The effect of temperature characteristic variation due to thermal control design on the antenna of satellite laser communication terminals

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Abstract. Cassegrain telescopes are widely used as optical antenna in satellite laser communication terminals, which are assembled outside the satellite when operating in orbit. The thermal environment in space will result in temperature variation and thermal deformation of the telescopes. Then tracking-pointing performance and communication performance will be affected consequently. So, thermal control design of telescope must be taken to make the temperature distribution vary in a certain range, which is permitted to assure the performance and stability of optics. For laser communication terminals in satellite of geosychronous Earth orbit, the effects on figure error of telescope due to three kinds of heating type of thermal control system are analyzed in this paper. It is shown that radial heating type brings the smallest figure error to telescope, followed by circumferentially-equal-area heating type. circumferentially-equal-radius heating type brings the biggest error of all. The result of this paper will bring certain reference to the thermal control design of telescopes in laser communication terminals on satellites in orbit.

1. Introduction

Laser communication system (LCS) is expected to be an important development direction for ultra-high-data-rate satellite communication because of many advantages: huge communication capability, high security, low weight and consumption [1-3]. The asymmetric temperature distribution and variation on telescope will bring thermal deformation to telescope in space, which will result in tracking-pointing performance and communication performance degradation. Usually, thermal control system is used to keep the temperature a certain range on telescope which is receptive to assure performance. So it is necessary to study the temperature distribution on telescopes and thermal aberration after thermal control. The thermal control method and type are also very important for the performance of telescopes.

Researchers began to study the thermal deformation of optics caused by variation of temperature field in 1970s. Applewhite researched the temperature distribution effect on some space cameras in 1992 [1]. Volkmei assessed the temperature features of the solar telescope in 2008 [2]. Myung *et al* analyzed the performance of TMT telescope using finite element method by the software of ANSYS and I-DEAS in 2009 [3]. Song *et al* studied the influence to the SiC reflectors in periscopic laser communication terminals due to temperature variation in 2010 [4]. Segato *et al* put forward a new theory to study the thermal deformation of space optical system in 2011 [5], while Ron *et al* [6] assessed the optical performance of astronomical telescope composed by lightweight reflectors at low

IOP Conf. Series: Materials Science and Engineering **283** (2017) 012015 doi:10.1088/1757-899X/283/1/012015

temperature.

Although many researchers focus their further studies on the thermal deformation of optics due to temperature field, no study on performance contrast of different heating methods to telescope in satellite laser communication was reported yet. Given this, we study three different heating methods to the telescope in LCS, which are radial heating method, circumferentially-equal-area heating method, and circumferentially-equal-radius heating method. For these three methods, the numerical simulation of optical performance of telescope is performed in this study.

2. Numerical analysis of the thermal deformation due to stable temperature field

2.1. Model construction

The CAD model of optical antenna and support structure are elaborated in this paper, as is shown in figure 1. The primary mirror is fixed in the base which gives around-support to the primary mirror. The second mirror is fixed by three brackets which are connected with the base with screws. For the simulation reason, the screws are not given in the model. The boundary conditions will be set instead of the screws. The primary mirror and the second mirror need to be well coaxial to keep a good imaging quality for telescopes. For the telescope of LCTs in space, the materials of the telescope are very important. For less temperature sensitivity and good mechanical property, the material of the primary mirror and second mirror is Zerodur, the material of the primary mirror base is Titanium alloy, and the material of the brackets is invar.

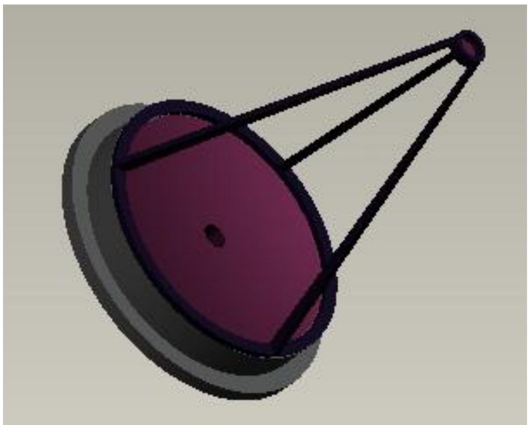


Figure 1. The CAD model of the telescope in LCT.

