“First characterization of the next generation lunar laser retroreflector, MoonLIGHT”

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Abstract. The aim of this work is to describe and characterize next generation lunar laser retroreflectors, which introduce new solutions with respect to those employed by the Apollo missions for Lunar Laser Ranging (LLR) applications. To this aim, but also for other applications, the SCF_Lab (Satellite/lunar/GNSS laser ranging/altimetry and Cube/microsat Characterization Facilities Laboratory) located in INFN-LNF (Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Frascati) created a new industry standard test procedure, the SCF-Test, through which it conducts tests on the primary payload, Cube Corner Retroreflector (CCR). This work focuses on the optical analysis performed in the SCF-Lab on MoonLIGHT (Moon Laser Instrumentation for General Relativity High accuracy Tests) lunar retroreflector.

1. Introduction

First characterization of CCRs is important for different applications in aerospace activities, such as Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR). The SCF-Test establishes a procedure in order to verify CCR performances that could be affected by a faulty geometry or by the exposition to different radiation sources in space, causing a strong thermal gradient within, thus, resulting in a gradient in the refraction index of the CCR. Uncoated CCRs reduce the development of such thermal gradients. At present, uncoated Commercial Off-The-Shelf (COTS) CCRs, 1-inch (25.4 mm) diameter are being used and tested in a spherical array for LARES-2 satellite (LAser RElativity Satellite 2). Tests on a large sample of COTS aim to check if their optical performances are comparable with custom ones, in order to evaluate their price/quality ratio. On the other end, the SCF_Lab is also testing a next generation uncoated custom CCR for LLR applications, MoonLIGHT, for which a more detailed description and analysis will be exposed in next paragraphs.

2. Lunar Laser Ranging

2.1. Operating principle

The LLR consist in time-of-flight (ToF) measurements realised sending a short laser pulse from ground station to the orbiting satellite equipped with CCRs [1]. A CCR is a trihedral prism made by three orthogonal surfaces, which
reflect the narrow laser beam exactly in the same direction of the incoming one. A CCR is made of fused silica (SiO$_2$), characterized by high resistance to thermal shocks, high transparency in the Sun spectral range and high radiation resistance [1-3]. Its working consists in an application of Snell’s law of refraction (eq.1), that relates the refraction indices of two different media $n_1$ and $n_2$ with the angles that the incident ray forms with the surface’s normal when it encounters the interface between the two media.

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) . \quad (1)$$

When the laser passes from air (1) to fused silica (2), it reaches the back interface with air (see fig.1, left panel), where total internal reflection (TIR) occurs if $\theta_2 \geq 90^\circ$, so when $\theta_1$ overcomes the limit angle $\theta_{lim}$, given by eq.2.

$$\theta_{lim} = \arcsin \frac{n_1}{n_2} \quad (2)$$

From geometrical consideration it comes that laser must be nearly perpendicular to the CCR frontal surface. Assuming inside three smooth perpendicular surfaces, TIR can be deduced by reflection’s law. Looking at fig.1 on the right, laser enters with an angle $i_1$, it reflects on first mirror with an angle $r_1$, arrives on the second mirror with an angle $i_2$ and it exits with an angle $r_2$. Since $i_1 = r_1$ and $i_2 = r_2$, it comes that outcoming angle $\alpha$ is equal to $i_1$. The CCR retroreflection is obtained composing three mirrors that imply three consecutive procedures as the described one.

Fig.1. TIR in a CCR. Right image from [4], left one from [5].

2.2. The application

LLR is used to conduct high-precision measurements of distances between the Earth and lunar surface and it represents a primary technique to study the Earth–Moon system. From 1970s to our days, the Apollo missions placed on the lunar surface large arrays (developed by the University of Maryland, UMD), composed of 100-300 CCRs with 38 mm diameter (fig.2). These arrays have provided a large contribution to the studies of General Relativity issues, in addition to information about physical and geological features of our satellite [3].

Fig.2. The Apollo 14 mission retroreflectors placed on the Moon's surface from [6].

