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# Thermal distortion dynamics of the HartRAO Lunar Laser Ranger optical telescope: impacts on pointing, characterisation and modelling


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## Abstract

Currently Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa is developing a Satellite/Lunar Laser Ranger (S/LLR) based on a 1 metre aperture telescope. This is done in collaboration with the National Aeronautics and Space Administration (NASA) and the Observatoire de la Côte d'Azur (OCA). The S/LLR is required to make ranging observations with sub-centimetre level accuracy. Various components of the S/LLR are currently being integrated, coupled with the development of operating models for the telescope. This includes, for example, the pointing and thermal dynamic models which depend on temperature variations within the telescope. In particular, this study aims to develop a model based on thermal measurements of the structure, as thermal effects adversely influences the pointing of the telescope. Excellent pointing will increase the chance of being on-target to the retroreflectors located on the lunar surface. As the first step, we present simulation results through the use of transient heat conduction on the thermal behaviour of the telescope, in particular the tube and primary mirror. The results reveal a temperature gradient of about 1 ºC, which means that both the tube and especially the mirror may respond very slowly to ambient temperatures ($T_\infty$). Furthermore, the simulation produced a similar temperature gradient on the tube and mirror for rapidly changing ambient temperatures with a range of 13 ºC. These findings provide an indication of the thermal behaviour of the telescope's critical components with respect to the changing thermal environment, guides the installation locations of the thermal sensors on the telescope, and provide options for developing a thermal dynamic model which would correct for thermal variations that affect the pointing of the telescope.


## 1. Introduction

Over the past 40 years, the placement of corner cube retroreflector (CCR) arrays on the lunar surface led to the evolution of the lunar laser ranging (LLR) technique, which provides high-precision distance measurements between the Earth and Moon. Currently the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in South Africa is developing a Satellite/Lunar Laser Ranger (S/LLR) based on a 1 metre aperture Cassegrain telescope. This development is done in collaboration with the National Aeronautics and Space Administration (NASA) and the Observatoire de la Côte d'Azur (OCA). The HartRAO S/LLR is required to make ranging observations with sub-centimetre level accuracy. Various components of the HartRAO S/LLR are currently being integrated, coupled with the development of operating models for the telescope. This includes, for example, the pointing and thermal dynamic models which depend on the temperature variations on the telescope [1]. In particular, this study aims to develop a model based on thermal measurements of the structure, as thermal variations of the structure affect the pointing of the telescope. We want to utilise our thermal model to correct for the various related deformations of the telescope in order to effectively counteract resulting pointing offsets. As the first step, we present simulation results on the analysis of thermal gradients and the related deformations on the telescope tube and primary mirror (Figure 1).

