A Lunar Laser Ranging Retroreflector Array for the 21st Century

Professor Douglas Currie
Department of Physics, University of Maryland, College Park, College Park Maryland 20742
NASA Lunar Science Institute, NASA Ames Research Center, Moffett Field, CA
Istituto Nazionale di Fisica Nucleare Laboratori, Nazionali di Frascati, CP 13, Frascati, Italy
currie@umd.edu

Dr. Simone Dell'Agnello
Simone.DellAgnello@lnf.infn.it
Istituto Nazionale di Fisica Nucleare Laboratori, Nazionali di Frascati, CP 13, Frascati, Italy

Dr. Giovanni Delle Monache
giovanni.dellemonache@lnf.infn.it
Istituto Nazionale di Fisica Nucleare Laboratori, Nazionali di Frascati, CP 13, Frascati, Italy

1. Abstract

Over the past forty years, Lunar Laser Ranging (LLR) to the Apollo Cube Corner (CCR) Retroreflector arrays [1] has supplied almost all of the significant tests of General Relativity. The LLR program has evaluated the PPN parameters and addressed, for example, the possible change in the gravitational constant and the properties of the self-energy of the gravitational field. In addition, LLR has provided significant information on the composition and origin of the moon. These arrays are the only experiment of the Apollo program that are still in operation. Initially the Apollo Lunar Arrays contributed a negligible portion of the error budget used to achieve these results. Over the decades, the performance of ground stations has been greatly upgraded so that the ranging accuracy has improved by more than two orders of magnitude, i.e., a factor of 140. Now, after forty years, because of the lunar librations the existing Apollo retroreflector arrays contribute a significant fraction of the limiting errors in the range measurements.

The University of Maryland, as the Principal Investigator for the original Apollo arrays, is now proposing a new approach to the Lunar Laser CCR array technology [2]. The investigation of this new technology, with Professor Currie as Principal Investigator, is currently being supported by two NASA programs and by INFN/LNF. Thus after the proposed installation on the next Lunar landing, the new arrays will support ranging observations that are a factor 100 more accurate than the current Apollo LLRRAs, from the centimeter level to the micron level.

The 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 design of the new array, there are three major challenges: 1) Validate that the specifications of the CCR required for the new array, which are significantly beyond the properties of current CCRs, can indeed be achieved. 2) Address the thermal and optical effects of the absorption of solar radiation within the CCR, reduce the transfer of heat from the hot housing to the CCR and 3) 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, Code V and locally developed IDL software, and the results of the thermal vacuum testing conducted at the INFN/LNF's SCF facility at Frascati, Italy 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 with respect to the Apollo LLRR Arrays and current satellite retroreflector packages will be described. The new requirements for ground stations will be briefly addressed. This new concept for 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.

2. Teams of Collaborators

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

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 of this team are:

Douglas Currie	PI	University of Maryland, College Park, NLSI, Moffett Field, CA & INFN-LNF
Bradford Behr		University of Maryland, College Park, MD
Tom Murphy		University of California at San Diego, San Diego, CA
Simone Dell’Agnello		INFN/LNF Frascati, Italy
Giovanni Delle Monache		INFN/LNF Frascati, Italy
W. David Carrier		Lunar Geotechnical Institute, Lakeland, FL
Roberto Vittori		Italian Air Force, ESA Astronaut Corps
Ken Nordtveldt		Northwest Analysis, Bozeman, MT
Gia Dvali		New York University, New York, NY and CERN, Geneva, CH
David Rubincam		GSFC/NASA, Greenbelt, MD
Arsen Hajian		University of Waterloo, ON, Canada

MoonLIGHT Team – centered at the INFN-LNF in Fracati, Italy

This group at the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (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:

