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Note: Silicon carbide telescope dimensional stability for space-based gravitational wave detectors

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Space-based gravitational wave detectors are conceived to detect gravitational waves in the low frequency range by measuring the distance between proof masses in spacecraft separated by millions of kilometers. One of the key elements is the telescope which has to have a dimensional stability better than 1 pm $Hz^{-1/2}$ at 3 mHz. In addition, the telescope structure must be light, strong, and stiff. For this reason a potential telescope structure consisting of a silicon carbide quadpod has been designed, constructed, and tested. We present dimensional stability results meeting the requirements at room temperature. Results at -60 °C are also shown although the requirements are not met due to temperature fluctuations in the setup. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4767247]

The field of gravitational wave astronomy and astrophysics is on the verge of taking its place alongside electromagnetic and particle astronomy and astrophysics but will provide a unique perspective on the Universe that cannot be obtained any other way. The reference mission in the last decade has been the joint ESA-NASA mission LISA[1–3] (Laser Interferometer Space Antenna). More recently, budget constraints at NASA have forced a delay in plans for a joint mission. Alternate mission designs have been explored at both ESA and NASA. These re-scoped missions are discussed under the acronyms NGO (New Gravitational-wave Observatory) at ESA[4] and SGO (Space-based Gravitational-wave Observatory) at NASA.[5] Virtually all of these new designs use LISA-like interferometry measurement systems which differ by factors of two to three in laser power and telescope diameter, orbits, mission lifetime, arm lengths, etc.

A critical element of the science interferometer is the telescope which simultaneously gathers the light coming from the far spacecraft (SC) and sends out the outgoing beam to the far SC. For LISA, the allocated noise due to the telescope dimensional instability has been set to[6]

$$S_x^{1/2}(\omega) \leq 10^{-12} \cdot \left[1 + \left(\frac{2.8\,\text{mHz}}{\omega/2\pi}\right)^4\right]^{1/2} \quad \text{m Hz}^{-1/2} \qquad (1)$$

in the LISA measurement bandwidth (MBW): from 0.1 mHz to 1 Hz. In this note we present the dimensional stability results of a potential silicon carbide (SiC) telescope spacer at room temperature and at $\simeq -60$ °C (expected operating temperature of the LISA telescope).

A possible LISA SiC telescope spacer design is shown in Fig. 1. The quadpod structure, although mechanically overdefined, was chosen to maintain a high degree of reflection symmetry along the horizontal and vertical axes to minimize the impact of the shadow on alignment sensing. Each active area of the quadrant detector will see the shadow of one strut maintaining the high degree of symmetry needed for alignment sensing. We use the simplified quadpod structure shown in Fig. 1 to test the stability of such a telescope. The four struts, the primary plate, and the secondary plate were purchased from Coorstek. The diameter of the primary is 0.475 m (in LISA the foreseen mirror is 0.4 m) and 12 mm thick. The secondary is 0.135 m in diameter (in LISA the mirror will be 0.05 m) and 7 mm thick. Several holes were machined in the primary and the secondary plates in order to install high-reflectivity mirrors to create a Fabry-Pérot cavity used to determine the stability of the spacer. Four struts 0.621 m long were placed between the primary and the secondary forming an angle of 75° resulting in a distance of $\ell_0 = 0.619$ m including the thickness of the primary and secondary plates.

The assembly of the parts was done using hydroxide-catalysis bonding[7,8] which allows for precision alignment, exhibits a good shear strength (∼5 MPa[8]) and can fill gaps in rough surfaces (<24 μm). *Sister blocks* (small blocks of size 3 mm × 4 mm × 20 mm) were used to strengthen the bonds (∼12 MPa)—see Fig. 1. The material of the *sister blocks* was also SiC and epoxy was used for the bonding (EP21TCHT-1, master bond).

The dimensional stability of the SiC telescope spacer was measured using an optical setup based on the Pound-Drever-Hall (PDH) technique.[9] PDH was used to lock one laser to the optical cavity installed in the telescope spacer. Likewise another laser was locked to a reference (Zerodur) cavity. The beat-note frequency fluctuations, $S_{\text{bn}}^{1/2}$ (in units of Hz $Hz^{-1/2}$), were used to calculate the dimensional stability, $S_x^{1/2}$, of the telescope spacer:[9] $S_x^{1/2}(\omega) \simeq (\ell_0/\nu) S_{\text{bn}}^{1/2}(\omega)$ where $\nu = 281.95$ THz (laser frequency, $\lambda = 1064$ nm). The thermo-mechanical setup is shown in Fig. 2.