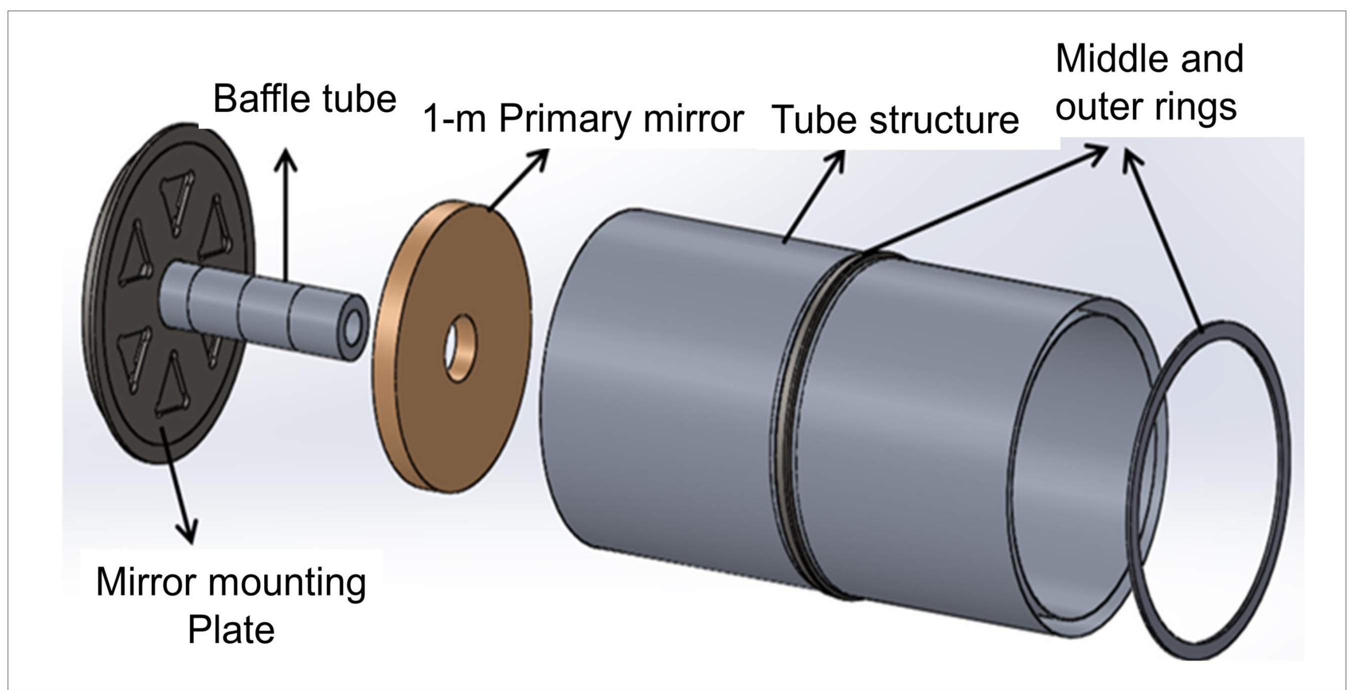


**Figure 1:** An exploded view of the tube system of the HartRAO S/LLR showing various related structural components.

## 2. Thermal properties of the material

Table 1 lists the selected thermal properties [2] of the telescope tube and mirror (Figure 1) that were critical input parameters during thermal analysis conducted in this study.

**Table 1:** Selected Material properties used in these simulations.

| | Primary Mirror (Zerodur) | Tube (Aluminium) | Mirror mounting plate (Stainless steel) |
|---|---|---|---|
| Thermal Conductivity λ [$Wm^{-1}K^{-1}$] | 1.46 | 247 | 14 |
| Specific heat $C_p$ [$J.kg^{-1}K^{-1}$] | 820 | 900 | 490 |
| Coef. Therm. Expansion [$ppm.K^{-1}$] | 0.10 | 23.6 | 17.3 |
| Density *p* [$kg.m^{-3}$] | 2500 | 2700 | 7850 |

## 3. Methodology

### 3.1. Analysis of thermal gradients

A temporal analysis of thermal gradients ($\Delta T$) on the telescope components, specifically the tube and 1 m primary mirror, was performed using the transient heat conduction option of the ANSYS software. Both the tube and mirror were subjected to an initial temperature ($T_i$) of 9 ºC and subsequently exposed to varying ambient temperatures typical of the HartRAO site ($T_\infty$) during the time period 00:00 and 11:30 am. For conduction, we assumed stationary air around the telescope components by adopting a constant heat transfer coefficient of 0.025 $W/m^2C$. This analysis provided insight into the conduction heat transfer rate and $\Delta T$ across the telescope tube and mirror. Further, this analysis was extended to estimate the thermal deformations of the respective telescope components as a result of $\Delta T$.

### 3.2. Analysis of structural deformations

The analysis of thermal deformations of the telescope tube and mirror were primarily based on material length and volume changes due to thermal gradients, expressed as $\alpha_l \Delta T$ and $\alpha_v \Delta T$ respectively [3]. In particular, the symbol $\alpha_l$ represents the linear coefficient of thermal expansion (CTE) and represents the amount of strain on a material with a change in temperature. The symbol $\alpha_v$ represents the volume CTE (the extent to which the volume of a material changes subject to $\Delta T$). This analysis was conducted using the ANSYS software package to provide a spatial and temporal indication of the thermal structural deformations including the resulting displacements in the x, y and z directions.

