Infrared contrast characteristic of satellites

LV Xiang-yin\textsuperscript{1,2,3}, Jin Wei\textsuperscript{1,2,3}

\textsuperscript{1}Key Laboratory of Infrared and Low Temperature Plasma of Anhui Province, Hefei 230037, China
\textsuperscript{2}Advanced Laser Technology Laboratory of Anhui Province, Hefei 230037, China
\textsuperscript{3}State Key Laboratory of Pulsed Power Laser Technology, Hefei 230037, China

Abstract. Using infrared characteristic of space target for detecting and identifying the space target is a kind of effective method. Infrared radiation contrast study of satellite has great significance for both detecting and identifying the satellite, and monitoring satellite condition. In this paper, the method to calculate the radiant heat flux of satellite is given firstly. Then, the mathematical model of the surface temperature of satellite is obtained and the numerical calculation is done. The calculated numerical data is similar to the telemetry data, which proves that the orbit flux and temperature models are correct. Finally, the infrared radiant contrast of every surface on the satellite’s body and solar panels were calculated and analyzed. The results show that, on the one hand, satellite infrared radiation in long wave infrared band is larger than that in medium wave infrared band. From the point of view of the range coverage, use the long wave infrared is more advantageous to detect satellite. And on the other hand, satellite infrared contrast in medium wave infrared band is much larger than that in long wave infrared band. From the point of view of the resolution of image detail, use the medium wave infrared is more advantageous to identify satellite.

1. Introduction

As a main space target, satellite detection and recognition has become an important research topic. The research on infrared characteristics of satellites is the basic technology for identifying and acquiring information of satellites. The calculation and analysis of satellite infrared contrast is an important part of studying satellite infrared characteristics. It has certain reference value for satellite detection to judge whether the satellite is invalid or not, and infrared recognition of true and false satellites.

For example, satellite solar panels act as generators. Its normal work is the premise of payload operation such as electronic equipment on satellite. It is of great significance to detect and judge whether the satellite solar panels are in normal working state. The change of infrared radiation characteristics of solar panels can provide an important basis for detecting and judging whether they are in normal working state. The infrared characteristics of solar panels can also provide an important reference for judging whether the satellite is invalid or not. For different surfaces of the satellite body, the infrared radiation of the payload is different when the payload is in different working conditions. However, the detection of the absolute value of infrared radiation on any surface is easy to be affected by many complex factors, resulting in errors in judgment. However, the contrast between different surfaces can provide a good basis for judging.

Up to now, there are many studies on temperature field related to satellite thermal control, and few studies on satellite infrared characteristics. In China, Shurui\textsuperscript{[1]} and Li Ming\textsuperscript{[2]} have established...
theoretical models of infrared radiation of satellites, but no numerical calculation has been carried out. Han Yuge and others have studied the infrared characteristics of satellites, especially the radiation surface[3]. Sun Chengming and others have studied the modeling methods of infrared characteristics of satellites[4-5]. Guo Ming and others have carried out infrared modeling and analysis of satellites under the background of stars simulation[6]. None of the above studies involves the infrared dynamic characteristics related to satellite orbit operation, nor the band characteristics and contrast of satellite infrared.

From the calculation of orbital heat flow, this paper presents a calculation method for calculating the transient temperature field on the satellite surface changing with the satellite orbit operation and carries out numerical calculation. By comparing the temperature calculation data with the telemetry data, the correctness of the orbital heat flow and temperature model is verified. On this basis, contrast of infrared radiation in mid-infrared band 3-5 um and far-infrared band 8-14 um between different satellite surfaces are calculated and analyzed.

2. Calculations of orbital heat flow

The infrared characteristics of satellites mainly depend on the temperature distribution of the target itself and the background radiation characteristics. And the temperature distribution depends on the energy exchange relationship between the satellite and the surrounding background besides the structure of the satellite. That is to say, it depends on the orbital heat flow, specifically solar radiation, earth reflection and earth radiation.

2.1 Solar Radiation Received on Satellite Surface

The solar radiation received per unit area of the satellite surface is

\[ E_{\text{solar}} = \zeta E_{\text{sun}} F_{\text{sun}} \]  

(1)

In the formula, \( \zeta = 1 + 0.33 \cos(360n/370) \), the corrected value caused by the distance between the sun and the earth ( \( n \) is the number of days in a year), \( E_{\text{sun}} = 1353 \text{W/m}^2 \), called the solar constant, \( F_{\text{sun}} \) the angle factor of the direct solar radiation from the target surface.

