GLUC-2010.1.7.B.9

LLRRA21/MOONLIGHT: A 2ND GENERATION LUNAR LASER RANGING ARRAY FOR PRECISION GRAVITY TESTS AND LUNAR SCIENCE MEASUREMENTS

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ABSTRACT

Over the past forty years, Lunar Laser Ranging (LLR) to the Apollo Cube Corner (CCR) Retroreflector arrays [1], the only experiment of the Apollo program that are still in operation, has supplied almost all of the significant tests of General Relativity. It has evaluated the Post Newtonian parameters and provided significant information on the composition and origin of the moon. To achieve these results the main source of error was the performance of ground stations, but now stations has been greatly upgraded and the ranging accuracy has improved by a factor of 140. Now because of the lunar librations the existing Apollo retroreflector arrays give the predominant contribution to the LLR error budget.

The University of Maryland, Principal Investigator (PI) of Apollo arrays, is now proposing to NASA a new Lunar Laser CCR array technology [2], of which the Professor Currie is the PI, that is currently being supported by two NASA programs and by Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali di Frascati (INFN-LNF). The new arrays will support ranging observations that are a factor 100 more accurate than Apollo LLRRAs, from centimeter to micron level. INFN-LNF is co-proposing this payload to ASI and ESA.

New fundamental physics and the lunar physics [3] that this new Lunar Laser Ranging Retroreflector Array for the 21st Century (LLRRA-21) can provide will be described. In the new design, there are three major challenges:

validate that the CCR specifications required for the new array can indeed be achieved; address the thermal/optical effects of absorption of the solar radiation within the CCR, reduce the heat transfer from the hot housing to the CCR; define a method of emplacing the CCR package on the lunar surface such that the relation between the optical center of the array and the center of mass of the moon remains stable over the lunar day/night cycle.

The design approach, the computer simulations using Thermal Desktop and CodeV software, and the results of the thermal vacuum testing conducted at the INFN-LNF's Satellite/lunar laser ranging Characterization Facility (SCF) of the new array will also be presented. The new lunar CCR housing has been built at INFN-LNF. The innovations in the LLRRA-21 and its packages will be described. The LLRRA-21 is being considered for the NASA Manned Lunar Landings, for the NASA Anchor Nodes for the International Lunar Network and for the proposed Italian Space Agency's MAGIA [4] lunar orbiter mission.

1. TEAMS OF COLLABORATORS

The current degree of success of this project is the result of the support of many individuals and organizations.

LSSO Team centered at the University of Maryland, College Park

This was the initial group that addressed the LLRRA-21 concept with Professor Currie. The collaborative research effort was then supported by the Lunar Science Sortie Opportunities (LSSO) program at NASA headquarters. The members are:

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Moon Laser Instrumentations for General relativity High-accuracy Tests (MoonLIGHT) Team – centered at the INFN-LNF in Fracati, Italy

This group at the INFN-LNF in Frascati, Italy has developed the SCF (i.e., the thermal vacuum chamber) and collaborated in developing models and simulations supporting the LLRRA-21 program. This group has been supported by internal INFN funds:

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2. BACKGROUND AND OVERVIEW

The University of Maryland led the team that provided NASA with Lunar Laser Ranging Retroreflector Arrays for the Apollo Missions. These were carried to the moon during Apollo 11, Apollo

14 and Apollo 15. After four decades, these arrays are still in operation, and are the only experiment on the moon still producing scientific data. In the past 40 years, Laser Ranging to these arrays has provided most of the definitive tests of the many parameters describing General Relativity (GR).

In addition, the analysis of the LLR data, in collaboration with some data from other modalities, has greatly enhanced our understanding of the interior structure of the moon [5,6,7,8].

However, over the past four decades, the ground station technology has improved by a factor of more than 100, such that the Apollo lunar arrays now contribute a significant portion of the ranging errors. This is due to the lunar librations which are responsible for the "tipping" of the Apollo arrays so that one corner of the array is more distant than the opposite corner by several centimeters. Thus even if a very short laser pulse were sent to the moon, the return pulse would be spread out in time, so one could obtain a range estimate with an accuracy of no better than a few centimeters (for a single shot).

