Silicon Carbide telescope investigations for the LISA mission

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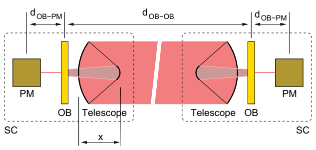
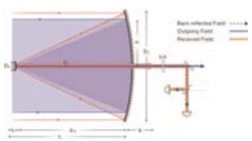
Abstract

Space-based gravitational wave (GW) detectors are conceived to detect GWs in the low frequency range (mili-Hertz) by measuring the distance between free-falling proof masses in spacecraft (SC) separated by 5 Gm. The reference in the last decade has been the joint ESA-NASA mission LISA. One of the key elements of LISA is the telescope since it simultaneously gathers the light coming from the far SC ($\simeq$100 pW) and expands, collimates and sends the outgoing beam (2 W) to the far SC. Demanding requirements have been imposed on the telescope structure: the dimensional stability of the telescope must be $\simeq$1 pm Hz$^{-1/2}$ at 3 mHz and the distance between the primary and the secondary mirrors must change by less than 2.5 μm over the mission lifetime to prevent defocussing. In addition the telescope structure must be light, strong and stiff. For this reason a potential on-axis telescope structure for LISA consisting of a silicon carbide (SiC) quadpod structure has been designed, constructed and tested. The coefficient of thermal expansion (CTE) in the LISA expected temperature range has been measured with a 1% accuracy which allows us to predict the shrinkage/expansion of the telescope due to temperature changes, and pico-meter dimensional stability has been measured at room temperature and at the expected operating temperature for the LISA telescope (around -65^{o}C). This work is supported by NASA Grants NNX10AJ38G and NNX11AO26G.

Requirements, design and construction

Alternative Cassegrain quadpod on-axis design:





Requirements

- Noise budget: $S_x^{1/2}(f) \leq 1\,\text{pm Hz}^{-1/2}\sqrt{1+\left(\frac{2.8\,\text{mHz}}{f}\right)^4}$ $\quad 0.1\,\text{mHz} < f < 1\,\text{Hz}$
- Long-term dimensional stability: $\Delta x \leq 2.5\,\mu$m
- CTE required $<10^{-6}\,\text{K}^{-1}$
- Material needs to be strong, stiff and lightweight: Silicon Carbide

Objectives

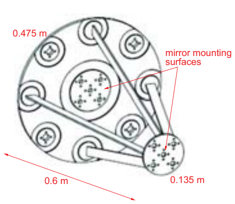
- Measurement of the dimensional stability at room temperature and at -65^{o}C
- CTE characterization from $+25^{o}$C to -60^{o}C
- Stray light investigation —see G. Mueller and Aaron Spector poster (Back-reflection from an on-axis telescope for space-based gravitational wave detectors)

SiC properties (properties are vendor dependent)

- Low coefficient of thermal expansion (CTE): $\simeq 2\times10^{-6}\,\text{K}^{-1}$ (at room T)
- High thermal conductivity: 100 to 200 W m^{-1} K^{-1} (at room T)
- Low porosity: 0% (up to a few %)
- Good strength weight/ratio

Design: quadpod structure

- Four struts to prevent measurement errors in the quadrant photodetectors
- Diameter primary: 0.475 m (mirror 0.4 m)
- Diameter secondary: 0.135 m (mirror $\sim$0.05 m)
- Distance primary-secondary: 0.6 m
- Several holes machined to place Michelson interferometers and Fabry-Pérot cavities to determine longitudinal and angular stability of the structure

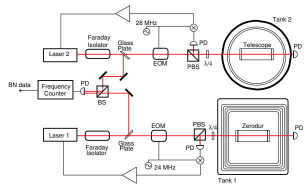


Dimensional stability: set-up and results

Optical set-up

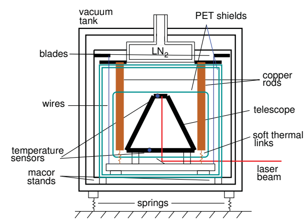
- Fabry-Pérot between primary and secondary of the telescope spacer ($\mathcal{F} \approx$600)
- Laser locked to the cavity (PDH)
- Beat-note between reference cavity (Zerodur) and telescope cavity

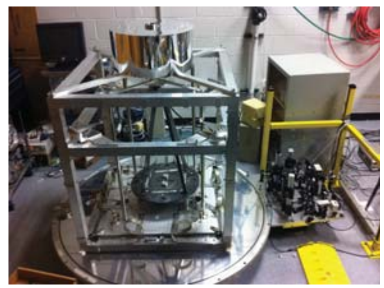
$$\delta x \propto \delta f_{\text{BN}}$$