At the beginning, the ranging error due to the Apollo arrays geometry was negligible respect to the fraction caused by ground stations, because LLR was done by long laser pulses radiated by Earth, bigger than array dimension. Since then laser pulses have become shorter, the ranging capability has improved by more than two order of magnitude and now LLR arrays, affected by librations, dominates the ranging error budget. Lunar librations are due to the eccentricity of the lunar orbital motion around the Earth and Moon’s inclination. Therefore, during the monthly lunar period, the tilt angle between the normal to the panel and the direction to Earth changes, till becoming 8° in longitude and 7° in latitude. When the retroreflector is tipped, we don’t know from which corner (the nearest or the further to the Earth) a photon is reflected. Considering the panel of Apollo 15 has an area of 1 m$^2$, the inclination causes an enlargement of the return laser pulse of 30 cm, implying a ToF increase of ±0.5 ns. The error is halved for Apollo 11 and 14 arrays, that have an area of 0.5 m$^2$. In order to obtain better results, it’s necessary to time many single photoelectrons returns and reduce the error by the root means square of the single photoelectron one [3], [7].
2.3. MoonLIGHT

To improve the measurement accuracy, in 2006 INFN-LNF with UMD started a collaboration for the development of a new generation retroreflector, the “Lunar Laser Ranging Retroreflector Array for the 21st Century” (LLRRA-21) [2], [3], [7]. The key idea of the project consists in developing a single and larger CCR, MoonLIGHT, with a diameter of 100 mm (ML100) or 75 mm (ML75), that would substitute the CCRs array. Both MoonLIGHT and Apollo CCRare showed in fig.3

Fig.3. MoonLIGHT retroreflector ML100 (left) next to a 1st generation Apollo reflector (right), from [8].

3. Measurements on MoonLIGHT

The SCF-Lab is a clear room ISO 7, equipped with two cryostats, two Sun Simulators (SS), two optical benches and the infrared camera. Each cryostat, painted inside with Aeroglaze Z306 black paint (0.95 emissivity and low outgassing) reaches temperature of 77 K using liquid Nitrogen and pressure of $10^{-6}$ bar, simulating space conditions. In addition, the SS produces a beam with a spectrum corresponding to the AM0 (zero atmosphere condition) a 1 Sun in space (1366.1 W/m²). The optical bench is a table dedicated to optical devices necessary to reproduce the path of the laser beam through long distances and acquire optical measurements [1], [3], [7].

3.1. Optical analysis

The optical analysis realized for this work is referred to air isothermal condition, so this test is exclusively realised using the optical bench. The CCR is placed on the optical bench with its flat surface perpendicular to the incoming laser. Since the CCR presents three edges, in order to evaluate its Dihedral Angle Offset (DAO), it is tested three times, choosing the edge marked with the serial number as the first and putting it in upper position, then rotating it clockwise of 120°. The incoming inspection consists in pulsing a linearly polarized continuous laser beam with wavelength $\lambda=532$ nm, the most used one by laser ranging stations, sending the horizontal component to the CCR. The optical path in the far field limit is simulated by an optical circuit composed of lenses, beam splitters, a beam expander and others optical components, across which the laser passes before radiating the CCR’s surface. The CCR reflects the laser beam and the optical response is given by the two FFDPs for the horizontal and vertical components, acquired separately by two Charge-Coupled Devices (CCD) cameras through Firewire. The FFDP represents the diffraction waveform projected on the plane. In this kind of tests is important to analyse the total FFDP, i.e. the sum of the two components. Fig.4 gives an example of how a total FFDP appears for ML75.

Fig.4 Total FFDP of ML75 edge2, from data acquisition.

The reason why both horizontal and vertical components are acquired, is that as seen for uncoated CCRs the behaviour is strongly influenced by the incidence angle. In particular, the horizontal component presents a distribution with a peak in the centre and a series of minor decreasing peaks, while vertical response is weaker with a distribution that in general presents four symmetric peaks around the minimum in the centre. The measured
irradiance \( I \) (W/m\(^2\)), that corresponds to the radiation intensity of the reflected beam, gives the radiant exposure \( R \) (J/m\(^2\)) measured by the CCDs (given a shutter time \( t_s \)), as it is clear from eq.3:

\[
R = I \cdot t_s \tag{3}
\]

The shutter time must be chosen in such a way that the resulting \( R \) does not overstep the maximum possible value for the software. A larger CCR means a higher response, so to reduce \( R \) we need to reduce \( t_s \), at the same time the shutter time used for horizontal component must be shorter than the one used for vertical component.