Simone Dell’Agnello	PI	INFN-LNF, Frascati, Italy
Giovanni Delle Monache		INFN-LNF, Frascati, Italy
Douglas Currie		U. of Maryland, College Park, MD, NLSI , Moffett Field, CA & INFN-LNF
Roberto Vittori		Italian Air Force & ESA Astronaut Corps
Claudio Cantone		INFN-LNF, Frascati, Italy
Marco Garattini		INFN-LNF, Frascati, Italy
Alessandro Boni		INFN-LNF, Frascati, Italy
Manuele Martini		INFN-LNF, Frascati, Italy
Nicola Intaglietta		INFN-LNF, Frascati, Italy
Caterina Lops		INFN-LNF, Frascati, Italy
Riccardo March		CNR-IAC & INFN-LNF, Rome, Italy
Roberto Tauraso		U. of Rome Tor Vergata & INFN-LNF, Frascati,Italy
Giovanni Bellettini		U. of Rome Tor Vergata & INFN-LNF, Frascati,Italy
Mauro Maiello		INFN-LNF, Frascati, Italy
Simone Berardi		INFN-LNF, Frascati, Italy
Luca Porcelli		INFN-LNF, Frascati, Italy
Giuseppe Bianco		ASI Centro di Geodesia Spaziale (CGS) “G. Colombo”, Matera, Italy

3. 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.

In addition, the analysis of the Lunar Laser Ranging (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.

4. Science Objectives of the LLRRA-21 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 General Relativity 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 General Relativity and Quantum Mechanics and 2) the role and reason for the acceleration of distant galaxies (i.e., Dark Energy).

Lunar Science

Much of our knowledge of the interior of the moon is the product of Lunar Laser Ranging [7,8,9,10], 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.

5. 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 Cube Corner Reflectors to the Required Tolerances
    Angular Tolerances ~2.5 times More Restrictive than State of the Art
    Large Size is a Challenge w.r.t. 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 – A Long Term Stability of 10 microns w.r.t. 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 Temp.
  Support CCR with INVAR Rod and provide Temperature Compensation in Housing

6. Fabrication Challenges

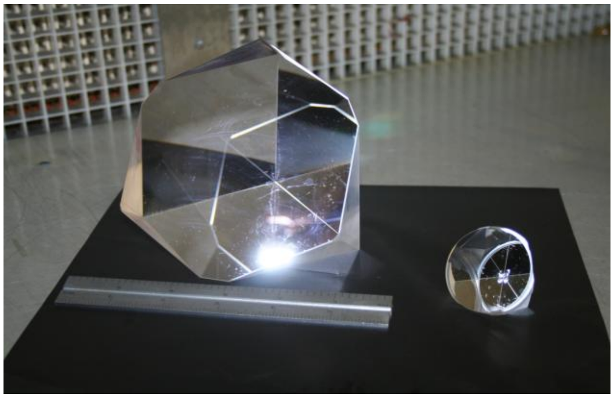

Fig. 1 Shows the Flight Certified 100 mm CCR that has been fabricated to the specifications with Apollo CCR In fact, the offset angles for the back faces exceeded the specifications by almost a factor of two.

The fabrication of a Cube Corner Reflector (CCR) that would support the LLRRA-21 concept has not been achieved in the past. This is much larger than any previous CCR (a factor of 18 in mass compared to the largest of the CCRs fabricated for Apollo arrays and/or satellite systems). This affects the availability of material of the required homogeneity, the fabrication and polishing procedures and the measurement methods. In addition, the tolerances on the back surface angles (0.2 arc seconds) are more restrictive by a factor of 2.5 than the current state-of-the-art for LR CCR fabrication. To address this, we have commissioned the fabrication of a CCR of the required tolerances and also meet the full documentation required for space flight. This has been accomplished by ITE, Inc. of Beltsville, MD. The angles are almost a factor of two better than the specifications, leading to excellent performance. The material selection is primarily driven by three requirements: 1) it must have an extremely uniform index of refraction (i.e., very good homogeneity), 2) it must be resistant to darkening by cosmic radiation and 3) it must have a very low absorption of solar radiation. To satisfy these requirements, this CCR has been fabricated of SupraSil 1. For the next generation of CCRs for LLRRA-21, we plan to use SupraSil 311 which has even better homogeneity.