Currently, the University of Maryland leads a program to develop, design and validate LLRRAs that are composed of 100 mm solid CCRs. These new arrays (i.e., the LLRRA-21) should be capable of supporting ranging accuracies that are a factor of more than 100 better than the Apollo arrays, that is; an accuracy of 100 to 10 microns.

This effort is a collaboration of the University of Maryland with the Frascati branch (LNF) of the Institute for Nuclear Physics (INFN) of Italy. This joint effort is addressing the design, analysis, thermal and optical simulation, fabrication and thermal vacuum testing of a concept for the lunar array.

3. SCIENCE OBJECTIVIES OF THE LLRRA-21/MOONLIGHT PROGRAM

The science objectives of the overall Lunar Laser Ranging Program (LLRP) address a variety of goals which primarily fall into three categories:

General Relativity

Almost all of the most accurate tests of General Relativity are currently derived from LLR to the Apollo arrays [9,10,11]. Over the long term, we expect to improve the current accuracy of these tests by factors as large as 100. This will address many tests concerning the validity of GR at a new level of accuracy. This is especially important as we confront two of the major issues in fundamental physics, astrophysics and cosmology, that is, 1) the conflict between the current formulations of GR and Quantum Mechanics and 2) the role and reason for the acceleration of distant galaxies (i.e., Dark Energy). We will also try to constrain the parameter(s) which describe spacetime torsion.

Lunar Science

Much of our knowledge of the interior of the moon is the product of LLR [5,7,8], often in collaboration with other modalities of observation. These physical attributes of the lunar interior include the Love numbers of the crust, the existence of a liquid core, the Q of the moon, the physical and free librations of the moon and other aspects of lunar science.

Cosmology

The improved accuracy of the LLRRA-21 would support the detection of the effects predicted by the Dvali-Gabadadze-Porrati model [12] of Dark Energy and the acceleration of distant galaxies.

4. TECHNICAL CHALLENGES OF THE LLRRA-21

The primary technical objectives of the design of the LLRRA-21 are to provide adequate laser return to earth-based ground stations and to be stable over the long term – decades – with respect to the center of mass of the moon.

The major technical/engineering challenges that follow from the technical objective are then:

a) Fabrication of large CCR to the required tolerances.
   Angular tolerances ~2.5 times more restrictive than state of the art.
   Large size is a challenge with respect to homogeneity of fused silica material.
b) Thermal control to reduce thermal gradients to acceptable levels.
   Thermal gradients produce gradients in the index of refraction.
   Thermal gradients cause spread of return beam and low returns.

c) Emplacement goal – along term stability of 10 microns with respect to Center of Mass of the moon.
Defeat day/night motion of the regolith which is ~400 microns.
Anchor the CCR to regolith at a depth of ~1 m where there is negligible change in temperature.
Support CCR with INVAR Rod and provide temperature compensation in housing.

5. FABRICATION CHALLENGE

The CCR has been fabricated and is within specs. This is much larger than any previous CCR. The specs of material homogeneity and the tolerances on the back surface angles (0.2 arc seconds) are more restrictive than the current state-of-the-art for LR CCR fabrication. To address this, the fabrication of a CCR has been accomplished by ITE, Inc. of Beltsville, MD. In order to satisfy these requirements we chose SupraSil 1; (see Fig.1). For the next generation of CCRs for LLRRA-21, we plan to use SupraSil 311.

Fig. 1 Shows the Flight Certified 100 mm CCR that has been fabricated to the specifications with Apollo CCR. In fact, the offset angles for the back faces exceeded the specifications by almost a factor of two.

6. THERMAL/OPTICAL PERFORMANCE CHALLENGES

One of the most critical challenges is the issue of heat flows or thermal gradients inside the CCR. Since the index of refraction of the fused silica, depends upon temperature, thermal gradients in the CCR will cause the index of refraction to vary within the CCR and thus it will not act as a diffraction limited mirror. For this reason, we need to adjust the design to control these gradients and finally evaluate the effects of these thermal gradients on the Far Field Diffraction Pattern (FFDP), which represents the intensity of the laser beam reflected back to ground by the CCR. This is accomplished using dedicated programs developed in parallel in Frascati and the University of Maryland. To perform these simulations, we use Thermal Desktop, a software package of C&R Technologies of Boulder CO and CodeV by ORA Inc. The three primary sources of heat that cause the thermal gradients:

Absorption of Solar Radiation within the CCR:
during the lunar day, the solar radiation enters the CCR and portions of this energy are absorbed by the fused silica. Since the different wavelengths in the solar radiation are absorbed with different "strengths" the head is deposited in different parts of the CCR.

