Dimensional Stability Ground Test and in-Orbit Prediction of SiC Telescope Frame for Space Gravitational Wave Detection

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ABSTRACT Telescope is the key element of space brone gravitational wave detector. Its dimensional stability is required to be better than $1 \, \text{pm/Hz}^{1/2}$ at 0.1 mHz. And SiC is the current most likely material for manufacturing telescope with high dimensional stability. Therefore, a potential SiC telescope frame is designed and tested. In addition, in orbit dimensional stability is predicted by a numerical model. The ground dimensional stability of SiC frame is tested with a fiber-based interferometer, and the temperature change data are collected at the same time. The results of which show that when room temperature fluctuation frequency is greater than 10 mHz, the dimensional stability is about $300 \, \text{pm/Hz}^{1/2}$. A numerical model is established which is consistent with the measured data. The in-orbit dimensional stability is evaluated using the numerical model and the thermal environment of Taiji, whose numerical simulation results shows that when space temperature fluctuation frequency is about 0.1 mHz the dimensional stability would be $6.49 \, \text{pm/Hz}^{1/2}$.

I. INTRODUCTION

To achieve the goal of direct detection of low-frequency gravitational wave signals, space borne gravitational wave detection program Taiji plans to build a space laser interference link as shown in Figure 1, which is based on the Michelson interference principle [1]. In this interferometric link, the proof mass, the high-precision interferometer, and the telescope form a laser interferometer measurement system (IMS) [2], which is the core system for acquiring gravitational wave signals. In the IMS, the proof mass converts the gravitational wave signal into the variation in the distance between the two proof masses located on two spacecraft separately, the high-precision interferometer is responsible for reading out this distance variation, and the telescope is responsible for collecting the laser light coming from the remote spacecraft and sending out the local laser light to the

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remote spacecraft simultaneously to establish a stable laser transmission link [3]. The key to the detection of space-borne gravitational wave is to realize the precise measurement of the distance change between the two proof masses [4], and the total distance measurement between them can be divided into three parts: (i) the distance measurement d_1 of the proof mass to the high-precision interferometer, on spacecraft 1, (ii) the distance measurement d_{12} between the high-precision interferometers separate located on the spacecraft 1 and spacecraft 2, (iii) the distance measurement d_2 of the proof mass to the high-precision interferometer, on spacecraft 2. This means that in order to achieve highly sensitive gravitational wave signal detection, it is necessary to ensure that the d_1, d_2, and d_{12} remain extremely stable. It is worth noting that the dimension of the telescope is directly in series with the total distance measurement [4], and any change in the dimension of the telescope will translate into a change in the total distance, which in turn affects the accuracy of the interferometry.
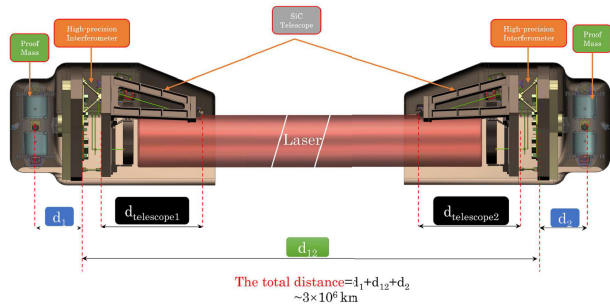
FIGURE 1. A single laser interferometric link. Telescopes are part of the link.

The gravitational wave signal is extremely weak. When the gravitational wave passes by, the variation in the distance between the two proof masses is only 30 pm even with a measurement baseline of 3×10^6 kilometers [5]. In order to keep such a small distance change from being annihilated by other noises, Taiji strictly limit the noise of each subsystem. For IMS, the noise mainly comes from the measurement noise and optical path noise and it is required to be lower than $8 \, \mathrm{pm}/\sqrt{\mathrm{Hz}}$ @0.1mHz$-$1 Hz [6]. While the optical path noise of the telescope is the main source of optical path noise of IMS, and its noise budget (NB) requirement (1) is less than $1 \, \mathrm{pm}/\sqrt{\mathrm{Hz}}$ @0.1mHz$-$1 Hz [6]. Such high optical path stability requirement brings great challenges to the material selection and structural design of the telescope.

$$NB = 12 \times \frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}} \times \sqrt{1 + \left(\frac{f_0}{f}\right)^4}, \quad (1)$$
$$0.1 \, \mathrm{mHz} \leq f \leq 1 \, \mathrm{Hz}, f_0 = 2.8 \, \mathrm{mHz}$$

where f is the measurement frequency band and f_0 is the laser frequency.

