^2)
1	COMET.9284	COMET.6779	0.005 853 2	0.000 854	
2	COMET.9284	COMET.6780	0.000 345 592 1	0.000 159	
3	COMET.9284	COMET.7270	0.003 559 96	0.000 625	
4	COMET.9284	COMET.7271	0.001 363 961	0.000 339	
……					5.855E-04
N-3	COMET.9310	COMET.7271	5.18E-05	2.39E-06	
N-2	COMET.9310	COMET.7272	0.009 397 84	0.000 433	
N-1	COMET.7273	0.000 536 977	0.000 248		
N	COMET.9310	COMET.7274	0.002 102 518	9.69E-05	

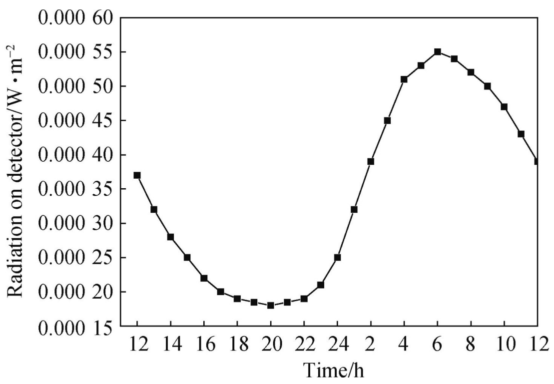

Fig.7 Radiation curve of instrument background radiation produced by primary mirror on detector in one day

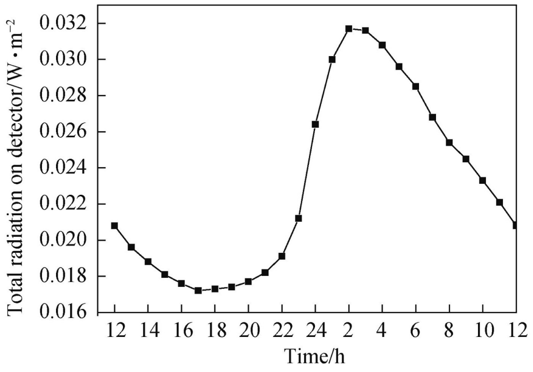

Fig.8 Total instrument background radiation curve generated by optical-mechanical components on detector in one day

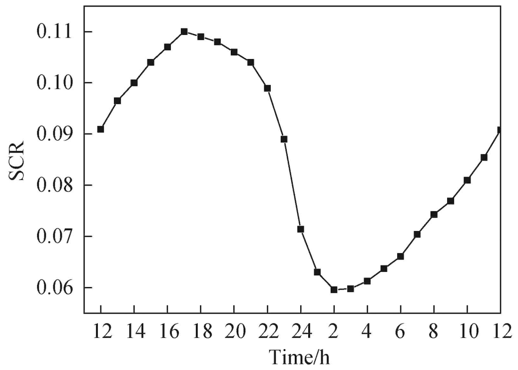

Fig.9 SCR curve formed by instrument background radiation in one day

3 On-orbit background radiation measurement

When the satellite attitude is stable to the ground, the SCR varies with the temperature field of the instrument as shown in Fig.10 according to the image data of channel 3 collected by the camera on April 12, 2017 (corresponding to the solar altitude angle of + 8.8 °). The variation range of SCR varies from 0.059 to 0.096 with time as the *x*-axis.

The instrument background radiation of Channel 3 is simulated by TRSLIM and TSLAM respectively. Table 6 shows the simulated SCR and the on-orbit SCR. 3:00, 8:00, 12:00, 15:00, 18:00 and 22:00 are selected for

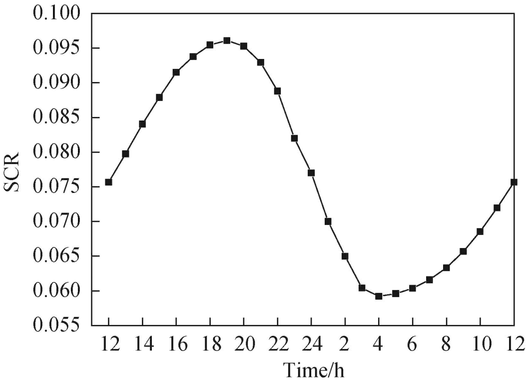

Fig.10 Variation curve of SCR at band 3 in one day

comparison, and the TRSLIM, the TSLAM and on-orbit test are compared. The error of TRSLIM and on-orbit measurement is less than 17%, and that of TSLAM and on-orbit measurement method is 114%. It can be seen that the simulation accuracy of TRSLIM is much higher than that of TSLAM.

In TSLAM, the temperature field is several characteristic temperature conditions provided by the thermal control personnel, and then these temperature fields are manually assigned to the optical and mechanical components in TracePro for background radiation simulation. It is impossible to calculate the changing temperature field in real time, and the simulation time takes one or two weeks. If TRSLIM is used, the temperature field of each optical machine element is the real-time temperature field on-orbit simulated directly by the thermal radiation stray light integrated software. Combined with the radiation factor, the instrument background radiation can be calculated directly. The simulation time is only half a day, which greatly improves the efficiency.

It can be seen that TRSLIM has two advantages over TSLAM. First, the real-time calculation of the SCR can be obtained by the temperature field changing with time. The background radiation analysis and thermal analysis is integrated into one process. Secondly, the non-uniform temperature field in orbit can be simulated. The temperature field is closer to the actual situation in orbit, and the simulation accuracy is improved greatly.

Tab.6 Comparison of SCR from on-orbit measured, TRSLIM and TSLAM

Time	On-orbit test values	TRSLIM		TSLAM	
		Simulation value	Errors from on-orbit test values	Simulation value	Errors from on-orbit test values
3:00	0.059	0.06	1.69%	0.112	89.83%
8:00	0.064	0.074	15.63%	0.13	103.13%
12:00	0.078	0.091	16.67%	0.144	84.62%
15:00	0.089	0.103	15.73%	0.189	112.36%
18:00	0.095	0.109	14.74%	0.204	114.74%
22:00	0.089	0.098	10.11%	0.179	101.12%

4 Summary

In this paper, the TRSLIM is used to analyze the instrument background radiation of on-orbit infrared camera. The approximate temperature and uniform temperature field in the TSLAM are replaced by the real temperature field which tends to be on-orbit and has a temperature gradient. Combined with the radiation transfer factor, the background radiation of the instrument and the SCR of the camera on the detector is calculated. Comparing the SCR calculated by TRSLIM and TSLAM, the error of TRSLIM is less than 17%. Compared with the TSLAM, the TRSLIM is real-time and intuitive, the calculation results are closer to the actual situation in orbit, and has higher simulation efficiency and accuracy.

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