Heat Flux flowing through the Mechanical Mounting Tabs:
if the CCR is at a temperature that is different than the housing temperature there will be a flux of heat passing into (or out of) the CCR. We have designed a modification of the KEL-F mounting rings that greatly reduces the conductivity but will also survive launch.

Radiation Exchange between CCR and the Surrounding Pocket:
the back surfaces of the Apollo CCR views the aluminum that makes up the housing. If the temperatures of the CCR and the aluminum are different there is a radiation exchange of thermal energy which in turn causes a flux in the CCR as the heat exits out of the front face to cold space.

In the Apollo array this is not been a serious issue, but for the much larger LLRRA-21 it is, so we need to reduce this effect. Thus we enclose the CCR into two thermal shields, with a very low emissivity (2%), that has been fabricated by Epner Technologies of Brooklyn, NY; (see Fig. 2).

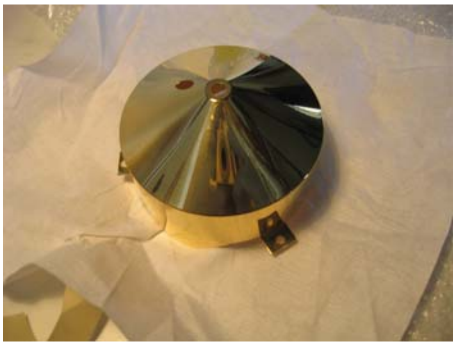

Fig. 2 Inner thermal shield with low emissivity gold coating

7. RESULTS OF THERMAL/OPTICAL SIMULATION

In order to discuss the results of the thermal and optical simulations in a form that addresses the required properties, we wish to determine the variation of the temperatures or the gradient from the tip of the back of the CCR to the front face (TtFF; Fig. 3) and the optical performance of the CCR, that is determined by its FFDP (Fig. 4).

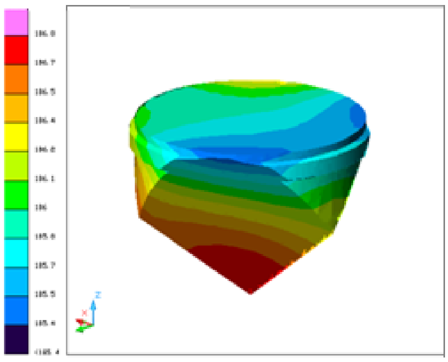

Fig. 3 A typical distribution of temperature in the CCR for a given set of conditions. This image is the first in a series of day by day temperature distributions through a lunation.

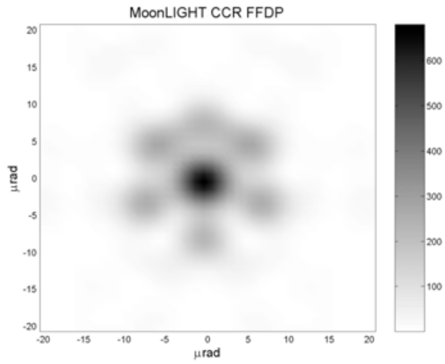

Fig. 4 FFDP of LLRRA-21 under its design specification of offset angles (0.0’’ 0.0’’ 0.0’’). Grid is in angular dimensions (µrad).

This directly affects the divergence of the outgoing beam and thus the signal strength back on the earth. Thermal simulations performed on the current configuration show that the variation of the ΔT between the front face and the tip of the CCR is within about 1K (Fig. 5). We are still proceeding to optimize this further. There are optical design procedures that may allow us to reduce the effective temperature difference from the tip to the face to 0.5 degrees.