Silicon carbide (SiC) and Carbon Fibre Reinforced Polymer (CFRP) are considered to be the most likely materials for manufacturing telescope with ultra-high optical path stability because of their excellent mechanical properties and low coefficient of thermal expansion (CTE) [7]–[9]. In 2008, J.C. Machado *et al.* [10] built a dimensional stability detector based on the principle of heterodyne laser interferometry with its own stability of $1 \, \mathrm{pm}/\sqrt{\mathrm{Hz}}$. Then, they measured the CTE of the CFRP spacer with the detector and the results showed that the longitudinal CTE of the CFRP spacer was $(-2.6 \pm 0.5) \times 10^{-7}/K$, which met the requirement for building an ultra-stable telescope. However, the test did not take into account the fact that outgassing and dehydration would change the dimension of the CFRP spacer. In 2011, J. Sanjuán *et al.* [11] manufactured a CFRP telescope frame to simulate the supporting structure of the primary and secondary mirror. They used a laser interferometer to measure the overall CTE, dimensional stability and long-period outgassing effect of the frame. The test results showed that the overall CTE of the frame was $2.87 \times 10^{-6}/K$, which met the low frequency (0.1 mHz) stability requirement ($1 \, \mathrm{pm}/\sqrt{\mathrm{Hz}}$) when the ambient temperature stability was $450 \mu K/\sqrt{\mathrm{Hz}}$.

They also pointed out that the outgassing phenomenon of the CFRP would significantly affect the dimensional stability of the structure.

The effect of outgassing phenomena on the dimensional stability of the CFRP materials has led researchers to consider the potential applications of SiC [12]. In 2012, J. Sanjuán *et al.* [13] built a SiC telescope frame and tested its dimensional stability at room temperature (23°C) and space temperature (-60°C) separately. Their test results showed that the SiC telescope frame met the dimensional stability requirement ($1 \, \mathrm{pm}/\sqrt{\mathrm{Hz}}$) when the room temperature fluctuation frequency was greater than 0.5 mHz and the space temperature fluctuation frequency was greater than 10 mHz.

Although some achievements have been made in the above-mentioned researches, there are still some deficiencies. According to (2), dimensional stability $S_{x,T}^{1/2}(\omega)$ is only related to the temperature fluctuation $S_T^{1/2}(\omega)$ in a small temperature fluctuation range [10]. Meanwhile it should be noted that none of the above-mentioned experiments reproduce the fluctuation of space temperature where the telescope should be located in. Therefore, these results cannot accurately reflect the in-orbit dimensional stability of the telescope.

$$S_{x,T}^{1/2}(\omega) = l_0 \alpha(T) S_T^{1/2}(\omega). \quad (2)$$
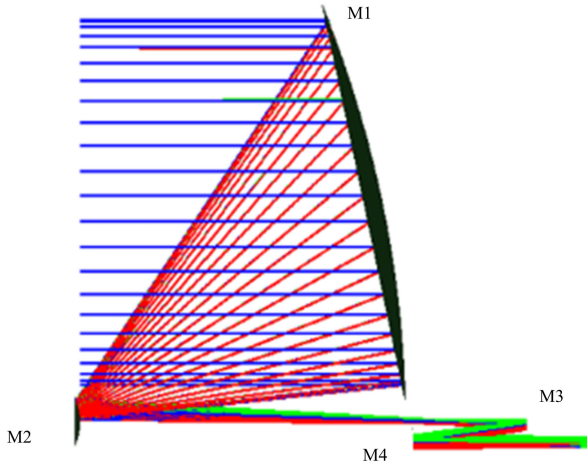
In this paper, to accurately predict the in-orbit dimensional stability of the telescope, we have carried out three aspects of work: (i) ground-based dimensional stability experiment were conducted at room temperature, (ii) a numerical model was developed and the reliability of the numerical model was verified using the results of the ground-based dimensional stability experiment, (iii) the space thermal environment was analyzed with the numerical model and the in-orbit temperature variation data and dimensional stability data of the telescope were obtained. The reliable numerical model and detailed space thermal conditions ensure the accuracy of the in-orbit dimensional stability results of the telescope. The dimensional stability of the SiC telescope frame at room temperature was tested by a fiber-based interferometer and the room temperature fluctuation data was collected simultaneously. Then, the data was imported into the numerical analysis software as the heat load to obtain the dimensional stability. The validity of the numerical analysis model of the SiC frame was verified by the correlation test between the simulation data and the experimental data. Next, through the analysis of the space thermal environment of the Taiji orbit, we got the in-orbit temperature fluctuation data of the telescope and the data was imported into the numerical model to obtain the precise in-orbit dimensional stability of the SiC telescope frame.