7. Thermal/Optical Performance Challenges

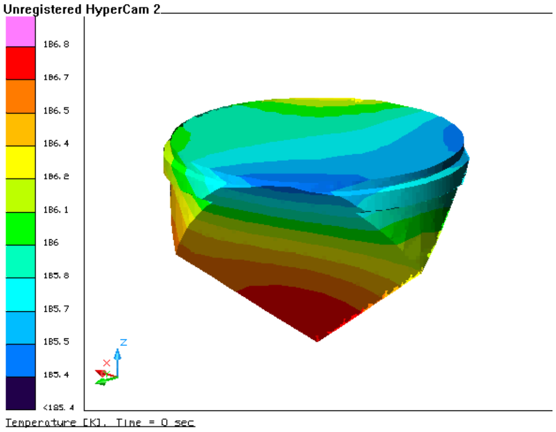

Fig. 2 A typical distribution of temperature in the CCR for a given set of conditions. This image is the first in a series of day by day temperature distributions through a lunation.

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 understand in detail the magnitude of the gradients caused by the various effects, then adjust the design to control these gradients and finally evaluate the performance with the control procedures in place. We first need to determine the heat deposition. 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.

This analysis yields a three dimensional matrix describing the temperature distribution in the CCR for a given configuration and set of parameters. These simulations are being carried out at Frascati and at the University of Maryland. A program developed at the University of Maryland using IDL of RSI Inc. converts the three dimensional temperature matrix into a two dimensional phase front which captures the error induced by the temperature gradients. Both Code V and another IDL program developed at the University of Maryland are being used to convert the phase error into a far field diffraction pattern which defines the strength of the signal that will be seen as a laser return at the ground station.

We now address 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. To address this, we must analyze each narrow band (1 nm) of the solar radiation separately and then sum the heat deposition at each node. Thus for each narrow band, we must determine the amount of energy in the AMOS2 solar spectrum [13]. We then use the band-by-band absorption data from Heraeus [14] to determine the amount of heat deposited at each node that a given ray passes through. This three dimensional matrix of heat inputs is then used as an input to the Thermal Desktop in order to compute the thermal gradients.

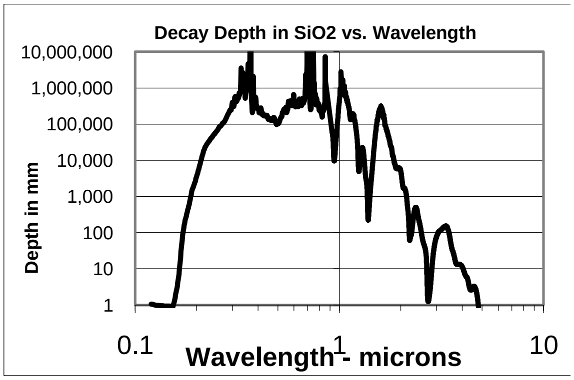

Fig. 3 Illustrates the exponential decay depth, used to determine where the solar radiation is deposited

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. This will cause a flow of heat between the housing and the CCR which will then cause a problem with beam spread. For the Apollo arrays (and for the following satellite systems like LAGEOS) KEL-F rings that have a low conductivity have been used. However, this conductivity is unacceptably large for LLRRA-21. In order to meet the requirements of the LLRRA-21, we have designed a modification of the KEL-F design that greatly reduces the conductivity but will also survive launch.

