ANALYSIS OF INFLUENCE OF THE SOLAR WINDOW'S THERMAL CHARACTERISTICS ON THERMAL STABILITY OF OPTICAL COMMUNICATION ANTENNAS

by

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Space laser communication optical antennas have very high requirements for the stability and uniformity of the temperature field. The GEO satellite-borne laser communication is affected by the violent alternating solar heat flow, which causes the thermal disturbance of the in-orbit temperature field of the extra-satellite optical antenna to become unstable. Reduce optical communication time. For this reason, the paper proposes a "sun window" as a solar spectral filter device to shield solar radiation, combined with the thermal design of the optical antenna system, based on thermal simulation analysis to study the effectiveness of the solar window to suppress the thermal disturbance of the optical antenna temperature field. The research results show that the thermal control optimization design of the optical antenna system based on the "sun window" has a significant effect in suppressing the thermal disturbance of the optical antenna temperature field: the stability of the temperature field of the primary mirror is increased by 2.2 times, the stability of the temperature field of the secondary mirror is increased by 10.6 times. The uniformity of the temperature field of the secondary mirror is increased by about ten times, and the time that meets the requirements of the stability and uniformity of the optical communication antenna temperature field can be up to 24 hours per day, which is more than three times that of the solution without the "sun window".

Key words*: GEO, solar window, laser communication, optical antenna, temperature field*

Introduction

With the urgent need for large-capacity, highresolution, and highspeed data transmission technology in spacecraft communication, space laser communication, as an emerging digital transmission technology, has large modulation bandwidth, large information capacity, vital confidentiality, and lightweight compared with current satellite microwave communications. Moreover, it is convenient for on-board operation and other advantages, a transmissionol that meets future communication development needs. The USA, Europe, and Japan, and my country have successfully implemented laser communication tests between satellites, satellites, and moons. Because the optical antenna for satellite-borne laser communication is exposed in

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space, the thermal space environment's influence on the optical system's performance has received widespread attention when it is in orbit. Some scholars have studied the influence of the satellite-borne laser communication by the thermal environment in the sunlit area and shadow area. The sun's rays will cause the wavefront distortion of the optical antenna, resulting in the displacement of the receiving spot and the beam divergence. Based on the analysis of the finite element model of the mirror, some scholars have fitted the thermal distortion of the mirror caused by the temperature gradient and uniform temperature to obtain the temperature and reflection. The relationship between aiming error and far-field power attenuation caused by mirror thermal deformation. Some scholars have pointed out that the reflector's thermal deformation will cause the transmission beam to expand and wavefront distortion, thereby deteriorating the air-to-ground laser communication link's performance. The aforementioned studies have shown that the laser communication transmission link requires an accurate phase, and the effects of the thermal space environment must be reasonably protected [1]. By controlling the stability and uniformity of the temperature field of the optical antenna, the thermal deformation is restricted to the allowable range. It can ensure the quality and time of on-orbit optical communication.

The methods commonly used for space thermal protection at home and abroad include hot or *sun windows* (solar spectral filtering devices). The fatal flaw is to block light signals. Therefore, solar windows with selective filtering are preferred, transmitting light signals and suppressing other solar spectrum heat radiation. Some scholars have used solar windows on NASA's lunar laser communication terminal to weaken the external space environment's thermal impact. Some scholars have proposed the design principle of solar window filtering, which weakens about 82% of solar radiation energy. Based on finite element analysis, solar windows' thermal and optical performance affects optical antennas' thermal stability. It obtains the best parameter design to extend the on-orbit optical communication time to 12 hours per day. However, this time is still far from the 24 hours per day continuous communication requirements of GEO satellites, and there is a lack of systematic research on the combination of solar windows and optical antenna thermal design [2]. This paper takes GEO satellite-to-ground laser communication optical antenna system as an example to research the thermal control optimization design of an optical antenna system based on a solar window, focusing on the evaluation of the solar window's effectiveness in suppressing the thermal disturbance of the space laser communication optical antenna in orbit.

Introduction optical antenna

The GEO satellite-to-ground laser communication optical antenna is used to receive and transmit optical signals between satellites and ground stations to realize satellite-to-ground communication. The optical antenna has a large aperture. The paper adopts the Cassegrain optical system design, mainly composed of a primary optical mirror, a secondary optical mirror, a telescope tube, a hood, and an antenna support structure, as shown in fig. 1.