II. OPTICAL SYSTEM AND OPTICAL MECHANICAL STRUCTURE DESIGN OF TAIJI TELESCOPE

The Off-axis Optical system becomes the mainstream optical system design of space borne gravitational wave detection telescope due to its non-central occlusion, large magnification and strong stray light suppression ability [14]. Taiji plans
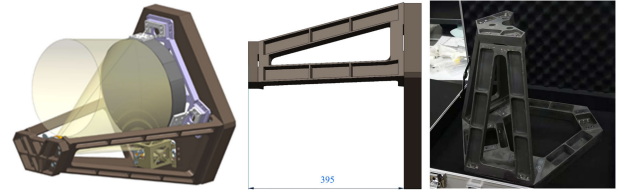
TABLE 1. Taiji telescope optical system parameters.

	Parameter	Requirement
1	Optical aperture	200 mm
2	Optical efficiency	> 0.853
3	Working wavelength	1064 nm
4	Field-of-View (spatial acquisition)	$\pm 200\,\mu$rad
5	Field-of-View (science)	$\pm 20\,\mu$rad out-of-plane $\pm 8\,\mu$rad in-plane
6	Laser beam magnification	$40x$
7	Surface Flatness	$\lambda/70$RMS ($\lambda = 1064$ nm)
8	Wavefront quality over science field of view	$\leq \lambda/30$RMS ($\lambda = 1064$ nm)
9	Scattered light	$< 1 \times 10^{-10}$ of transmitted power

FIGURE 2. Optical system design of Taiji telescope.

FIGURE 3. Optical structure design of Taiji telescope.

the secondary mirror assembly and the bottom frame carried the primary mirror assembly. The actual measuring distance between them was 395.02 mm. The distance change between M1 and M2 was the overriding source of optical path noise [15], while the dimension change of the telescope frame was the main reason that responsible for the distance change. Therefore, we could characterize the optical path stability of the telescope through the dimensional stability of the telescope frame.

III. DIMENSIONAL STABILITY TEST PRINCIPLE AND TEST SYSTEM

In this work, we used a fiber-based interferometer to measure the dimensional stability, because it could be more accurate than the Michelson interferometer in atmospheric conditions [16]. The structure of the fiber-based interferometer is shown in Figure 4. It consisted of an optical fiber collimator and a mirror with an angle to the optical axis. When a laser passed through the end face of the fiber, 4% of the laser was immediately reflected back into the fiber core to form the reference beam (E_r). While the rest 96% of the laser passed through the connector surface, reflected by the mirror to focuses on the connector surface. About 3.8% of it was reflected by the connector surface again and would finally be reflected by the mirror to focuses on the fiber core to form the measurement beam (E_m). The fields E_r and E_m are described by (3), (4).

$$E_r = A_r e^{-i\Phi_r} e^{i2\pi f_r t}, \tag{3}$$
$$E_m = A_m e^{-i\Phi_m} e^{i2\pi f_m t}, \tag{4}$$