Radiation Exchange between CCR and the Surrounding Pocket

In the case of the Apollo CCR arrays, the back surfaces of the CCR views the aluminum that makes up the housing. This is machined aluminum that has a relatively high emissivity/absorptivity. 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 case of the Apollo arrays this is not been a serious issue, either in the analysis or in the performance of the arrays. However, for the much larger LLRRA-21 it is more serious and we need to reduce this effect in order to maintain an acceptable tip-to-face temperature difference. Thus in order to combat this effect, we enclose the CCR in thermal shields that prevent this radiative flow of heat. This is accomplished by the use of two shields with a very

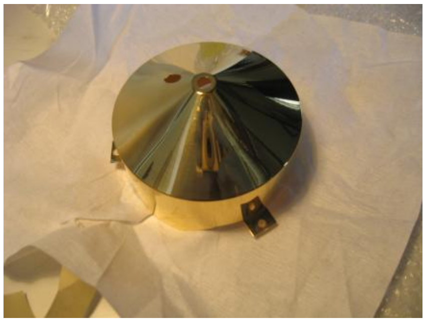

Fig. 4 Inner Thermal Shield with Low Emissivity Gold Coating

low emissivity, that is, 2% and that can be expected to maintain this low emissivity over a period of long time. Such a shield has been fabricated by Epner Technologies of Brooklyn, NY in order to evaluate manufacturability and in order to perform thermal vacuum tests to evaluate the effectiveness of this solution.

8. Results of Thermal Simulation

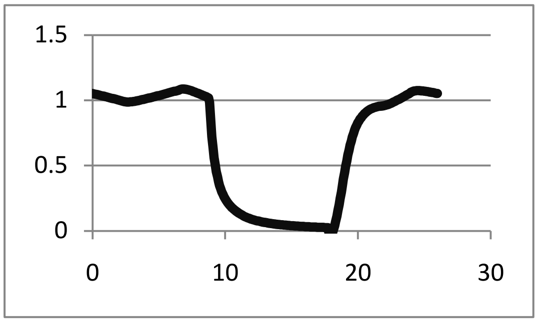

Fig. 5 Tip-to-Face Temperature variation over a single lunation. This is an acceptable 1^{o}K.

In order to discuss the results of the thermal simulations in a form that addresses the required optical 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). This directly affects the divergence of the outgoing beam and thus the signal strength back on the earth. Thus we need to determine how this TtFF gradient changes during a lunation (i.e., the changing sun angle during the day/night cycle on the moon). It is this gradient that will change the index of refraction and thus disturb the strength of the return beam to the earth. In figure X we see the variation of the gradient, which is approximately 1 degree with the current configuration. We are still proceeding to optimize this further. In addition, certain optical procedures can be used to further reduce the effect of the beam spreading. In addition, there are optical design procedures that allow us to reduce the effective temperature difference from the tip to the face to 0.5 degrees. 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.

9. Thermal Challenges

Overall with housing and regolith

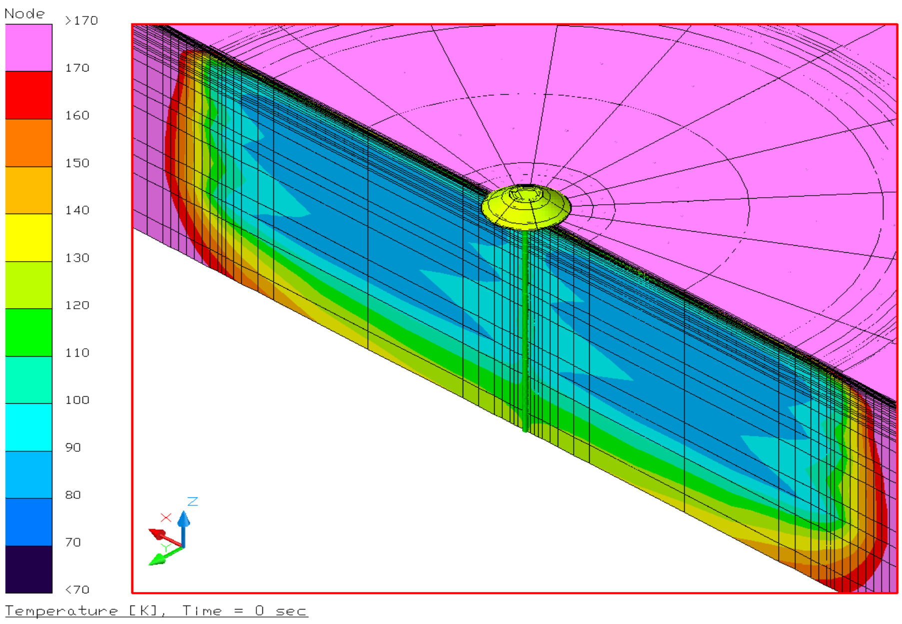

Fig. 6 Temperature distribution in the regolith with mushroom housing and 2 meter thermal blanket after equilibrium.