2.2 Earth Reflections Received on Satellite Surface

The solar radiation is incident on the earth and its atmosphere, and the reflected part reaches the surface of the satellite, which constitutes the reflection of the earth. In calculating the earth reflections, the earth surface should be divided into several faces, and the solar radiation reflected from each face to the satellite surface should be calculated separately. Then the solar radiation reflected from each face to the satellite surface can be superimposed to obtain the earth reflections to the satellite surface.[7]

The radiation energy density of the earth reflection radiation on a satellite surface can be deduced theoretically.

\[ E_{\text{earth}} = \rho E_{\text{sun}} \int_{-\pi/2}^{\pi/2} \frac{\sin \eta \cos \alpha_1 \cos \alpha_2}{l^2} dA_e \]  

(2)

In the formula, \( l \) is the distance between the earth surface \( dA_e \) and the satellite surface, \( \eta \) is the incident angle of the sun to the earth surface \( dA_e \), \( \alpha_1 \) is the angle between \( l \) and the earth surface \( dA_e \) normal, \( \alpha_2 \) is the angle between \( l \) and the satellite surface normal. The \( dA_e \) integral region is the visible range of the satellite surface to the earth surface irradiated by the sun.

2.3 Earth Radiation Received on Satellite Surface

In fact, the earth is an irregular sphere. In order to simplify the calculation model, we regard it as a regular sphere with a radius of 6379 km, and take the annual average of the radiant exitance of the
earth $M_{\text{earth}} = 237 \text{ W/m}^2$. The radiation energy density of the earth received from a certain surface of the satellite is as follows

$$E_{\text{earth}} = \frac{M_{\text{earth}}}{\pi} \int \cos \alpha_1 \cos \alpha_2 \, dA$$  \hspace{1cm} (3)

In the formula, the integral range of the earth surface is the visible range of the satellite surface to the earth surface.

The above radiation heat flux received by satellite will vary with the change of relative position of satellite with the sun and the earth as time goes on in orbit. It should be calculated in combination with six elements of satellite orbit and coordinate transformation which describe satellite orbit equation\[8\]. The process is rather complicated, and the process is not described in detail here.

3. Calculation of Satellite Surface Temperature

The infrared radiation of the target is determined by the surface temperature and emissivity. Emissivity is an inherent property of materials. Usually, for a specific target, once the surface material is fixed, the emissivity is determined. The surface temperature of an object is affected by various complex factors. The determination of the target surface temperature is the key to study the infrared radiation characteristics of the target.

3.1 Differential equation of heat conduction

The surface temperature of a satellite depends on its heat exchange with its surroundings and with itself. Thermal convection can be neglected in the space outside the atmosphere, so only heat conduction and radiation are considered.

The equation describing the law of temperature distribution in a heat conducting body is called a heat conduction differential equation. For satellites, the thermal conductivity differential equation is used to calculate the temperature distribution of satellites with space and time under the radiation and heat transfer boundary conditions on the outer surface, and the temperature distribution and its change with time on the satellite surface are obtained.

The heat conduction differential equation is based on the law of conservation of energy and Fourier law. Its general form in Cartesian coordinate system is as follows

$$\rho \frac{\partial T}{\partial \tau} - \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) - \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) - \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) \Phi = 0$$  \hspace{1cm} (4)

In the formula, $\rho$ is density; $c$ is specific heat capacity; $\tau$ is time; $k$ is thermal conductivity; $\Phi$ is heating power per unit volume of microelement.

3.2 boundary condition

The boundary condition guides the connection or interaction of heat exchange between the thermal object on its boundary surface and the external environment. For unsteady heat conduction, it is often the external driving force for the process to occur and develop. For any surface of a satellite, its boundary conditions can be written as

$$k \frac{\partial T}{\partial n_{\text{boundary}}} = \alpha_{\text{sun}} E_{\text{sun}} + \alpha_{\text{earth}} E_{\text{earth}} + \alpha_{\text{sun ref}} E_{\text{sun ref}} - M_{\text{out}}$$  \hspace{1cm} (5)

In the formula, $\alpha_{\text{sun}}$, $\alpha_{\text{earth}}$, $\alpha_{\text{sun ref}}$ are the absorptivity of solar radiation, earth reflection and earth radiation on the satellite surface, $M_{\text{out}}$ is the radiation energy per unit area of the satellite surface into space, $M_{\text{out}} = \varepsilon \sigma T^4$, and in the formula, $\varepsilon$ is the emissivity of the outer surface of the satellite, $\sigma$ is Stefan-Boltzmann constant.