A_r, A_m are amplitude factors, Φ_r, Φ_m are phase factors and f_r, f_m are frequency factors. The response of detector to the interferometric beam is described by (5). Since the two beams came from the same laser, we have $f_r = f_m$ and the process is homodyne interferometry. The $\Delta\Phi = \Phi_r - \Phi_m$ is phase difference between the two beams. Equation (6) describes the relationship between the change of displacement Δx and the phase difference $\Delta\Phi$. Therefore, according to the (6), Δx can be obtained whenever $\Delta\Phi$ is detected.

$$O_{Dect} = 2A_r A_m \cos\left(2\pi(f_r - f_m) \cdot t - (\Phi_r - \Phi_m)\right), \tag{5}$$
$$\Delta x = \frac{4\pi}{\lambda}\Delta\Phi. \tag{6}$$

A change in the refractive index of air affects the displacement test accuracy, and the air refractive index is affected

to use an off-axis, four-mirror-anastigmat optical system as shown in Figure 2. The primary mirror M1 is parabolic, the secondary mirror M2 is hyperbolic, and both the third mirror M3 and the fourth mirror M4 are spherical. The detailed optical system parameters are shown in Table 1. At present, the wavefront quality of the optical system can meet the task requirements, and its P-V is better than 0.0225λ and RMS is better than 0.01λ.

According to the optimization results of the optical system design, the optical structure of the telescope is shown in Figure 3. To achieve the goal of high stiffness and super lightweight, we chose silicon carbide (SiC) as the material of the telescope frame, which has a CTE of 2.281×10^{-6}/°C (Provided by the manufacturer). At the same time, to reduce the difficulty of fabrication, the SiC frame assembly was divided into three parts: bottom frame, top frame, and symmetrical double arms. Each part of the frame was manufactured separately and finally connected into a single unit by pre-embedded parts and bolts. The top frame carried
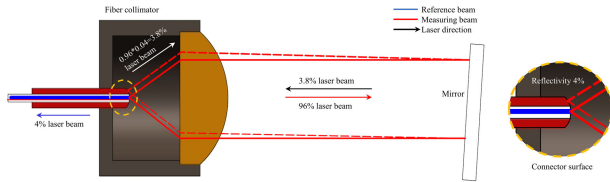
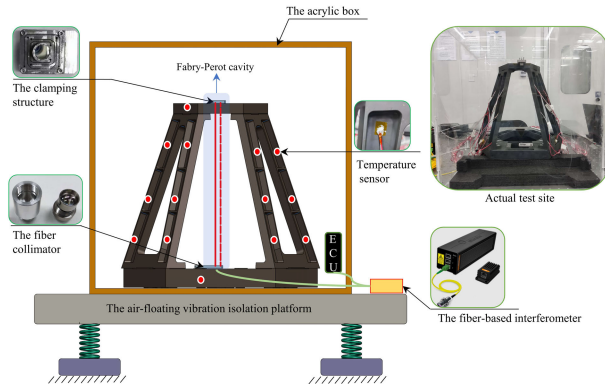**FIGURE 4.** Structure of the fiber-based interferometer.

FIGURE 5. The SiC telescope frame dimensional stability test system.

by various factors, including gas flow, temperature, humidity, and pressure [17]. Therefore, in the actual experiment, we used an acrylic box to reduce the air disturbance, while the compensation of the refractive index of air is realized by the Environmental Compensation Unit (ECU). The ECU adopts the indirect measurement of air refractive index (PTF), which calculates the refractive index of air by collecting ambient temperature, humidity and pressure data, and PTF is the most commonly used method for measuring the refractive index of air [18], [19]. According to the air refractive index, the change of laser wavelength can be calculated, and the accuracy of interferometry can be guaranteed by compensating the change of wavelength. Moreover, in order to reduce the influence of the ground vibration, the whole test system was placed on the air-floating vibration isolation platform. To form an interference path between the top frame and the bottom frame, a clamping structure was designed to hold the mirror, which was made of zero-expansion invar alloy (CTE is $0.7 \times 10^{-7}/K$) and mounted on the top frame. We placed 14 temperature sensors on the arms of the SiC telescope frame and recorded the temperature change by a temperature acquisition card. The SiC telescope frame dimensional stability test system is shown in Figure 5.