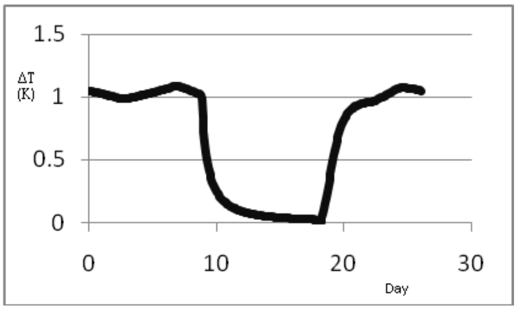

Fig. 5 Tip-to-Face temperature variation over a single lunation for a specific CCR orientation. This is an acceptable 1K.

As a result, we have demonstrated (in simulation) that the thermal effects of the solar absorption, the mount conduction and the exchange of radiation with the pocket can be controlled to a sufficient degree.

8. CURRENT HOUSING DESIGN

We are successively refining our designs based upon maximizing the overall performance by jointly optimizing the effects of the various different phenomena that affect the overall performance. This has been addressed using the computer simulations discussed in the above sections and using the data obtained with the thermal vacuum measurements.

This addressed both the design for the robotic emplacement and the use of the 100 mm solid CCR in the MAGIA mission and/or in the ILN Anchor nodes and/or any other similar geophysical surface mission. Note that the deployment scheme with a rover (like the one suggested by ASI [13]) or a lander (like the one now considered by ESA [14]) will vary. Thus we illustrate the current payload design in Fig. 6. that is the configuration that was used for the above simulations.

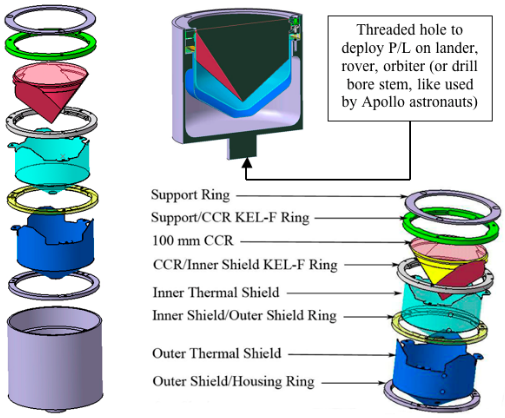

Fig. 6 Views of current design of MoonLIGHT-ILN/LLRRA-21 CCR with its internal mounting elements and outer metal housing.

This is the configuration that has been used in the most recent (March 2010) thermal/optical-vacuum tests. This design has also been proposed to the Italian Space Agency for a precursor test on the MAGIA lunar orbiter (Phase A study, see [15,16]), which will carry our 100 mm CCR into lunar orbit (if it receives final approval).

9. THERMAL VACUUM CHAMBER TESTING

Up to this point, the discussions have addressed concepts for the LLRR-21 and thermal and optical computer simulation developed to validate the design concepts. We now address the thermal vacuum testing to further validate the design issues. To accomplish this, we need to provide two classes of measurements. The first is the thermal behavior of the test configuration. A solar simulator that has a good representation of the AMO2 solar spectrum is used to provide the solar input. To evaluate the thermal performance of the designs, we use both thermo-resistors and an infrared video camera. The former must be specially configured in order that the wires not conduct more heat than the test item. The latter yields temperatures over the entire test object at each instant. On the other hand, to address the relation between the thermal performance and the optical performance, we currently measure the far field diffraction pattern (Fig. 7).

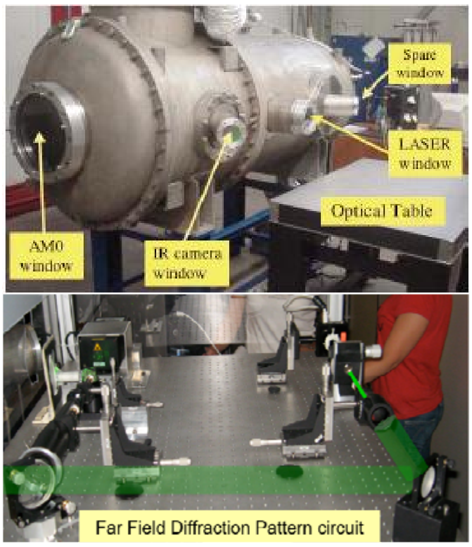

Fig. 7 Photos of thermal vacuum chamber with the optical table for measuring FFDP.