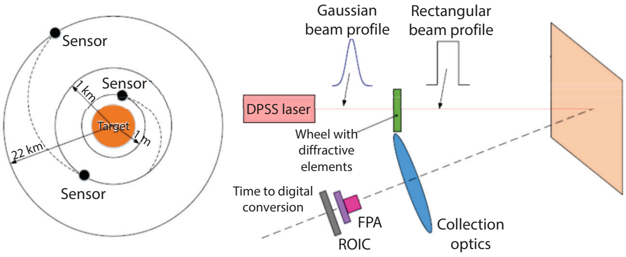

Figure 1. Schematic diagram of the composition of the laser communication optical antenna system

The optical primary and secondary mirrors are glass mirrors. The primary and secondary mirrors are assembled into an optical antenna system through a supporting structure, which is the core component for realizing optical communication and has strict temperature field stability and uniformity requirements. The temperature control indicators are shown in tab. 1.

Table 1. Temperature control index of the optical communication antenna

Operating mode	Optical primary mirror	Optical secondary mirror
Preparation mode	22.5 ±2.5 °C, the thermal difference of the primary mirror ≤2.5 °C	22.5 ±4.0 °C the thermal difference between the secondary mirror and the primary mirror ≤6.0 °C
Follow and communication mode		
Maintenance mode		

The satellite-to-ground laser communication terminal is installed on the outer surface of the satellite-to-floor-Y (north) direction, and the optical communication antenna keeps pointing to the ground. The primary source of heat in GEO space is solar radiation, and the heat flow from the satellite to the ground (optical antenna installation surface) outside the sun changes drastically, as shown in fig. 2 for seasonal changes.

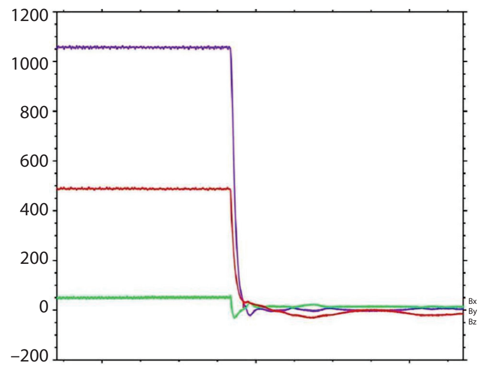

Figure 2. The heat flow curve of the GEO satellite to the ground outside the Sun

The main thermal control measures adopted by the optical antenna include: the inner surface of the hood and the telescope tube is coated with matt black paint, and the outer surface of the hood is pasted with F46 film to dissipate heat; the outer surface of the telescope tube is actively heated for temperature control and coated with multiple layers. The thermal insulation components isolate the space heat from the influence [3]. The primary optical mirror's reflective surface is treated with the metal coating with low absorption and low emission, and the temperature field controls its thermal radiation by adopting an active heating and temperature control mounting seat. The secondary optical mirror controls its heat conduction and radiation temperature through a heat protection tube that adopts active heating and temperature control. The outer surface of the heat protection tube is covered with multi-layer heat insulation components.

Thermal analysis

Thermophysical model

The GEO satellites are geostationary orbit satellites with an orientation the ground. The operating orbital parameters: orbit height $h = 36000$ km, eccentricity $e = 0$, inclination $i = 0°$, and orbit period $T = 24$ hours. Consider only solar radiation the equinox solar constant, S, is taken as 1367 W/m^2, and the maximum solar constant is 1414 W/m^2. For the GEO space environment, the only heat exchange methods are conduction and radiation. The thermal network model of an orbiting spacecraft can be simplified and described:

$$(cm)_i \frac{\mathrm{d}T_i}{\mathrm{d}t} \sum_j E_{ij} \sigma (T_j^4 - T_i^4) + \sum_j D_{ij} (T_j - T_i) + Q_{pi} + Q_{si} \tag{1}$$

where $(cm)_i$ is the heat capacity of node i, t – the time, Q_{pi} – the internal heat source of node i, Q_{si} – the external heat flow absorbed by node i, E_{ij} – the thermal radiation angle coefficient, D_{ij} – the heat transfer coefficient, σ – the Stephen Bohr Ziman constant. Based on the aforementioned thermal network model, the Monte-Carlo method calculates each node's thermal radiation angle coefficient in the simulation analysis process [4]. When solving the temperature field, based on solving the local energy conservation and global energy conservation in the area, the paper uses the control volume method to establish the discretized finite difference equation. It completes the instantaneous numerical calculation and solution of the thermal network equation.