IV. RESULTS AND ANALYSIS OF THE DIMENSIONAL STABILITY OF SIC TELESCOPE FRAME AT ROOM TEMPERATURE

At room temperature, 14-channel temperature sensor data and the corresponding dimensional stability data were recorded in $10\,000\,$s. There is a small difference in temperature at different locations ($\pm 0.08°C$), but the amplitude and trend of temperature changes at each location are basically the same,
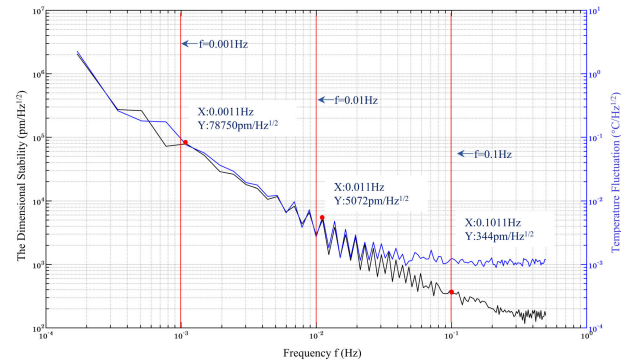

FIGURE 6. The power spectrum analysis of temperature fluctuation and dimensional stability.

so it can be considered that the telescope frame is in a uniform temperature field. Therefore, when processing the measured temperature data, we took the average of 14 groups of data as the equivalent ambient temperature. Both the temperature data and the dimensional stability data were random, required to be analyzed by the method of power spectral. As the sampling frequency of the temperature acquisition card was different from that of the fiber interferometer (which was bigger), we first unified the sampling frequency of the them before the power spectrum analysis to show the analysis results more clearly.

Figure 6 shows the results of power spectrum analysis of the temperature fluctuations and the dimensional stability. When the room temperature stability was greater than $0.0011°C/Hz^{1/2}$, the dimensional stability was better than $300\,pm/Hz^{1/2}$ for $f > 10\,$mHz. When the frequency is @$2-10\,$mHz, the dimensional stability was better than $5\,nm/mHz^{1/2}$, while when the frequency was around $0.1\,$mHz, it would be about $78\,nm/mHz^{1/2}$.

Although some measures have been taken to reduce the impact of environment on the test results which has been conducted on the ground and in the atmosphere, there are still inevitably some disturbances. In order to confirm that the room temperature fluctuation is the main cause of the dimension change in the SiC telescope frame, a correlation test was also conducted. In this work, we used the Pearson correlation test to calculate the correlation coefficient between temperature T and displacement S, as shown in (7), and we finally get the correlation coefficient ρ which was $0.990\,261\,7$.

$$\rho = \frac{\sum_{i=1}^{n}(S_i - \bar{S})(T_i - \bar{T})}{\sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2 \sum_{i=1}^{n}(T_i - \bar{T})^2}}, \quad (7)$$

$$\bar{S} = \frac{1}{n}\sum_{i=1}^{n} S_i, \bar{T} = \frac{1}{n}\sum_{i=1}^{n} T_i,$$

The relationship between the temperature fluctuation and dimensional stability is shown in Figure 6, where a linear dependence between them could be seen obviously, which is consistent with the physical law as expressed in (2).

Therefore, it could be concluded that the temperature fluctuation was the main reason for the dimension change of the SiC telescope frame. The slope of the fitting curve in Figure 7 was 9.21×10^5, and the slope divided by the equivalent length l ($l = 395$ mm) was the CTE of the SiC telescope frame, which was $2.332 \times 10^{-6}/K$.