Mechanical set-up

- Vacuum chamber and PET shells surrounding the telescope
- LN_2 reservoir (and thermal links) to cool to -60^{o}C
- Two-stage ground isolator system



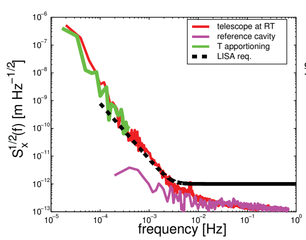


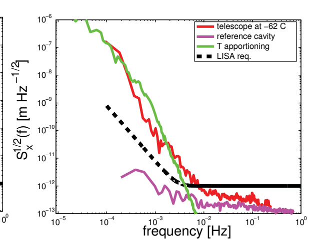
Room temperature results

- Requirement met for f >0.3 mHz
- f <2 mHz: length fluctuations due to temperature fluctuations ($\delta x = \ell_0 \alpha(T)\delta T$)

Results at -62^{o}C

- Requirement met only for f >10 mHz
- For f >10 mHz temperature fluctuations drive the length fluctuations due to the copper rods linking LN_2 reservoir to the telescope spacer





- The expected temperature in LISA is expected to be at least one order of magnitude than the one achieved during the experiment at -62^{o}C and thus the spacer should meet the dimensional stability requirement since unexpected behavior (due to bonding, inhomogeneities, etc.) has not been detected

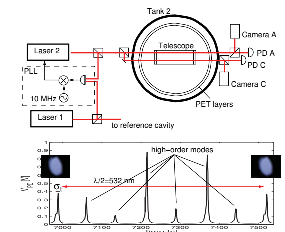
Coefficient of thermal expansion: set-up and results

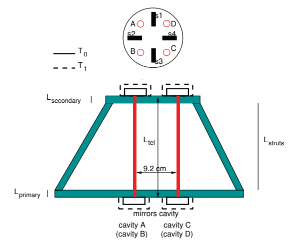
Thermal expansion (contraction) is responsible for two critical issues:

- Sets the required telescope temperature stability during science model
- Determines the shrinkage of the telescope when it is cooled from room temperature to its operating temperature

Set-up

- Two Fabry-Pérot cavities installed in the telescope spacer: the change in length is measured by monitoring the 00-modes in the transmitted light of the cavities (by means of cameras and photodetectors): $\Delta x_{00} = \lambda/2 = 532$ nm
- The laser is locked to the a reference laser by means of a phase-lock loop to avoid errors due to laser frequency drifts
- The temperature of the four struts is measured with Pt-1000 sensors with noise levels of 0.5 mK
- The sensors are calibrated between them with an accuracy of $\pm 0.05^{o}$C over the measured range
- One of the four temperature sensors is used as a reference and the other three follow the former using heaters attached to the struts. The temperature of the fours struts is kept within the calibration accuracy ($\pm 0.05^{o}$C)





Results

The estimated CTE is :

$$\widehat{\alpha}(T) = (1.207 \pm 0.015)\times10^{-6}T + (2.039 \pm 0.003)\times10^{-6}, \quad -50^{o}\text{C} \leq T \leq 25^{o}\text{C}$$

which implies that the telescope temperature stability must be

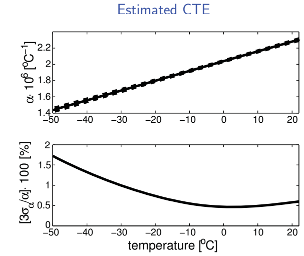
$$\widetilde{\delta T}(f) = 1.32\,\text{K Hz}^{-1/2}\sqrt{1+\left(\frac{2.8\,\text{mHz}}{f}\right)^4} \qquad 0.1\,\text{mHz} < f < 1\,\text{Hz}$$

The expected temperature stability is 35 μK Hz$^{-1/2}$ at 0.1 mHz and rolling-off as f^4 which is compliant with the required stability. The estimated shrinkage of the telescope is

$$\Delta x = \int_{+25^{o}\text{C}}^{-65^{o}\text{C}} \widehat{\alpha}(T)dT = -100.14 \pm 0.8\,\mu\text{m}$$

where the uncertainty is less than 2.5 μm which rise to the hope that the telescope could be constructed on ground in a way that it is in focus during science operations if the operating temperature can be predicted well enough ($\pm 2^{o}$C).

Estimated CTE



Δx error