3.3 Solution of Satellite Surface Temperature

The temperature field on the satellite surface at any time can be determined by the initial value given by the thermal conductivity differential equation and boundary conditions. In the calculation, a
a three-axis stabilized satellite is taken as an example, which is mainly composed of solar panels and satellite body. The shape of the satellite body is cuboid, and there is no heat conduction between the surfaces. Because of the complexity of the problem, the computer is usually used to solve it, and the finite difference method can be used in the process of solving it. For this reason, the satellite should be spatially discretized and divided into several discrete elements, each of which is called a node. For each node, the energy conservation equation for volume is established. The key is to establish the energy conservation equation for boundary nodes according to boundary radiation conditions. By combining the energy conservation equations of each node, the distribution of temperature field can be obtained by solving the equations.\[^9\]

For interior nodes, the difference form of thermal conductivity differential equation can be used directly. For boundary nodes, different boundary nodes have different expressions. This is because different nodes have different heat exchanges with the outside world. Specifically, according to the energy conservation method, the equations should be established one by one. By solving the equations, the temperature distribution on each surface of the satellite can be obtained. Fig. 1 shows the temperature variation of satellite solar panels with time. Fig. 1 (a) is the calculated data of two periods of satellite operation, and Fig. 1 (b) is the telemetry data of one period of satellite stable operation from literature.\[^10\]

As can be seen from Fig. 1, the temperature of satellite solar panels is related to the initial temperature during a short period of initial operation, and then the influence of the initial temperature is quickly eliminated. Thereafter, the change of temperature mainly depends on the change of orbital heat flow. The calculated values in a period after stable operation are basically consistent with the temperature variation law of telemetry data, which shows the correctness of the calculation model of track heat flow and temperature. At the same time, there is a certain deviation between the temperature calculation value and the telemetry data. This is mainly due to the limitation of the related parameters, such as material physical parameters and orbit parameters, given by the literature which provides the telemetry data, which results in the deviation between the temperature calculation value and the telemetry data.

\[
L_s = \frac{1}{\pi} \int_{\lambda_1}^{\lambda_2} e^{-\frac{c_1}{\lambda^3}} \frac{1}{e^{\frac{c_2}{\lambda^2}} - 1} d\lambda
\]

4. Computation of Satellite Infrared Contrast

4.1 Calculation of Satellite Infrared Radiation

The infrared radiation of the target is mainly composed of two parts: the emitted infrared radiation and the reflected infrared radiation. In order to simplify the calculation, the target is regarded as diffuse grey body. Since any amount of radiation can be calculated by the calculation of radianc, this paper takes the calculated value of radianc as the result.

1) Self-radiation

After calculating the temperature of a certain surface of the target, the radiation brightness of the target in the band $\Delta \lambda (\lambda_1 \sim \lambda_2)$ can be calculated as follows

\[
L_s = \frac{1}{\pi} \int_{\lambda_1}^{\lambda_2} e^{-\frac{c_1}{\lambda^3}} \frac{1}{e^{\frac{c_2}{\lambda^2}} - 1} d\lambda
\]

2) Reflective radiation
The reflection radiation of space objects to the environment is mainly composed of the direct radiation of the sun, the radiation of the earth and the reflection of the earth.

(a) Reflection of direct solar radiation

The reflective brightness of a satellite surface to direct solar radiation in the band $\Delta\lambda$ ($\lambda_1 \sim \lambda_2$) is as follows

$$L_{\text{sun,dir}} = \frac{\rho_{\lambda_2} k_{\lambda_2-\text{sun}} E_{\text{sun}} F_{\text{sun}}}{\pi}$$

In the formula, $\rho_{\lambda_2}$ is the reflectance of a satellite surface in the band and $k_{\lambda_2-\text{sun}}$ is the ratio of solar radiation energy in the band to solar radiation energy in the whole band.

(b) Reflection of Earth radiation

The reflective brightness of a satellite surface to the earth radiation is

$$L_{\text{earth}} = \rho_{\lambda_2} k_{\lambda_2-\text{earth}} M_{\text{earth}} \int \frac{\cos \theta_1 \cos \theta_2}{r^2} dA$$

In the formula, $k_{\lambda_2-\text{earth}}$ is the ratio of the earth radiation energy in the band $\Delta\lambda$ to the total radiation energy in the whole band, and $dA$ integral range of the earth surface is the visible range of the satellite surface to the earth surface.

(c) Reflection of the Earth reflection

The reflectance of indirect solar radiation from a satellite surface is as follows

$$L_{\text{unref}} = \rho_{\lambda_2} k_{\lambda_2-\text{sun}} E_{\text{un}} F_{\text{sun}} \int \frac{\cos i \cos \theta_1 \cos \theta_2}{r^2} dA$$

In the formula, $dA$ integral range is the visible range of the satellite surface to the earth surface irradiated by the sun.