This is the crucial test of a CCR package and is performed with the CCR in the chamber (Fig. 7). For the next run, we plan to implement a phase front measurement (which is optimal for diagnosing the details of the performance). Various configurations and designs of the CCR and the housing have been and are being tested in the SCF Facility at INFN-LNF with the solar simulator, the temperature data recording with an infrared camera and the measurement of the FFDP, (see Fig. 8).

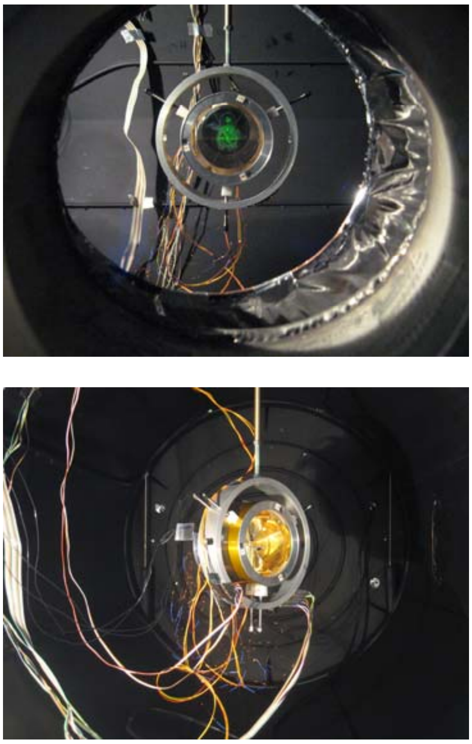

Fig. 8 Two photos of MoonLIGHT cube corner retroreflector tested in spatial condition.

10. ANALYSIS OF EXISTING LLR DATA

In Table 1 we report the fundamental physics tests that have been carried out with these data set by NASA-JPL [17].

Science Measured	Time scale	1st Generation Accuracy (cm)	2nd Gen. 1 mm	2nd Gen. 0.1 mm
PPN, β	Few years	$\lvert\beta-1\rvert<1.1\times10^{-4}$	10^{-5}	10^{-6}
WEP	Few years	$\lvert\Delta a/a\rvert<1.4\times10^{-13}$	10^{-14}	10^{-15}
SEP	Few years	$\lvert\eta\rvert<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
$\dot{G}/G$	~5 years	$\lvert\dot{G}/G\rvert<9\times10^{-13}yr^{-1}$	5×10^{-14}	5×10^{-15}
$1/r^2$	~10 years	$\lvert\alpha\rvert<3\times10^{-11}$	10^{-12}	10^{-13}
K_{gp}	Few years	$\lvert K_{gp}\rvert<6.5\times10^{-3}$	6.5×10^{-4}	6.5×10^{-5}

Table 1: General Relativity Science Objectives

In collaboration with J. Chandler, J. Battat and T. Murphy, we are starting to use the Planetary Ephemeris Program (PEP) [18], a software developed by the Center for Astrophysics (CfA). PEP was designed not only to generate ephemerides of the Planets and Moon, but also to compare models with observations.

There are a diverse set of observations that PEP can handle, but we care primarily about LLR observations. In particular, the software is able to

calculate the residuals of the distances between observed data, coming from measurements acquired by LLR, and computed data, derived from expectations of GR and of terrestrial and lunar Geodesy. We have performed a very preliminary analysis of LLR data from three stations: McDonald Observatory in Texas (USA), Grasse in France and APOLLO in New Mexico (USA). The latter station provides the best quality data since 2006. On March 25, 2010 the Matera Laser Ranging Observatory in Italy, recorded LLR echos from the array of Apollo 15.