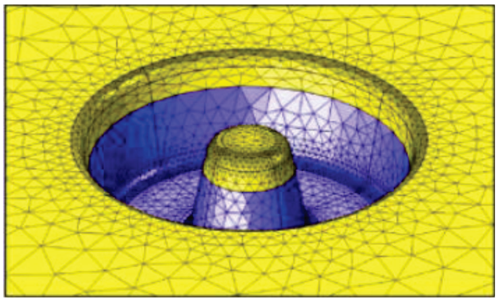

Figure 3. Finite element model of optical antenna

Thermal mathematical model

According to the optical antenna configuration and thermal design state, the paper uses the space system thermal module of the finite element software NXUG to establish the optical antenna thermal mathematical model, as shown in fig. 3. The irregular shape in the model is simplified into a regular shape according to the volume equivalent. The structural stiffeners, chamfers, screws, and gaskets are ignored, but the thermal resistance is calculated; because the optical antenna system and other connecting parts of the terminal are insulated, therefore, the mutual thermal influence is ignored in the model [5]. The *sun window* is installed between the hood and the telescope lens barrel through screw connection and heat insulation. The thermo-optical characteristics of the *sun window* are designed according to the best parameter design values. The thermophysical parameters used in the model are shown in tab. 2.

Table 2. Thermal property parameters of each component of an optical antenna

Part	Material	Density [kgm^{-3}]	Thermal conductivity [Wm^{-1}K^{-1}]	Specific heat capacity [Jkg^{-1}°C^{-1}]	Solar absorption ratio	Infrared emissivity
Primary mirror	Glass-ceramic coated metal film	2530	1.6	800	0.01	0.01
Second mirror	Fused silica	2200	1.4	891.7	0.01	0.04
Telescope tube and hood	Magnesium aluminum alloy	1900	117	921	–	–
	Matt black paint	–	–	–	0.95	0.85
		–	–	–	0.4	0.68
	Polyimide film	–	–	–	0.55	0.67
	CCAg	–	–	–	0.3	0.75
Sun window	Fused silica coated filter film	2200	1.4	891.7	0/0.178 (Transmittance)	0.8

Thermal analysis conditions

Studies have shown that in extreme hightemperature conditions at the end of its life, an optical antenna's temperature field severely exceeds the index requirement's upper limit is the bottleneck restricting optical communication. According to the change law of heat flow outside GEO space and the degradation trend of thermal control coating, the optical antenna is installed in the satellite-Y direction (north), the summer solstice and the equinox at the end of life are determined to be two hightemperature extreme conditions. In comparison, the full sun shines, and the summer solstice's thermal environment is even worse [6]. Therefore, the following study takes the summer solstice at the end of life as the background operating conditions and designs four typical thermal control states for simulation and comparative analysis, tab. 3.

Table 3. Thermal analysis conditions settings

Program	Hood	Sun window	The state of the multi-layer outer surface of the telescope tube	Calculation conditions
1	Installation	No	Polyimide film	Late summer solstice
2	Installation	Installation	Polyimide film	Late summer solstice
3	Installation	Installation	CCAg coating	Late summer solstice
4	No	Installation	CCAg coating	Late summer solstice

Result analysis

The summer solstice at the end of life

At the end of the summer solstice life, the temperature changes of the optical antenna components in Option 1 to Option 4 are shown in figs. 4 and 5. The temperature of each component is significantly affected by the external heat flow of space solar radiation. The maximum temperature peak occurs at the midnight sun's time (the maximum external heat flow). The primary mirror is greatly affected by its thermal inertia, and its maximum temperature peak appears slightly behind.

