Prototyping a thermal monitoring system for the one-metre aperture Lunar Laser Ranger tube assembly based at the Hartebeesthoek Radio Astronomy Observatory

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Abstract

The Hartebeesthoek Radio Astronomy Observatory of South Africa is currently developing a Lunar Laser Ranger (LLR) system in collaboration with National Aeronautics and Space Administration (NASA) and the Observatoire de la Côte d’Azur (OCA). This LLR will add to a limited number of operating LLR stations globally and it is therefore expected to achieve sub-centimetre range precision to the Moon. Key to this expected achievement is the development of a thermal monitoring system for the LLR telescope that can account for thermal effects, mainly induced by the telescope’s interaction with the varying thermal environment. In this paper, we present a prototype of the thermal monitoring system in which resistance temperature detectors (RTD) sensors were used to measure and predict temperature gradients on the telescope assembly. The experimental results were used to validate the predicted temperature gradients. Temperature regions (without sensors) of the telescope tube were mapped at the RMS that varied between 0.19 and 0.24 °C which confirms the accuracy of the interpolation method. For tube temperature in the range 19–21 °C, the calculated thermal gradients were found to be about 0.5 °C. The larger gradients (>> 1.0 °C) ought to be regulated to minimize their influence on pointing.

1. Introduction

Ground-based telescopes utilized for laser ranging observations of space-based targets can be affected by thermal gradients and related structural deformations, known to be detrimental to the telescope pointing performance [1]. This is more so on the Lunar Laser Ranger (LLR) one-metre aperture telescope that is being constructed at the Hartebeesthoek Radio Observatory (HRO) in collaboration with NASA and the Observatoire de la Côte d’Azur (OCA) of France. The HRO LLR is expected to make ranging observations to the corner cube retroreflectors located on the lunar surface with sub-centimetre level accuracy. Currently, a prototype pointing model operated on a 125 mm double refractor testbed telescope, placed in a fairly stable environment achieved RMS error values at the 0.5 arcsecond level [2]. Key to the achievement of the required 1 arcsecond pointing accuracy of the HRO LLR, is active thermal control measures for providing real-time temperature monitoring and modeling of temperature gradients and related deformations of the telescope structure. Such information could be useful in the pointing model to ensure correction of thermally-induced pointing errors. In particular, the objective of this work was to report on the progress results pertaining the prototype of a thermal monitoring system for the HRO LLR tube assembly.

2. Thermodynamic properties of the experimental tube

Table 1. show the selected thermal properties of the telescope tube (Figure 1) that were critical parameters for the Finite element (FE) thermal analysis in this study.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Heat C,</td>
<td>896-898</td>
</tr>
<tr>
<td>Density p (kg/m3)</td>
<td>2700</td>
</tr>
<tr>
<td>Convection coefficient h</td>
<td>5-25</td>
</tr>
<tr>
<td>Thermal Conductivity k</td>
<td>204</td>
</tr>
<tr>
<td>Thermal linear expansion α</td>
<td>23.6 x 10⁻⁶</td>
</tr>
</tbody>
</table>

3. Experimental setup

Figure 1. Illustration of the one-metre aperture LLR telescope showing the distribution of RTD sensors placed at marked positions (xz). RTD sensor measurements were used to predict tube temperature at unmeasured locations (+) where reference sensors are also placed. The back-end of the tube is insulated by the one-metre Zerodur primary mirror that is located at the back of the tube.

4. Conduction and convective heat transfer

4.1. Conduction boundary conditions

The heat transferred across the cylindrical telescope tube due to conduction is given by:

\[ T(x, z) = \int T(x', z) \cdot \frac{\nabla T}{\nabla x} \cdot \frac{\nabla x}{\nabla z} \cdot dQ(x, z) \] (1)

where \( r \) and \( z \) are the cylindrical coordinates, \( k_r \) and \( k_z \) represent the thermal conductivities of the tube along the \( r \) and \( z \) coordinates, respectively. \( Q \) is the heat transferred per unit volume.

4.2. Conduction and convective heat transfer

The heat transferred across the tube due to conduction and convection is given by:

\[ T(x, z) = \int T(x', z) \cdot \frac{\nabla T}{\nabla x} \cdot \frac{\nabla x}{\nabla z} \cdot dQ(x, z) + \int W(x, z) \] (2)

4.3. Finite element modelling of tube heat transfer

The mathematical description of the FE modeling equation for the cylindrical tube can be found in [4]. In this study, the predicted temperature \( T_p \) at the point without a sensor was obtained to approximate the temperature of the surface of the telescope tube (at 2-D level) through the following expression:

\[ T_p(x, z) = \int T(x', z') \cdot W(x, z) \] (3)

where \( W(x, z) \) denotes the measured value at the \( x \), \( y \) node of the element; and \( W(x, z) \) denotes the interpolation weighting function.

The resulting tube temperature gradients were obtained along the \( r \) and \( z \) coordinates computed as follows:

\[ \frac{T_r}{T_z} = \frac{\sum_{i=1}^{n} T_i \cdot w_i}{\sum_{i=1}^{n} w_i} \] (4) and \[ \frac{T_z}{T_r} = \frac{\sum_{i=1}^{n} T^*_i \cdot w_i}{\sum_{i=1}^{n} w_i} \] (5)

Figure 2. Temperature profiles of ambient air, the measured and predicted tube-surface temperature on the evening of the 24th (a), 25th (b) and 26th (c) September 2016. The predicted tube temperature in the respective days is accompanied by the corresponding RMSI graphs shown in (d), (e) and (f) which indicates the accuracy of the predicted temperatures at unmeasured locations around the tube i.e. error between the measured and predicted points.

4.3. Conclusion

The results obtained from the interpolating weighting function gives values that have an RMS ± 0.3 °C. Given the fact that these results were validated using (reference) sensors mounted onto the same tube surface, the proposed algorithm could predict temperatures that are located very far from measuring nodes.

Acknowledgements

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Selected references