In the analysis of the previous section, we assume certain parameters for the housing temperature etc. However, to be accurate, one must develop an integrated model in which one has a housing design, a model for the behavior of the regolith and the coupling of these effects. Such a model has been developed and the thermal behavior simulated through a full lunation. The results of one such run are shown in the Fig. 6, in which one has included the effect of the support rod (discussed in the next section), the solar effect on the housing, the thermal blanket and so on. In particular, this uses the mushroom design and uses an aluminum support rod. In fact, the plot of the temperature gradient across the CCR shown in Fig 5 was derived by this “whole” model. Again, Fig. 6 is one frame in a sequence that covers an entire lunation, after many lunation to establish the “final state” distribution.

10. Emplacement Challenge

To attain the required mechanical stability w.r.t. the center of mass of the moon, we must understand and simulate the temperature distribution in the regolith, the effects of the thermal blanket that will be spread about the CCR and the effects of heat conduction in the INVAR support rod. A locking depth is chosen such that the thermal motion effects are small. The blanket further reduces the thermal effects and also reduces the effects of the conduction in the support rod. This simulation cycles through the lunation and annual cycles

11. Current Housing Designs

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 manned emplacement and the use of the 100 mm solid CCR in the MAGIA mission and/or in the ILN Anchor nodes. Thus we illustrate the current designs in Fig. 7 and Fig. 8. Fig. 8 is the configuration that was used for the above simulations. Fig. 8 also illustrates the design that is most similar to the configuration that is being used in the thermal vacuum tests. Fig.7 is the design for the lunar surface. Other designs have been addressed for the Italian Space Agency MAGIA mission [15, 16] which will carry our 100 mm CCR into lunar orbit (if and when it receives final approval).