The histograms in Fig. 9 (lunar returns and fiducial returns) shows photon-by-photon data and represent a single LLR normal point

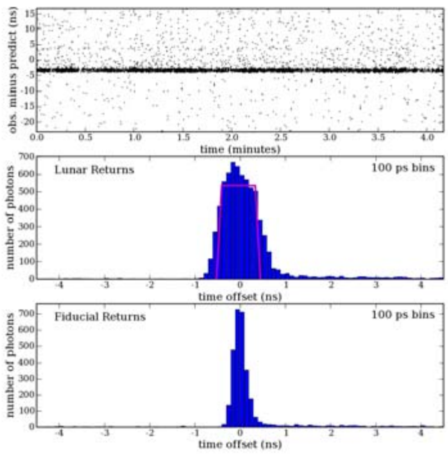

Fig. 9 Example run of Apollo 15. In the plot, the top panel shows a 40 ns window of observed round trip time minus the predicted range. Background noise and detector dark current appear as scattered dots, while the lunar return is in the middle. The middle panel shows a histogram of the lunar returns, while the bottom panel shows the local "fiducial" CCR return.
http://www.physics.ucsd.edu/~tmurphy/apollo/highlights.html

With PEP it is also possible to compute and solve numerically partial equations, in order to estimate parameter values and uncertainties.

As an exercise, we set the initial values of the Parametrized Post Newtonian (PPN) constants β and γ to 1.0, their value predicted by GR. The best-fit output values are:

$\beta = 0.999591$
$\gamma = 0.99798$,

a change of about 10^{-4} and 10^{-3} in their central values. At this stage, this is not meant to be any kind of measurement or error analysis, but some figure of merit of our initial understanding of PEP, in view of a long-term work in collaboration with CfA and the APOLLO team.

11. CURRENT CHALLENGES AND OBJECTIVES

In this section, we address the challenges that are still present in order to assure the feasibility of the experiment, the proper operation of the package on the surface of the moon and the withstanding of the launch conditions.

1) Continue simulations to optimize thermal performance, i.e. minimize the TtFF gradient:
    a. evaluate further modifications of the housing structure and the support rod;
    b. investigate optical procedures to minimize the beam spreading for a TtFF gradient;
    c. optimize the offset of the back faces to minimize the impact of velocity aberration.
2) Continue further thermal vacuum testing of designs at SCF:
    a. evaluate different design options
        i. MAGIA
        ii. ILN;
    b. validate thermal modeling and simulations.
3) Investigate new lunar regolith drilling capabilities:
    a. investigate honeybee gas assisted drilling;
    b. investigate robotic capabilities for ILN missions;
    c. investigate strategies for robotic emplacement of CCR;
    d. collaboration on drilling technologies with heat flow experiments;
    e. field tests of new drilling techniques in a simulated lunar regolith.
4) Analyze various sun shading designs.
5) Analyze launch requirements.

12. MISSION OPPORTUNITIES

The initial approach of our program was to define a package that would allow a very significant improvement in the accuracy of LLR in order to support the new vistas of lunar science, GR and cosmology. This initial effort was addressed to the next NASA Manned Lunar Landings and the research was supported by the LSSO program out of NASA Headquarters.

However, since then several other opportunities have arisen. The ILN has been proposed by NASA, which consists of the launch of four "Anchor Nodes" in about 2015. This is a robotic mission. The initial specification of the payload will contain a100 mm CCR for LLR.

In addition for the MAGIA mission [15,16] has been completed. It is awaiting a down selection in preparation to funding for the flight.

13. ACKNOWLEDGEMENTS

We wish to acknowledge the support of the University of Maryland via the NASA "Lunar Science Sortie Opportunities" (LSSO) program (Contract NNX07AV62G) to investigate Lunar Science for the NASA Manned Lunar Surface Science and the LUNAR consortium (http://lunar.colorado.edu), headquartered at the University of Colorado, which is funded by the NASA Lunar Science Institute (via Cooperative Agreement NNA09DB30A) to investigate concepts for astrophysical observatories on the Moon. In support of the research at Frascati, we wish to acknowledge the support of the Italian INFN-LNF, granted since the LSSO project, MoonLIGHT-

M(anned) [19]. We also wish to thank the support of ASI during the 2007 lunar studies and the 2008 Phase A study for MAGIA. D. G. Currie would also like to acknowledge helpful conversation with Jack Schmidt, Ken Nordtvedt and Ed Aaron.

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