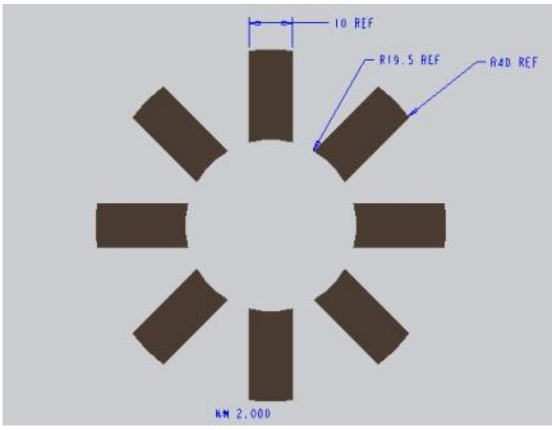


Figure 2. The model of radial heating plates.

2.2. Simulation of the figure of telescope under radial heating

The model with real size of the radial heating plates for telescope is shown in figure 2. When working in space, the environment is usually cold, although there is first order thermal control system. In this paper, the working temperature of telescope is set as 15℃ after first order thermal control for simulation. The main thermal passing progress of the telescope of LCTs in space is thermal conduction and thermal radiation. The convection is not considered in space. The solar radiation is not considered because of the cold environment to simplify the calculation. The parameter of heating plates in the simulation is set to be the temperature directly for the easy display of the temperature field. The symbol of temperature is simplified to be T in this paper. In the simulation, the environment temperature is set to be 15℃, and the value of T is between 25℃ and 29℃. The interval of temperature ΔT is set to be 0.5℃ in the analysis result. The back-uniform-heating method is used to do the thermal control for the second mirror because of its small aperture. The aimed temperature of heating is set to be 25℃.

The temperature field distribution and the reduced thermal deformation are shown in figures 3 and figure 4 under the radial heating method. It is shown from the result data, the highest temperature of the primary mirror rises from 22.6℃ to 25.8℃ as the temperature of the heating plates on the back of the primary mirror changes from 25℃ to 29℃. At the same time, the lowest temperature of the edge of the primary mirror rises from 19℃ to 20.5℃. As the temperature rises from 25℃ to 29℃, the biggest value of the deformation of surface of the primary mirror changes from 2.1 μm to 35.1 μm. Simultaneously, the smallest value of surface of the primary mirror rises from 0.71 μm to 14.1 μm.

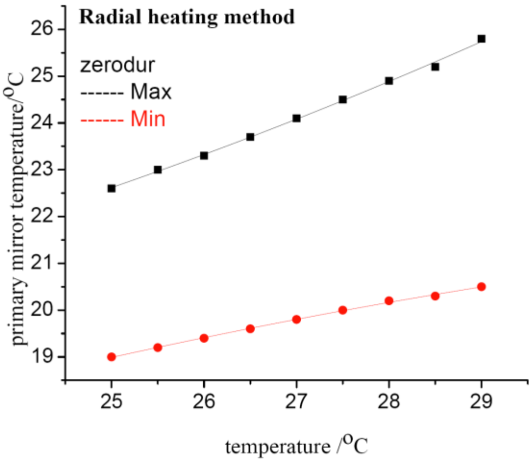


Figure 3. The temperature distribution curve of primary mirror under the radial heating method.

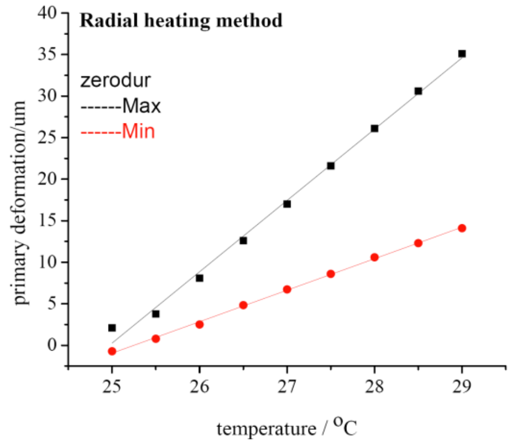


Figure 4. The thermal deformation curve of primary mirror under the radial heating method.

2.3. Simulation of the figure of telescope under circumferentially-equal-area heating method

The model with real size of the circumferentially-equal-area heating plates for telescope is shown in figure 5. The temperature field distribution and the reduced thermal deformation are shown in figures 6 and figure 7 under the circumferentially-equal-area heating method.

It is shown from the result data of figures 6 and figure 7, the highest temperature of the primary mirror rises from 22.3℃ to 25.2℃ as the temperature of the heating plates on the back of the primary mirror changes from 25℃ to 29℃. At the same time, the lowest temperature of the edge of the primary mirror rises from 19.2℃ to 20.8℃. As the temperature rises from 25℃ to 29℃, the biggest value of the deformation of surface of the primary mirror changes from 3.6 μm to 40.7 μm. Simultaneously, the smallest value of surface of the primary mirror rises from 0.2 μm to 16.4 μm.