An interesting phenomenon shown in Figure 6 is that, when the room temperature fluctuation frequency is greater than a specific value (about 2 mHz), the dimensional stability would be no longer related to the room temperature fluctuation again. To explain this phenomenon, we derived the transfer function between the room temperature fluctuation and the surface temperature of the structure. According to Newton's law of cooling, the heat flow for convective heat transfer between fluid and solid wall is:

$$\dot{q}_{air \to stru} = h \cdot (T_{air} - T_{stru}), \quad (8)$$

where the h is the heat transfer coefficient between the air and the structure affected by many factors, which is considered as a constant here. The temperature increasement of the structural surface is:

$$\dot{q}_{air \to stru} = C_{stru} \cdot \dot{T}_{stru}(t) = m \cdot c \cdot \dot{T}_{stru}(t), \quad (9)$$

the m, c are the mass and specific heat capacity of the structure respectively. From (8) and (9), we have:

$$T_{air}(t) - T_{stru}(t) = \frac{mc}{h} \dot{T}_{stru}(t). \quad (10)$$

Performing Laplace transform on the (10), we can get:

$$\widetilde{T}_{air}(s) - \widetilde{T}_{stru}(s) = \frac{mc}{h} \cdot (s\widetilde{T}_{stru}(s) + \widetilde{T}_{stru}(0)), \quad (11)$$

here $\widetilde{T}_{air}(s) \equiv \mathcal{L}[\widetilde{T}_{air}(s)]$ and $T_{stru}(0)$ is a constant, which is set to be zero. Let $s = i\omega$, we could easily get the transfer function between the room temperature fluctuation and the structure surface temperature:

$$H(\omega) = \frac{\widetilde{T}_{stru}(i\omega)}{\widetilde{T}_{air}(i\omega)} = \frac{1}{1 + \frac{1}{2\pi\beta}(i\omega)}, \quad \beta = \frac{h}{2\pi m \cdot c}. \quad (12)$$

Equation (12) is corresponding to a low-pass filter. Therefore, we could know that the dimensional stability was mainly affected by low-frequency temperature fluctuation. When the frequency exceeded a certain value, the dimensional stability measurement results were mainly affected by other noise (such as the laser frequency noise, the phase readout noise and etc.) and the measurement accuracy would be reduced at that time.

V. THE RELIABILITY VERIFICATION OF THE NUMERICAL MODEL BY THE RESULT OF GROUND DIMENSIONAL STABILITY TEST

It is well known that the space environment is quite different from the ground environment which is difficult to be fully simulated by ground-bases test equipment. According to (2), the dimensional stability of a telescope is only related to the variation of space environment temperature. Therefore,
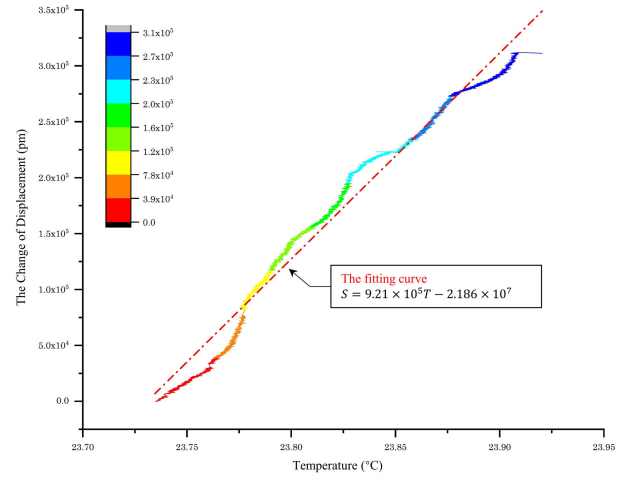

FIGURE 7. The power spectrum analysis of temperature fluctuation and dimensional stability.
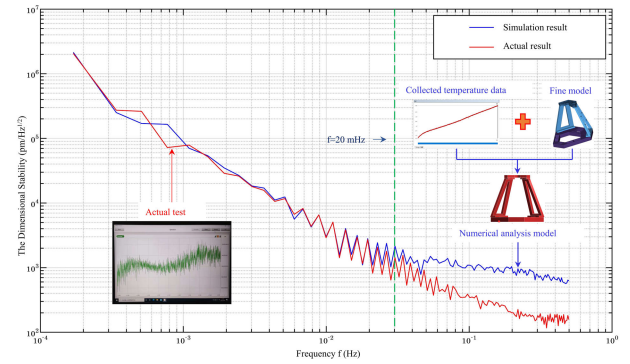

FIGURE 8. The numerical simulation result and the actual test result.

if we want to use the ground-based test equipment (space simulator) to test the in-orbit dimensional stability of the telescope, the space simulator must be able to simulate both the absolute space environment temperature ($-60°C$) and the temperature change (small change amplitude about $\pm 0.01°C$) of the space environment. However, it is difficult for the space simulator to simulate the space temperature change because of the temperature control accuracy, especially for low temperature(the control error is $\pm 1\%$).