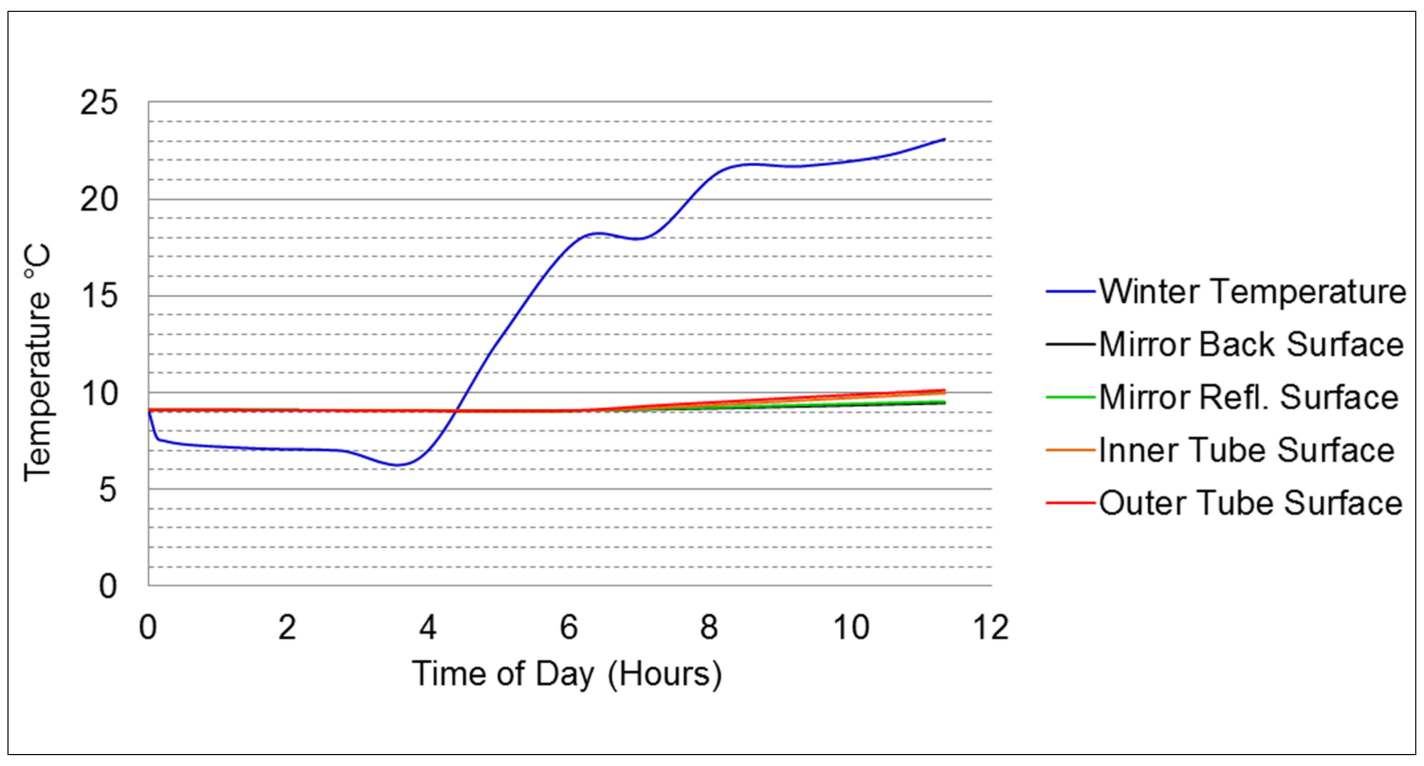


**Figure 2.** Thermal gradients on the tube and mirror surfaces in relation to ambient temperatures. These gradients were picked from Figure 3a only for the aforementioned surfaces.

## 4. Results

### 4.1. Analysis of thermal gradients

The results (Figure 2 and Figure 3a) reveal a structural temperature gradient of about 1 ºC, which means that both the tube and especially the mirror may respond very slowly to $T_\infty$. Further, the results show similar temperature gradients on both components for rapidly changing ambient temperatures with a range of ~13 ºC (Figure 2). These results could be used to guide the development of a dynamic thermal model for estimating the thermal variations of the HartRAO S/LLR telescope structure with respect to the varying environmental factors at the site.

### 4.2. Analysis of thermal deformations

The thermal analysis results presented in Section 4.1 were further used to estimate the structural deformations specifically on the tube, optical mirror and its contact surface i.e., mounting plate (Figure 3b). Figure 3b suggests total deformation in the range 2.9 µm to 40.7 µm during the time period 00:00 and 11:30am in this simulation. In particular, the resistance against $\Delta T$ of the mirror (Table 1) results in very minimal localised deformations of the mirror as well as its mounting plate (Figure 3b).