Ground vibrations coupled into the telescope structure which limited the noise level of the measurements. Such vibrations were found to be at frequencies higher than the LISA MBW, specifically between 5 Hz and 100 Hz. Signals about 1 nm $Hz^{-1/2}$ were measured around 30 Hz. This should not be a problem since these fluctuations were out of the MBW, however, we could not achieve the required stability having

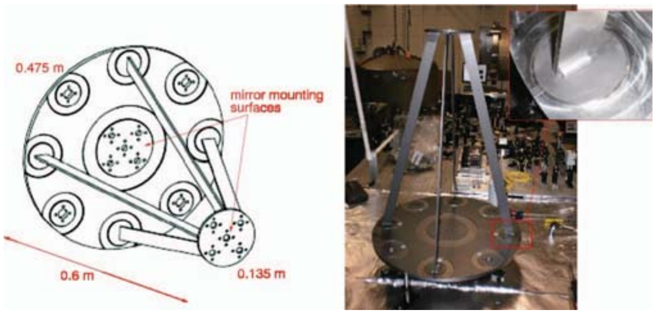

FIG. 1. Left: telescope spacer design. Right: mounted SiC telescope spacer. The inset shows one of the *sister blocks*.

such large fluctuations at high frequency due to different reasons such as aliasing in the frequency beat-note measurement (the frequency counter, HP53132A, has a sampling frequency around 1 Hz and the internal averaging does not avoid *aliasing* at the required level[10]) and pointing issues in the photodetectors. To minimize the vibrations in the telescope, a two-stage ground isolator system was installed—see Fig. 2. The first stage consisted of three commercial springs placed under the vacuum chamber which resulted in a natural resonance frequency of 1.5 Hz. The second stage consisted of a set of four blades (acting as springs) placed inside the vacuum tank that held the telescope spacer. This stage had a natural resonance frequency of 8 Hz.[11]

The dimensional stability, $S_x^{1/2}$, results are shown in Fig. 3. For the room temperature measurements the liquid nitrogen (LN) reservoir was not needed, the copper rods were removed and an extra layer of PET was added. Consequently, the temperature was much more stable. The red trace shows the measured dimensional stability where it can be seen that the requirement was met for $f \gtrsim 0.5$ mHz. The length fluctuations at frequencies below 0.3 mHz were due to temperature fluctuations [green trace, $S_T^{1/2}$] which were converted to length as

$$S_{x,T}^{1/2}(\omega) = \ell_0 \alpha(T) S_T^{1/2}(\omega), \qquad (2)$$

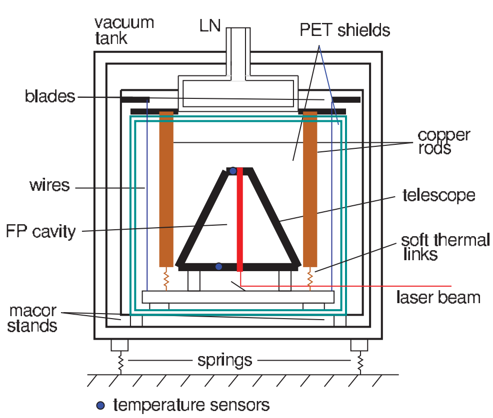

FIG. 2. A two-stages suspension system (springs + blades) was installed in order to decouple the telescope from ground vibrations. The telescope was surrounded by polyethylene terephthalate (PET) shields in order to achieve a benign thermal environment. A 25-liter LN reservoir was thermally linked to the telescope by means of four copper rods in order to be able to cool it. Temperature sensors were attached to the spacer. The pressure was kept at $\simeq 5 \times 10^{-5}$ Pa.

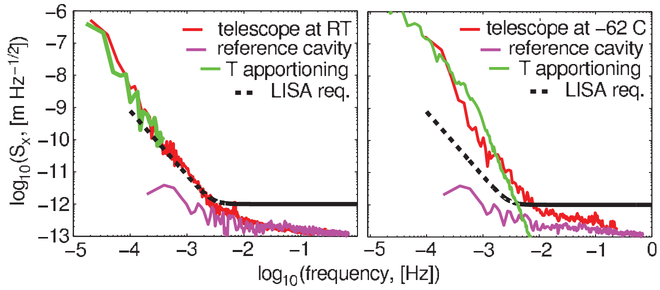

FIG. 3. Left: dimensional stability results at room temperature. Right: *idem* at −62 °C.