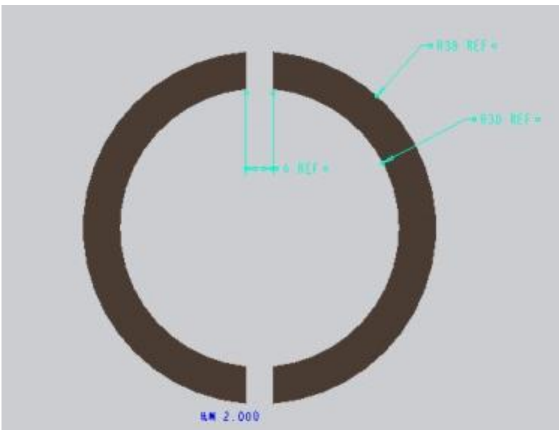


Figure 5. The model of circumferentially-equal-area heating plates.

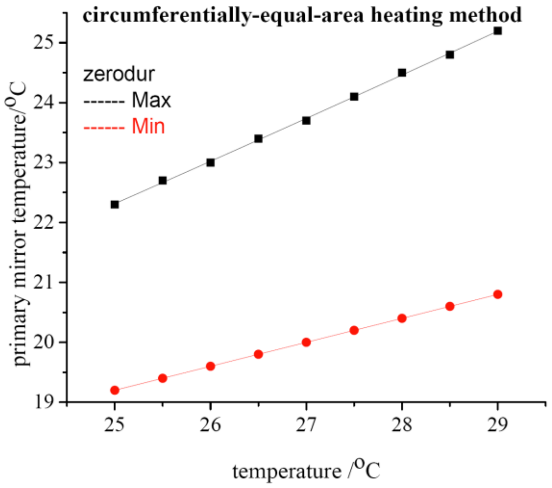


Figure 6. The temperature distribution curve of primary mirror under the circumferentially-equal-area heating method.

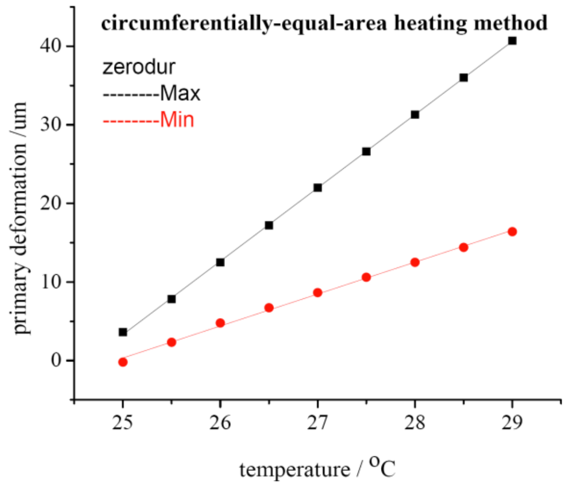


Figure 7. The thermal deformation curve of primary mirror under the circumferentially-equal-area heating method.

2.4. Simulation of the figure of telescope under circumferentially-equal-radius heating method
The model with real size of the circumferentially-equal-radius heating plates for telescope is shown in figure 8. The temperature field distribution and the reduced thermal deformation are shown in figures 9 and 10 by the circumferentially-equal-radius heating method.

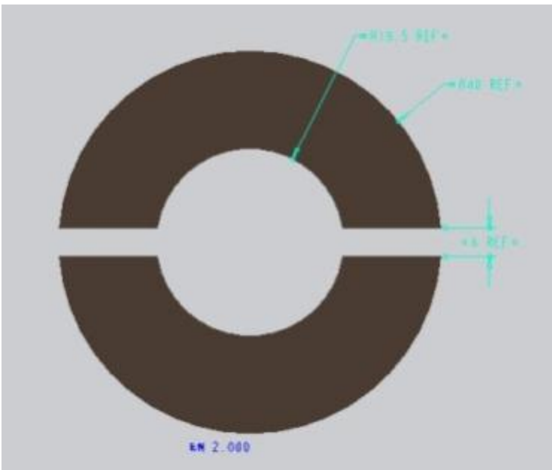


Figure 8. The model of circumferentially-equal-radius heating plates.

It is shown from the result data of figures 9 and 10, the highest temperature of the primary mirror rises from 23.2℃ to 26.5℃ as the temperature of the heating plates on the back of the primary mirror changes from 25℃ to 29℃. At the same time, the lowest temperature of the edge of the primary mirror rises to 21.5℃ from 19.7℃. As the temperature rises to 29℃ from 25℃, the biggest value of the deformation of surface of the primary mirror changes from 14.1 μm to 55.0 μm. Simultaneously, the smallest value of surface of the primary mirror rises from 5.7 μm to 23.6 μm.