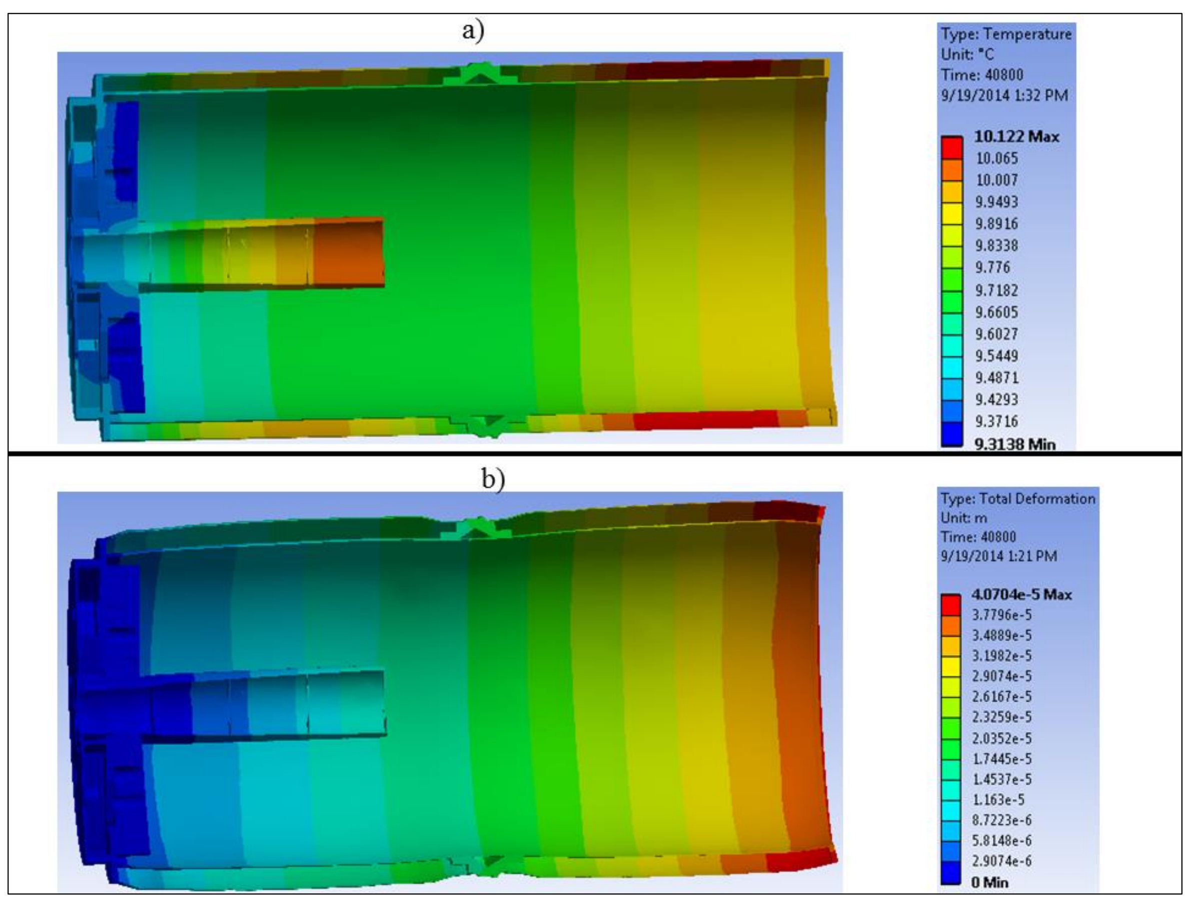


**Figure 3:** A cross section of the integrated tube system showing the temperature gradients (a) and the corresponding structural deformations in x, y and z directions (b).

However, the temperature gradients on the tube (Figure 3a) may cause significant expansion toward the front section of the tube (Figure 3b). This expansion suggests the possibility of defocussing and development of coma, due to the spider assembly carrying the secondary mirror moving with the telescope front. This may contribute to pointing errors during ranging as well as weak returns due to misfocussing. Therefore, developing a thermal dynamic model which can compensate for structural misalignments due to $\Delta T$ could play an important role in maximizing the pointing accuracy of the telescope.

## 5. Concluding remarks

These preliminary findings provide an indication of: i) understanding the thermal behaviour of the telescope's critical components with respect to the changing thermal environment, ii) guiding the strategic location of the thermal sensors on the telescope, and iii) options for developing a thermal dynamic model which could be assimilated into the telescope pointing model.


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