Therefore, we used the method of numerical simulation to predict the in-orbit dimensional stability of the SiC telescope frame. However, numerical simulation could be easily affected by human factors, such as the fineness of the model and the setting of analysis parameters, which can cause deviations between the simulation results and the actual test results.

Therefore, before the in-orbit dimensional stability simulation, we first validated the reliability of the established numerical model of the SIC telescope frame. Then, the temperature data obtained from the ground-based dimensional stability test was input into the numerical model as heat load (ignoring the heat transfer process) to obtain the numerical simulation result. Figure 8 shows the comparison of the simulation result with the test result. We could see that there was no significant
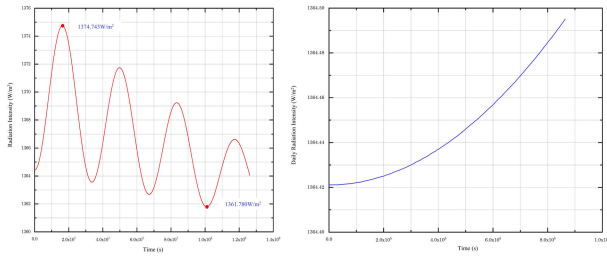
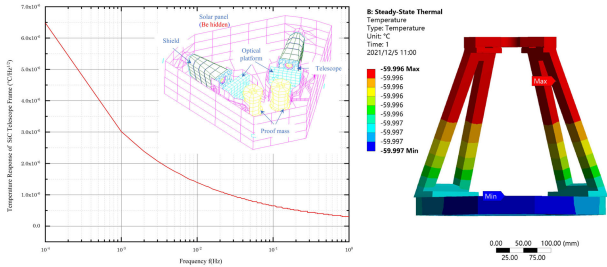**FIGURE 9.** Variation of solar radiation intensity received by Taiji satellite.

FIGURE 10. The temperature response of the telescope frame.

FIGURE 11. The prediction of in-orbit dimensional stability of the SiC telescope frame.

difference between them in the low-frequency range, which was enough to prove that the established numerical model was reliable.

VI. IN-ORBIT DIMENSIONAL STABILITY PREDICTION OF SIC TELESCOPE FRAME BY THE NUMERICAL MODEL

It is believed that there are two causes of the temperature fluctuation in the telescope frame: fluctuation in the solar constant and the power dissipation in the electronic components [20]. Also, there are two reasons that cause the fluctuation of the solar constant. One is the change in the relative distance between the satellite and the sun, and the other is the change in the intensity of sun's own radiation.

Taiji plans to launch three satellites in geosynchronous orbit and form an equilateral triangular formation with a side length of 3×10^6 kilometers [21]. Since the satellite orbit is far from the earth, the albedo of the earth can be ignored. The solar radiation intensity received by the satellite is only associated with the distance between it and the sun. Figure 9 shows the change in solar radiation intensity received by the Taiji satellite. The maximum radiation intensity at the perihelion is $1374.743\,27\,\mathrm{W/m^2}$ and the minimum radiation intensity at the aphelion is $1361.7795\,\mathrm{W/m^2}$. In addition, the variation of radiation intensity during a day is $0.08\,\mathrm{W/m^2}$ and the fluctuation frequency of radiation intensity is much less than $0.1\,\mathrm{mHz}$. It is obvious that the space thermal environment is very stable. Therefore, we could assume that the variation of the solar constant due to the distance does not affect the temperature of the telescope at all.