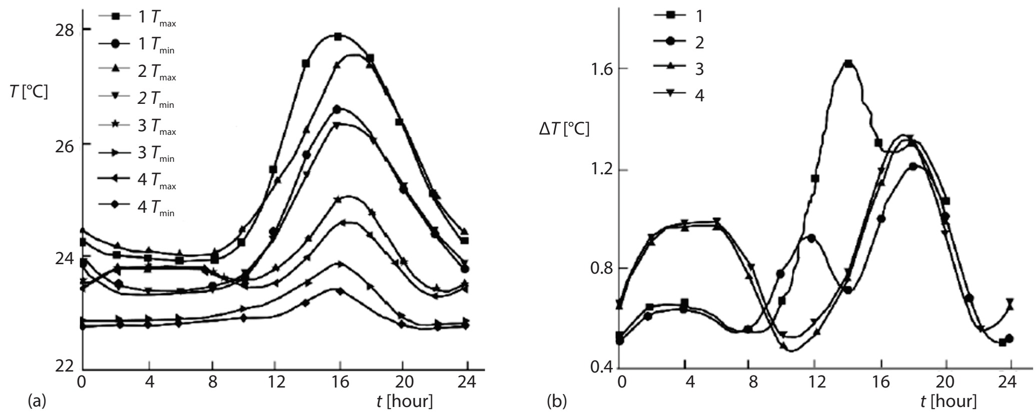

Figure 4. The temperature of the primary mirror at the end of the summer solstice (a) and the thermal difference of the primary mirror (b)

Optical primary mirror

Comparing the temperature field stability of the four schemes' primary mirror is shown in fig. 4(a). The basic scheme is not equipped with a sunny window, significantly affected by the sun's heat flow. The maximum temperature fluctuation range of the primary mirror is 3.9 °C per day, and the maximum temperature is 27.9 °C. The time exceeding the upper limit of the temperature index (25 °C) is about 11 hours. Compared with Option 1, after installing the *sun window* in Option 2 and Option 4, the fluctuation range of the primary mirror temperature is signifi-

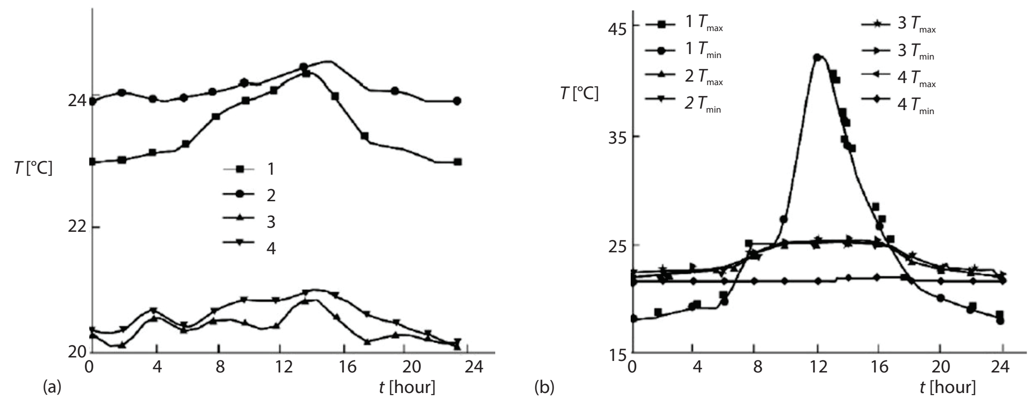

Figure 5. The average temperature of the telescope barrel (a) and the secondary mirror temperature (b) at the end of the summer solstice

cantly reduced, and the fluctuation range of Option 4 is reduced to 1 °C per day at least. It can be seen that the optical antenna is in an internal closed space after the solar window is installed, and the solar radiation in the incident optical system is effectively shielded by the solar window, which causes the thermal oscillation of the optical system to be effectively controlled. Comparing the temperature field stability of the primary mirror of Option 2 to Option 4, it can be seen that the outer surface of the multi-layer component of the telescope barrel changes from polyimide to CCAg heat dissipation coating, which meets the requirements of the temperature field stability index of the primary mirror (20-25 °C). The length of time is extended from 13 hours (Scheme 2) to 24 hours (Scheme 3 and 4). The stability of the temperature field of the primary mirror is significantly improved. The mechanism that the thermal state of the outer surface of the telescope lens barrel's multi-layer components affects the primary mirror's temperature field stability is that the telescope lens barrel is the primary channel for the optical system to dissipate heat to space. Although the sun window installation effectively shields the solar radiation, it also blocks the direct optical system [7]. Facing the cool and dark space to dissipate heat, causing the internal energy of the system to increase and raising the temperature level. When the outer surface of the multi-layer component of the lens barrel is changed from a polyimide film to a CCAg heat-dissipating coating, the solar external heat flow absorbed by the outer surface of the lens barrel is reduced, which is effective. Alleviate the insufficient heat dissipation capacity of the optical system, so the system temperature level drops and the temperature field stability is improved. Figure 4(b) compares the temperature of the telescope lens barrel of each scheme. When the multi-layer polyimide film on the lens barrel's outer surface becomes a CCAg coating, the lens barrel's temperature drops by about four °C, which can also confirm the previously mentioned mechanism analysis. It can be seen that the thermal control state of the optical system that matches the thermal, optical performance of the solar window is the key to ultimately improving the stability of the temperature field of the optical antenna.