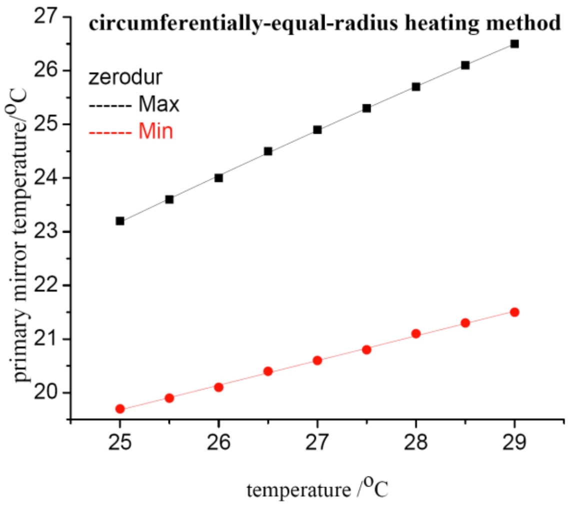


Figure 9. The temperature distribution curve of primary mirror under the circumferentially-equal-radius heating method.

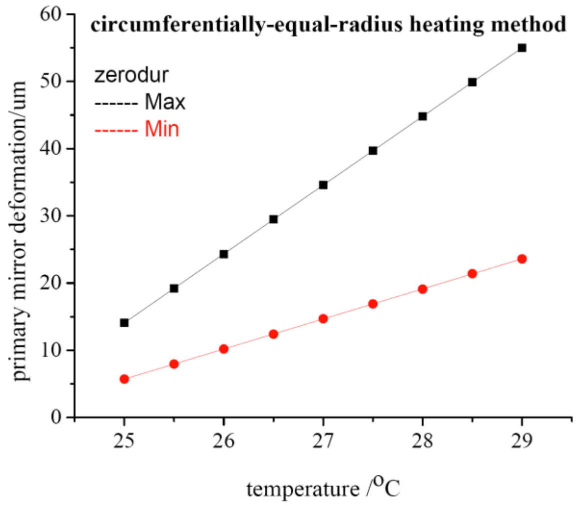


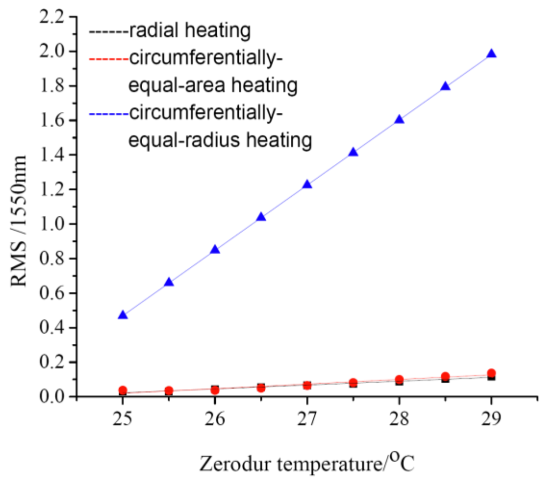
Figure 10. The thermal deformation curve of primary mirror under the circumferentially-equal-radius heating method.

3. Numerical analysis of the impact on performance of the telescope due to stable temperature field

This chapter mainly studies on the performance of the optical system with temperature variation. Because of the influence of the temperature field, the deformation of surface of the telescope occurs, resulting in the change of performance of telescope. This paper gives the wave-front aberration of telescope due to the thermal deformation under the three different heating methods above, including RMS value and P-V value. After that, the radial energy distribution and the MTF value are also analyzed.

3.1. Wave-front aberration analysis of telescope under three heating methods

Figures 11 and 12 give the RMS value and P-V value of the telescope at zero-FOV (field of view) under the three heating methods with the environment temperature being 15℃. This is because the comparability of RMS value and P-V value between different FOV values with a same wave length.



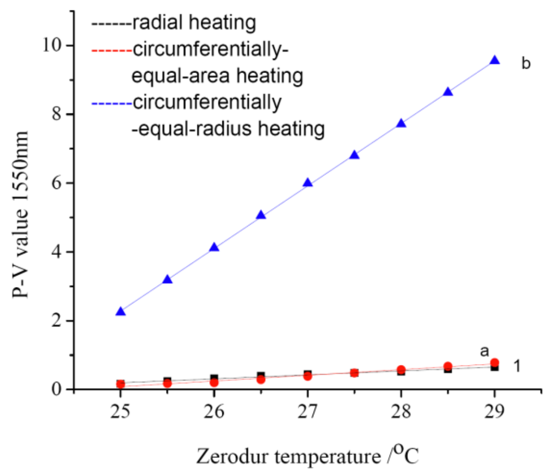


Figure 11. The RMS value variation curve at zero-FOV under the three heating method.