The radiance of the target reflection is

$$L_r = L_{\text{sun,dir}} + L_{\text{earth}} + L_{\text{unref}}$$

In summary, the total radiation brightness of the target is

$$L = L_r + L_r$$

4.2 Analysis of Satellite Infrared Contrast

Radiation contrast is defined as the ratio of the difference between target and background radiance to background radiance. This paper mainly analyses and calculates the infrared radiation contrast between the six planes of the satellite body and the solar panels facing the sun. According to the definition, the radiation contrast between the six planes of the satellite body and the solar panels is as follows

$$C = \frac{L_i - L_s}{L_i}$$

In the formula, $L_i$ is the radiant brightness of the satellite surface, and $L_s$ is the radiant brightness of the solar panel towards the sun surface.

Figure 2 shows the calculation results of contrast in 3-5 $\mu$m bands, and Figure 3 shows the calculation results of contrast in 8-14 $\mu$m bands. From figs. 2 and 3, it can be seen that the contrast of solar panels is less than zero in most of the time, whether in 3-5 $\mu$m or 8-14 $\mu$m bands. This shows that the radiation of solar panels is higher than that of the satellite body in most of the time. However, in a part of the time, the contrast of radiation between individual surfaces of the body and the surface of solar panels will be greater than zero, indicating that the radiation of individual surfaces of the body is sometimes higher than that of the sun energy battery board. This usually happens when the surface is close to the solar direction. Because the backside scattering of the solar panel is higher than the internal scattering of the body surface, the temperature of the body surface is higher than that of the solar panel. It can also be seen from the figure that although the radiation of each surface of the satellite in 8-14 $\mu$m band is much higher than that in 3-5 $\mu$m band, the radiation contrast between
each surface of the satellite and solar panels in 3-5 \textit{um} band is more significant than that in 8-14 \textit{um} band with time. This shows that medium wave infrared imaging is more suitable for satellite imaging with higher contrast.

Fig.2 The radiation contrast of every surface on satellite’s body to the surface to the sun of solar panels (3-5 \textit{um})
(a. surface to space, b. surface to earth, c. forward surface, d. backward surface, e. left surface, f. right surface)

Fig.3 The radiation contrast of every surface on satellite’s body to the surface to the sun of solar panels (8-14 \textit{um})
(a. surface to space, b. surface to earth, c. forward surface, d. backward surface, e. left surface, f. right surface)
5. Concluding remarks
The infrared radiation of different surfaces of satellites in a certain orbit varies significantly with time, and the infrared contrast of different surfaces is also very obvious. When the infrared system can imagine the satellite, it is more advantageous to use the infrared imaging in the 8-14 $\mu$m band of long wave to increase the operating distance, but in the aspect of contrast, using the infrared imaging in the 3-5 $\mu$m band of medium wave will be easier to distinguish the shape and contour of the satellite and other details, which is conducive to further recognition of the satellite.

References
[1] SHU R, ZHOU Y P, TAO K Y. The study of infrared spectrum of space target [J]. Optical Technique, 2006, 32(2): 196-199. (in Chinese)
[2] LI M, DU X P. The analysis of infrared spectrum of space target [J]. Aircraft Design, 2011, 31(1): 67-70. (in Chinese)
[3] HAN Y G, XUAN Y M. Infrared feature of the satellite [J]. Infrared and Laser Engineering, 2005, 25(1): 119-127. (in Chinese)
[4] SUN C M, YUAN Y, ZHANG X B. Modeling of infrared characteristics of deep space target [J]. Acta Physica Sinica, 2010, 59(10): 7523-7530. (in Chinese)
[5] SUN C M, YUAN Y, HUANG Z F, et al. Modeling and simulation on infrared imaging characteristics of space target [J]. Infrared and Laser Engineering, 2012, 41(3): 563-568. (in Chinese)
[6] GUO M, WANG X W. IR modeling and simulation of space target/star and space environment [J]. Infrared and Laser Engineering, 2010, 39(3): 399-404. (in Chinese)
[7] Dan D. V. Bhanderi, Thomas Bak. Modeling earth albedo for satellite in earth orbit [C]. AIAA 2005-6465, 2005
[8] XIAO Y L. Aviation spacecraft motion model building [M]. Beijing: Beihang University Press, 2003. (in Chinese)
[9] YANG SH M, TAO W Q. Heat transfer [M]. Beijing: Higher Education Press, 2010. (in Chinese)
[10] QIN W B, CHENG H E, LI P. Thermal analysis of solar Array with rigid substrate on spacecraft in orbit [J]. Journal of Harbin Institute of Technology, 2008, 40(5): 827-831. (in Chinese)