From fig. 5(a) comparing the temperature field uniformity of the primary mirror of the four schemes, it can be seen that the thermal difference of the primary mirror of the scheme 1 to scheme four can be controlled within the index requirement of ≤2.5 °C, and the thermal difference of the primary mirror of Scheme 1 is ≤1.6 °C, the thermal difference of the primary mirror of Scheme 2 to Scheme 4 is ≤1.3 °C, it can be seen that the solar window is beneficial to the improvement of the uniformity of the temperature field of the primary mirror.

Optical secondary mirror

Figure 5(b) compares the temperature field stability of the secondary mirror of the four schemes. Due to the secondary mirror's low thermal inertia, scheme one is not equipped with a sunny window, most affected by the heat flow outside the Sun. The secondary mirror temperature can reach the highest at midnight 41.8 °C, with a considerable fluctuation range of 24 °C per day, about 10 hours beyond the operating temperature range, especially the highest severe temperature exceeding. The Scheme 2 after installing the sunny window, the stability of the secondary mirror's temperature field is significantly improved [8]. The temperature fluctuation tends to be smooth and controlled within 3.3 °C per day, which is stable at 21.7-25.3 °C, which can meet the working temperature of the secondary mirror for 24 hours. The secondary mirror's temperature field in Option 4 is the most stable, with a fluctuation range of only 0.3 °C per day. The reason is that the solar window in Option 4 is not affected by the hood's heat, and the temperature of the solar window is very stable. The heat radiation of the solar window causes the heat of the secondary mirror. The disturbance can be ignored, so the temperature field stability of the secondary mirror is better.

Optical primary mirror and secondary mirror

The paper presents the thermal difference between the primary mirror and the secondary mirror for four schemes, except that the thermal difference between the primary mirror and the secondary mirror (≤17 °C) in Scheme 1 (no *sun window*) is about 4.5 hours and enormously exceeds the optical antenna. In addition the temperature field uniformity requirement (≤6 °C), the thermal difference between the primary mirror and the secondary mirror in Scheme 2 to Scheme 4 is ≤3.1 °C, which can meet the uniformity requirement of the optical antenna temperature field within 24 hours [9]. In Scheme 4, the thermal difference between the primary mirror and the secondary mirror is the most stable (1.5-1.9 °C). It can be seen that the *sun window* has an extremely significant effect on improving the uniformity of the temperature field of the primary and secondary mirrors.

Sun window

Since the two opposite surfaces of the hood and the *sun window* have high infrared emissivity, a robust thermal radiation coupling affects each other, so the two's temperature change law tends to be the same. Affected by the large fluctuations in the hood's temperature, the sunny window temperature in Scheme 2 and Scheme 3 fluctuates substantially within –22 to +22 °C, about 40 °C per day, and the maximum thermal difference are about 14 °C. In Scheme 4, due to the sunshade's absence, the temperature of the *sun window* is stable at 0-23 °C, the fluctuation range is only 0.5 °C per day, and the maximum thermal difference is about seven °C. It can be seen that after the hood is removed, the stability and gradient of the temperature field of the solar window are significantly improved so that the stability of the temperature field of the primary mirror is increased by 2.2 times, and the stability of the temperature field of the secondary mirror is increased by 10.6 times (plan four and plan 3 Compared).

Summarizing the previous analysis results shows that only scheme three and scheme four can meet the stability and uniformity index requirements of the optical antenna temperature field 24 hours a day, tab. 1). In comparison, Option 4 performs better and is the best solution.