Figure 12. The P-V value variation curve at zero-FOV under the three heating method.

It is shown that the RMS value and P-V value are almost the same under radial heating method and circumferentially-equal-area heating method, and varies within a small range. However, the RMS value and P-V value under circumferentially-equal-radius heating method are much bigger and vary within a much larger range.

3.2. Radial energy distribution analysis of telescope under three heating methods

The reference to measure radial energy distribution is the diameter of the light which has nighty percent energy of the optical field, which is called 'shaped diameter' below. Figure 13 gives the shaped diameter variation with temperature under the three heating methods.

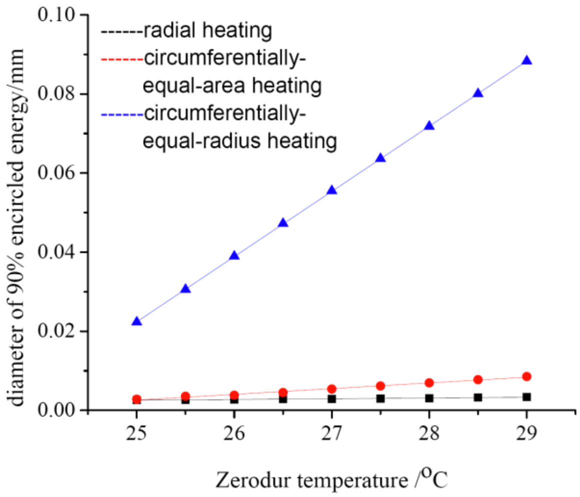


Figure 13. The shaped diameter variation curve under different heating methods.

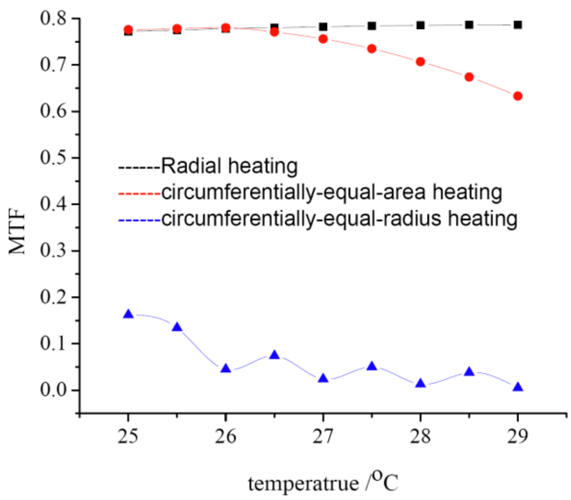


Figure 14. The MTF variation curve under different heating methods.

It is shown that the shaped diameter is almost the same under radial heating method and circumferentially-equal-area heating method when the temperature is small. As temperature grows, the difference of shaped diameter between the two heating methods becomes larger, and the circumferentially-equal-area heating method is the larger one. However, the shaped diameter of the circumferentially-equal-radius heating method is much bigger and varies within a much larger range.

3.3. MTF analysis of telescope under three heating methods

For the contrast purpose, the MTF value of the telescope is evaluated by the max space resolution of the COMS at 68lp/mm whose pixel size is 7.4 μm×7.4 μm. As the same, the MTF value of telescope at the zero-FOV is given in figure 14.

From the results, we can know that the MTF value is almost the same under radial heating method and circumferentially-equal-area heating method when the temperature is small. As temperature grows, the difference of MTF between the two heating methods becomes larger, and the circumferentially-equal-area heating method is smaller. However, the MTF value of the circumferentially-equal-radius heating method is much smaller and varies periodically.

4. Conclusions

The FEM simulation of telescope in LCTs is performed in this study using CAD and FEM software. By analyzing temperature and thermal deformation distribution, the variation result and difference of the optical performance of the telescope are given under the three heating methods. The variation regularity of optical performance is derived by different heating methods, including temperature distribution, RMS value of the surface, P-V value, shaped diameter of the light, and MTF value. It is shown that at the same temperature the radial heating method exerts the minimal effect on performance, the circumferentially-equal-area heating method is the second, and the circumferentially-equal-radius heating method has the strongest effect. We hope this work can contribute to the thermal control of telescopes in satellite laser communication terminals.

Acknowledgments
This research was supported by the National Natural Science Foundation of China (NSFC). The authors are grateful for a grant from NSFC.

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