The optical flux reflected back is expressed in terms of the optical cross section (OCS), which depends on the effective solid angle of the FFDP \( \Omega = \frac{\lambda^2}{2A} \), the reflectivity \( \rho \) and the CCR’s area \( A \).

\[
OCS = \frac{4\pi}{\Omega} \rho A = 4\pi \rho \left( \frac{A^2}{\lambda^2} \right). \tag{4}
\]

However, the acquisition program of each CCD measures \( R \) in CCD counts. To convert the OCS from CCD counts into its standard units \((10^8 \text{ m}^2)\), we normalize the total irradiance (from both horizontal and vertical polarization components) of the tested CCR \( I_{ML} \) (in CCD counts/s) to the total irradiance \( I_{AP} \) (in CCD counts/s) of the Airy peak of the diffraction pattern from a flat circular mirror with the same diameter of the CCR front face. This ratio will multiply the \( OCS \) in eq.4, obtaining eq.5, so the \( OCS \) expressed in standard units.

\[
OCS = 4\pi \rho \left( \frac{A^2}{\lambda^2} \right) \frac{I_{ML}}{I_{AP}}. \tag{5}
\]

The returning laser beam is subjected to the relative motion between the ground station and the Moon. The measured intensity results to be a function of the Moon velocity aberration (VA), measured in \( \mu \text{rad} \) as the deviation angle \( \theta_{VA} \) in the FFDP plane, given by eq.6, where we introduced orbital Moon velocity \((V_{orbm})\), the equatorial Moon velocity \((V_{eqm})\), the equatorial Earth Velocity \((V_E)\), the speed of light \((c)\) and the latitude of different ground station \((\varphi)\). Using the eq.5, we obtain that \( \theta_{VA} = 4\pi \cdot 4.5 \mu \text{rad} \), as it is shown in tab.1.

\[
\theta_{VA} = \frac{2}{c} \left[ V_{orbm} - V_{eqm} - V_E \cos \varphi \right] \tag{6}
\]

<table>
<thead>
<tr>
<th>Ground Station</th>
<th>Latitude (°)</th>
<th>( \theta_{VA} ) (μrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McDonald</td>
<td>30.68</td>
<td>4.11861092002668</td>
</tr>
<tr>
<td>APOLO</td>
<td>32.78</td>
<td>4.1784182737735</td>
</tr>
<tr>
<td>Matera</td>
<td>40.65</td>
<td>4.4330174325584</td>
</tr>
<tr>
<td>Grasse</td>
<td>43.75</td>
<td>4.54577344708510</td>
</tr>
</tbody>
</table>

Tab.1 Velocity aberration for different ground stations.

### 3.2. Far Field Diffraction Pattern analysis

The following analysis has been performed on ML75 (M703), choosing a shutter time for horizontal and vertical component respectively of 1.62 ms and 1.81 ms. From these results obtained by an elaboration with a MATLAB code, it is possible to see that the intensity at Moon VA falls before the first minimum, which position \( \varphi = 8.65 \mu \text{rad} \) is approximately given from eq.7, where \( d_{ML} = 75 \text{ mm} \) is the diameter of CCR.

\[
\varphi = 1.22 \frac{\lambda}{d_{ML}} \tag{7}
\]

This result can be confirmed looking at curves in figs.5-7 that describe how the OCS intensity, averaged over the azimuth angle of the FFDP plane, changes with VA. In parallel, figs.8-10 give the trend of intensity around azimuth angle at the Moon VA, \( \theta_{VA} = 4\pi \cdot 4.5 \mu \text{rad} \). Numerical values of OCS calculated at VA are summarized in tab.2.

<table>
<thead>
<tr>
<th>Edge</th>
<th>Max (m(^2))</th>
<th>Min (m(^2))</th>
<th>Average (m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.83724 \cdot 10^8</td>
<td>6.64583\cdot10^7</td>
<td>1.16994e \cdot 10^8</td>
</tr>
<tr>
<td>2</td>
<td>1.32042 \cdot 10^8</td>
<td>5.42323\cdot10^7</td>
<td>8.77427\cdot10^7</td>
</tr>
<tr>
<td>3</td>
<td>9.98828 \cdot 10^7</td>
<td>5.0716 \cdot 10^7</td>
<td>7.28945\cdot10^7</td>
</tr>
</tbody>
</table>

Tab.2 Maximum, minimum and average intensity in terms of OCS calculated in the range of Moon VA, for the three edges of ML75 (M703).
Fig. 5 Average intensity as function of VA, ML75 (M703) edge 1 up, from data analysis.

Fig. 6 Average intensity as function of VA, ML75 (M703), edge 2 up, from data analysis.

Fig. 7 Average intensity as function of VA, ML75 (M703), edge 3 up, from data analysis.