End of life point

For the end-of-life points and other hightemperature extreme conditions, the thermal analysis verification of the optical antenna temperature field indicators of the necessary plan one and the best plan four is carried out, and the temperature changes of the main components are shown in figs. 6 to 7. Solution 1 does not install the sunny window, and the temperature of each component is hugely affected by the heat flow outside the Sun, especially the secondary mirror is most affected by this, the temperature rises sharply during the Sun exposure, and the temperature drops sharply during the midnight shadow period [10]. The temperature field stability of the primary mirror is shown in fig. 6(a). The maximum temperature fluctuation range of the primary mirror in Option 1 is 3.4 °C per day, and the maximum temperature is 26.7° C. The time exceeding the upper limit of the temperature index (25 °C) is about 10 hours. Option 4 installing *sun windows* and optimizing the heat dissipation design of the optical system can effectively shield the thermal effects of the space. The stability of the temperature field of the main mirror is significantly enhanced, stable at 22.7-23.8 °C, and the maximum fluctuation range is about 0.6 °C per day. The temperature field uniformity of the main mirror of Scheme 1 and Scheme 4 is equivalent, as shown in fig. 6(b), the thermal difference is ≤1.15 °C, which satisfies the uniformity index requirements well.

Figure 7(a) Comparing the temperature field stability of the secondary mirror, it can be seen that the temperature of the secondary mirror fluctuates greatly by 28 °C per day in Scheme 1, and the maximum temperature reaches 44.9 °C, which is out of the working temperature range of the secondary mirror for about 16 hours. See tab. 1, which severely limits the optical communication time. In contrast, the temperature field of the secondary mirror in Scheme 4

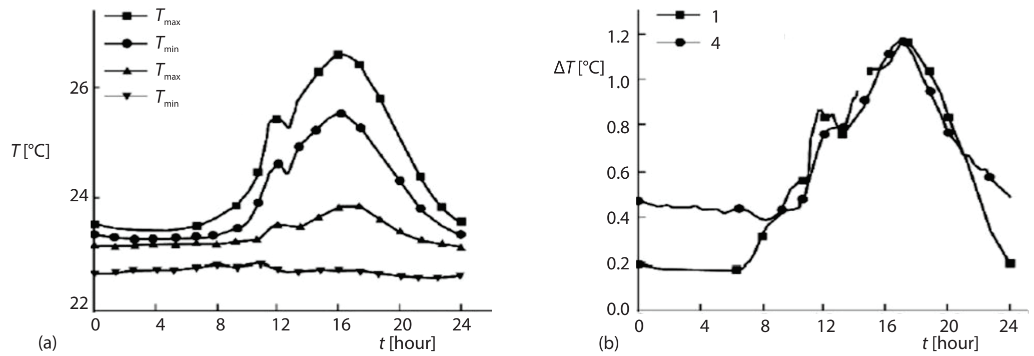

Figure 6. The temperature of the primary mirror at the final stage (a) and the thermal difference of the primary mirror (b)

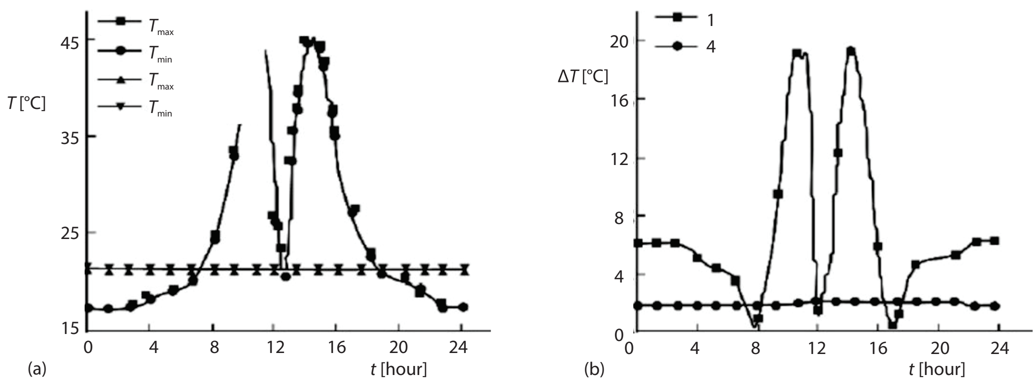

Figure 7. The temperature of the secondary mirror (a) and the thermal difference between the primary mirror and the secondary mirror (b)