where the coefficient of thermal expansion is $\alpha(25^\circ\,\mathrm{C}) = 2.34 \times 10^{-6}\ {}^\circ\mathrm{C}^{-1}$. For frequencies higher than 0.3 mHz the noise of the temperature sensors did not allow us to ensure that the length fluctuations from 0.3 mHz to 3 mHz were also due to temperature fluctuations, however, the fact that they follow the same trend as the temperature fluctuations for $f < 0.3$ mHz might indicate the same origin. The magenta trace shows the stability of the reference cavity and represents the noise limit of the measurement. At high frequencies ($f \gtrsim 3$ mHz) the measurement was limited by technical noise in the PDH technique.[9,12]

The results at −60 °C are shown in Fig. 3 (right panel). In this case the dimensional stability requirement was only met for $f \gtrsim 10$ mHz. At lower frequencies the temperature fluctuations were too high to meet the LISA requirements. In this measurement the LN reservoir was linked to the telescope structure by means of the copper rods. This, of course, degraded the temperature stability in the telescope which prevented it from reaching the required dimensional stability—see Fig. 4 [green trace, (v)]. The red trace in Fig. 3 (right panel) shows the length stability measurement using the beat-note signal and the green trace shows the effect of the temperature where $\alpha(-60\ ^\circ\mathrm{C}) \simeq 1.3 \times 10^{-6}\ \mathrm{K}^{-1}$. The discrepancy between the red curve and green curve comes from the fact that they were measured at different times and in slightly different conditions.

The analysis of the temperature stability during the experiments at room temperature and at −50 °C is shown below since temperature fluctuations were the main disturbance at low frequencies (milli-Hertz). Figure 4 shows the temperature stability of the LN reservoir when it was full (blue trace) and the temperature stability of the telescope structure at −50 °C (red trace) where the temperature sensors noise prevents to measure the actual temperature fluctuations above 1 mHz. However, from these data the transfer function between temperature fluctuations of the reservoir and the telescope can be easily estimated (black trace) for frequencies below 1 mHz. The experimental transfer function, $H_T(\omega)$, corresponds to a third-order low-pass filter with a cut-off frequency of 0.22 mHz ($\tau = 700$ s). From $H_T(\omega)$ and the temperature fluctuations of the LN reservoir (they are not limited by temperature sensor noise for $f < 30$ mHz) the expected temperature stability in the telescope can be estimated and its effect on the dimensional stability is shown in Fig. 3 (right panel, green trace).

Figure 4 summarizes the temperature stability and transfer functions involved in the measurements: curve (i) is the

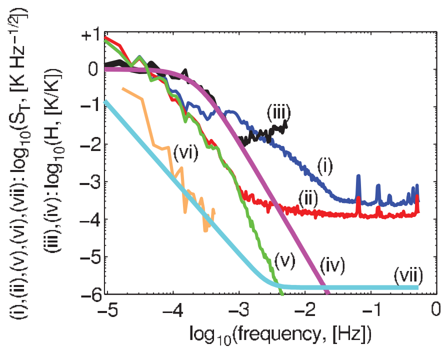

FIG. 4. Temperature stability and transfer functions in the telescope. See text for details.

temperature stability of the LN reservoir when its temperature is $-140\,^{\circ}$C, i.e., full of LN. The temperature sensor noise limits the measurement for $f > 30$ mHz. Curve (ii) is the temperature stability of the telescope (temperature sensor noise shows up for $f > 1$ mHz). Curve (iii) is the temperature transfer function between the LN reservoir and the telescope and curve (iv) is the fitted model. Using curves (iv) and (i) we can estimate the temperature fluctuations in the telescope: this is shown in curve (v). Curve (vi) shows the temperature fluctuations of the telescope at room temperature. Curve (vii) shows the required temperature stability at $-60\,^{\circ}$C.

In summary, the dimensional stability of a SiC on-axis telescope structure has been measured at room temperature and at $-60\,^{\circ}$C. The LISA requirement has been demonstrated at room temperature for $f \gtrsim 0.5$ mHz. At lower frequencies the temperature stability of the setup was not good enough to meet the requirement. At $-60\,^{\circ}$C the dimensional stability met the requirement for $f \gtrsim 10$ mHz. In these measurements the temperature stability limited the measurements for $f < 10$ mHz. However, the expected temperature stability in space-based gravitational wave detectors will be at least three orders of magnitude better and thus the spacer should meet the requirement.[9]

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