The fluctuations of the sun's own radiation intensity can be described by (13). According to the thermal design of Taiji at this stage, the equivalent heat flux density acting on the telescope is 0.002 times the initial solar radiation intensity.
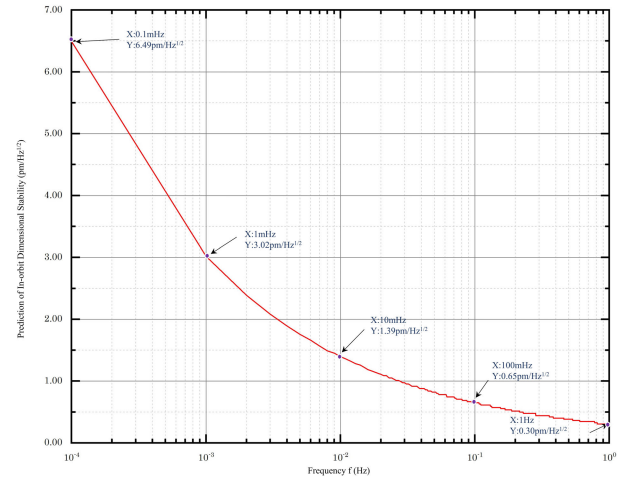
Referring to the thermal analysis program of LISA [16], we used finite element software to perform transient thermal analysis based on the equivalent heat flux variation law and steady-state thermal analysis of the telescope frame at the maximum and minimum values of the solar constant. As can be seen from the Figure 10, the temperature stability due to the solar constant variation is $6.52 \times 10^{-6}\,°C/\sqrt{Hz}$ at 1 mHz, and the maximum temperature is $-59.995\,520\,6°C$ at apogee while the maximum temperature is $-59.995\,551\,01°C$ at perigee (During this temperature range, the CTE provided by the manufacturer is $2.263 \times 10^{-6}/°C$).

$$\Delta S = 1.75 \cdot \left(\frac{f}{1\,\mathrm{mHz}} \right)^{-\frac{1}{3}} \mathrm{W}/(\mathrm{m^2} \cdot \sqrt{\mathrm{Hz}}) \qquad (13)$$

It is also worth noting that although the working state of the electronic components causes the temperature fluctuation in the telescope, we cannot simulate it accurately at this time, because the detailed spacecraft design of Taiji has not been developed and the actual power dissipation of the electronic components is also unknown. However, we can refer to the analysis results of LISA [15] by multiplying the equivalent heat flux by 1.5 to estimate the effect of the power dissipation of electronic components on the temperature fluctuation of the telescope. In this work, we obtain the in-orbit dimensional stability results of the SiC telescope frame through thermal and structural coupling analysis (as shown in Figure 11). The dimensional stability of the SiC telescope frame is $6.49\,\mathrm{pm}/\sqrt{Hz}$ when the frequency is $0.1\,\mathrm{mHz}$, and the dimensional stability is better than $1\,\mathrm{pm}/\sqrt{Hz}$ when the frequency is greater than $20\,\mathrm{mHz}$.

VII. CONCLUSION

In this work, we designed and manufactured a SiC telescope frame and measured its dimensional stability with a fiber-based interferometer at room temperature. The test results showed that the dimensional stability can reach

$300\,\text{pm}/\sqrt{\text{Hz}}@f > 10\,\text{mHz}$ when the room temperature stability is better than $0.0011°\text{C}/\sqrt{\text{Hz}}$. At the same time, we obtained the overall CTE of the frame as $2.332 \times 10^{-6}/°\text{C}$, which was close to the data provided by the manufacturer. In addition, we completed the space thermal environment analysis based on the numerical model, and the result showed that the temperature stability of the telescope was $6.5 \times 10^{-6}/°\text{C}/\sqrt{\text{Hz}}@f = 0.1\,\text{mHz}$. Finally, we predicted the in-orbit dimensional stability of the SiC telescope frame to be $6.49\,\text{pm}/\sqrt{\text{Hz}}@f = 0.1\,\text{mHz}$ through the thermal and structural coupling analysis. It is exciting that the dimensional stability of the designed SiC telescope frame in this work was very close to the requirement of Taiji. Next, we will work with the manufacturer to further reduce the CTE of SiC and complete the optical processing of the mirror to realize the direct measurement of optical path stability.

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