is very stable, constant at 21 °C, which again verifies the efficiency of the solar window in shielding space solar radiation [11]. The thermal difference between the primary mirror and the secondary mirror is shown in fig. 7(b). The thermal difference (≤19.4 °C) between the primary mirror and the secondary mirror in Scheme 1 exceeds the uniformity index requirements of the optical antenna temperature field (≤6 °C), the thermal difference between the primary mirror and the secondary mirror in Scheme 4 is ≤2.1°C, which can meet the uniformity requirements of the optical antenna temperature field 24 hours a day. It can be seen that the sun window has an extremely significant effect on improving the uniformity of the temperature field of the primary and secondary mirrors.

In summary, at the end-of-life point, Option 4 can also meet the stability and uniformity index requirements of the optical antenna temperature field 24 hours a day.

Analysis of compliance

For the two extreme high temperature conditions at the end of life, the summer solstice and the equinox, the compliance conditions of the optical antenna temperature field for the four options are shown in tab. 4. Scheme 2-Scheme 4 affected by the *sun window*, the stability and uniformity of the optical antenna temperature field are significantly better than Scheme 1 (not installed). Scheme 3 and Scheme 4 take heat dissipation optimization measures for the optical antenna system based on the installation of the *sun window.* After that, the stability and uniformity of the temperature field of the optical antenna are completely improved, and the temperature fluctuation of the secondary mirror can be reduced from 27.7-0.3°C per day, and the temperature fluctuation of the primary mirror can be reduced from 4.6-1.0 °C per day. The thermal difference between the primary mirror and the secondary mirror decreased from 19.4-1.9 °C. Among them, the temperature field of the primary and secondary mirrors in Option 4 is the most stable, which can meet the stability and uniformity index requirements of the optical antenna temperature field 24 hours a day, see tab. 1, which is 3-4 times the optical communication duration of the basic solution.

Table 4. Compliance statistics table

Working condition	Late summer solstice	Late summer solstice	Late summer solstice	Late summer solstice	Final equinox	Final equinox
Program	1	2	3	4	1	4
Main mirror temperature [°C]	23.3-27.9	23.4-27.4	22.8-25.0	22.8-23.8	23.2-26.6	22.6-23.9
Primary mirror thermal difference [°C]	≤1.62	≤1.21	≤1.32	≤1.32	≤1.15	≤1.15
Secondary mirror temperature [°C]	18.2-41.8	22.1-25.4	22.3-25.5	21.7-22.0	17.2-44.9	21.0-21.2
Thermal difference between primary mirror and secondary mirror [°C]	≤17.0	≤3.1	≤1.9	≤1.9	≤19.4	≤2.1
Time to meet the optical antenna temperature field index [hours]	8	12.5	24	24	6.5	24

Conclusions

This paper proposes three typical conditions for thermal control design of optical antenna systems based on solar windows, combined with GEO on-orbit solar radiation limit conditions, and simulates and analyzes the thermal disturbance of the optical antenna temperature field. The results show as follows.

- Solar windows effectively shield space solar radiation at the same time, it also prevents the optical system from dissipating heat to the space, causing the increase in the system's internal energy and raising the optical antenna temperature level, which is the internal cause of the antenna temperature exceeding the limit and shortening the optical communication time.
- The outer surface of the optical system adopts multi-layer heat insulation components with CCAg coating, which can effectively reduce the external heat flow that penetrates into the system, and can alleviate the heat dissipation of the optical system. It is a two-way technology of system heat insulation and heat dissipation that matches the thermal and optical performance of the solar window.
- The temperature fluctuation of the solar window is seriously affected by the hood, which is one of the factors that deteriorate the stability of the temperature field of the optical antenna. After the hood is removed, the temperature of the solar window remains stable, which can increase the temperature field stability of the primary mirror by 2.2 times and the secondary mirror the temperature field stability is improved by 10.6 times.
- The thermal control optimization design of the optical antenna system based on the solar window has a significant effect in suppressing the thermal disturbance of the temperature field of the optical antenna in orbit, especially for the stability of the secondary mirror temperature field and the uniformity of the primary and secondary mirror temperature fields. It can be increased by about 10 times, and it can meet the requirements of the stability and uniformity of the optical antenna temperature field 24 hours a day, and the optical communication time is more than 3 times longer than that of the basic solution without a solar window.

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