Fig. 8 Intensity at Moon VA as function of Azimuth angle, M75 (M703) edge 1 up, from data analysis.

Fig. 9 Intensity at Moon VA as function of Azimuth angle, M75 (M703) edge 2 up, from data analysis.

Fig. 10 Intensity at Moon VA as function of Azimuth angle, M75 (M703) edge 3 up, from data analysis.
### 3.3. Interferogram

The optical table is also equipped with a Fizeau Interferometer, an instrument frequently used to study the shape of an optical surface and the geometry. The analysis consists in pulsing a monochromatic laser beam that passes across a beam splitter, so that one beam goes in direction of a camera, the other is directed to two facing surfaces. One of them is a flat optical mirror, an extremely smooth surface that is used as reference for the other surface that must be tested, in general a fabricated surface, in this case the CCR. The reflected light from the first surfaces combines with the reflected light from the second surface, coming back as a unique beam that pass through the beam splitter and arrive at the camera. The result is a single measurement frame that represents the interference pattern, where interference fringes are visible. In fact, due to the different roughness of the two surfaces, the two reflected waves have different phases, so they generate interference. Patterns are acquired and analysed using an interferometry software, 4Sight. Fig. 11 shows an example of interferogram pattern: it appears as a circle with the same diameter of the CCR, the three edges and their reflections on the internal surfaces divide the circle into six islands, edges are obscured by a black mask because, being an intersection of two surfaces, they provoke discontinuity.

![Interferogram pattern](image)

Fig.11. Interferogram pattern for ML75 (M703), edge 2 up, from data analysis.

Every island is characterized by an interference pattern, black and white fringes indicate destructive and constructive interference, respectively. For this test we used a laser in the red spectrum ($\lambda = 633$ nm) and as in the previous analysis, data must be acquired for each one of the three edges up. The software uses a nomenclature that considers edges always defined with the same alphabetical order (A, B, C), as showed in fig.11. Anyway, in interpreting the results we need to remember that we rotated clockwise the CCR, so the correspondence between the number of edge and letter rotates too. Using as input the interference patterns, the software compares the surfaces and gives in output some geometrical properties of the CCR, reported in tables. The DAOs represent the deviations from the nominal orthogonality: negative and positive values mean acute and obtuse angles, respectively. ML75 (M703) has (-0.10, -0.16, 0.12) arcsec, as measured by the manufacturer (Zeiss), with a root mean square (RMS) of ±0.20 arcsec. Looking at tab.3 is possible to evaluate that edge 1 has a negative deviation from the nominal position, considering that RMS is little enough. For edges 2 and 3 we obtained little positive deviation, but a RMS = ±0.16 arcsec does not guarantee the reliability of the assumption. However the DAOs measured at the SCF_Lab are fully consistent, within the errors, with those provided by the manufacturer.

<table>
<thead>
<tr>
<th>Edge</th>
<th>Average</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge 1 Up</td>
<td>-0.11</td>
<td>-0.07</td>
</tr>
<tr>
<td>Edge 2 Up</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>Edge 3 Up</td>
<td>-0.09</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Tab.3 Dihedral Offset Angle experimentally evaluated for the three edges of ML75 (M703), average value and RMS.

Additionally, the software calculates the Peak-to-Valley distance and its RMS, given in wavelength units, it is referred to roughness of CCR’s surface. For every edge up, it gives six values that indicate the different values of Peak-to-valley evaluated for every island, that are averaged in the end. These results are summarized in tab. 5 and tab.6.
4. Conclusions

Optical and interferometric measurements have been performed at the SCF-Lab on different samples for MoonLIGHT CCR, acquiring results both for ML75 and ML100. In my thesis I summarized the results obtained for ML75 (M703). These results, together with the ones for ML100 CCR, need to be compared with Apollo arrays performances. During last years, lunar dust reduced Apollo arrays performances degrading the signal strength by a factor $\eta = 0.1$. As seen, the intensity of the returning signal depends on the fourth power of the diameter of the CCR. Introducing $\eta$ is possible to evaluate the actual signal intensity ratio between Apollo arrays and ML75: namely, the laser return intensity from ML75 (M703) is 1.5 times the one from the actual Apollo11 array and 0.5 times the one from the actual Apollo15. A part the value of the OCS at VA from a single big CCR, which is competitive with that from the larger Apollo arrays, the lower cost constrains and the immunity to lunar librations makes MooLIGHT an innovative substitute for the Apollo arrays.

I thank SCF-Lab for holding me during this educational experience.

5. References