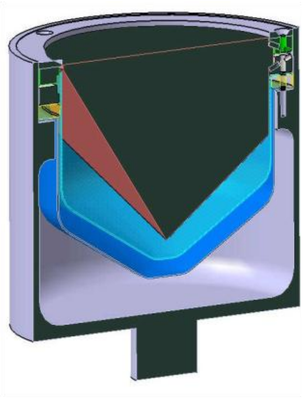

Fig. 7 Housing for MAGIA and ILN. Also housing tested in SCF

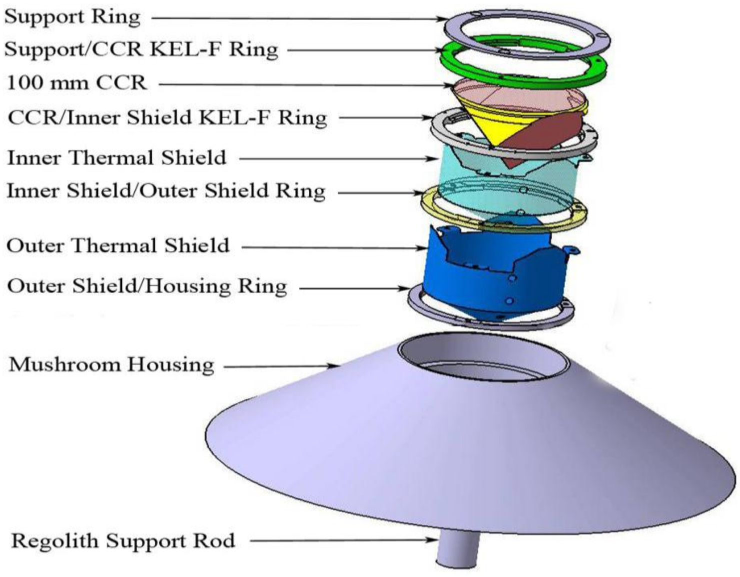

Fig. 8 This Figure Illustrates the Current Design for Manned Lunar Landing

12. Thermal Vacuum Chamber Testing

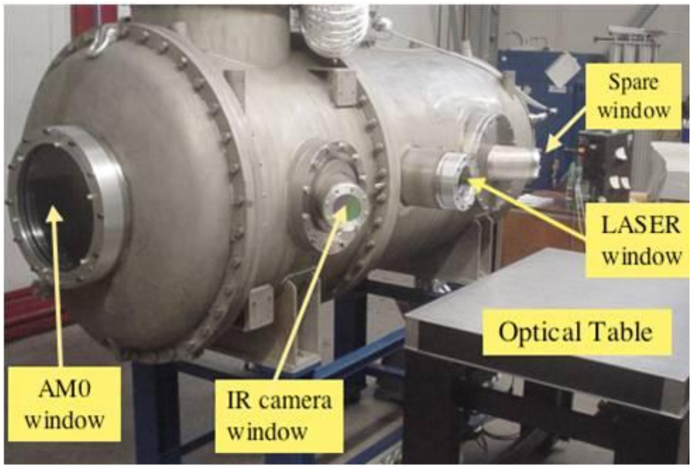

Fig. 9 SCF (thermal vacuum chamber in Frascati) indicating the windows for various functions

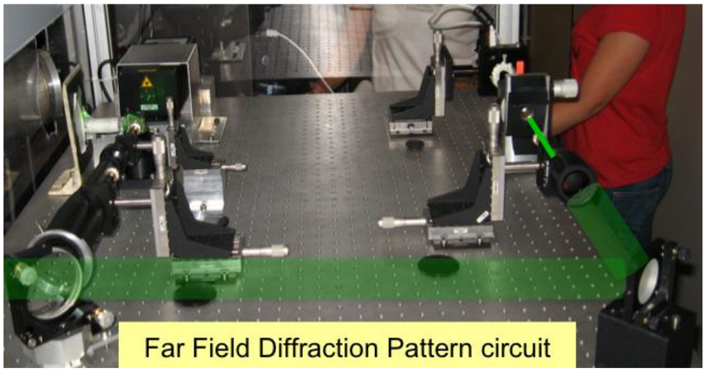

Fig. 10 Optical table for measuring the far field diffraction

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. This is the crucial test of a CCR package and is performed with the CCR in the chamber. 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 in Frascati, Italy with the solar simulator, the temperature data recording with an infrared camera and the measurement of the Far Field Diffraction Pattern (FFDP).

13. Launch Requirements

We are just beginning a study of the requirements of launch. This particularly addresses issues of the support of the CCR by the tabs in the vibration and acceleration environment of the launch. To this end, we have formulated a first example of a structural analysis with ANSYS [17,18]. In particular, we are addressing the contact between the CCR edge (i.e., the three tabs on the side of the CCR) and support plastic rings made of KEL-F. The role of the rings is particularly important since we have presumed a configuration with extremely low mount conductance. This will check the stability and strength of the tab support and the KEL-F line support for 10 g launch accelerations (e.g., in excess to the 6 g characteristic of the ATLAS V launch specifications). We are also performing a modal structural analysis of the inner gold plated thermal shield for an ATLAS V launch.

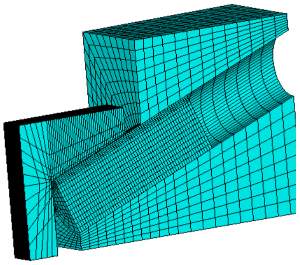

Fig. 11 ANSYS model for tab support

14. 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 to 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 in Frascati
    a. Evaluate different design options
        i. NASA Manned Lunar Landing
        ii. MAGIA – The Italian Space Agency Lunar Orbiter
        iii. ILN – The International Lunar Network Anchor Nodes
    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

15. Mission Opportunities

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

However, since then several other opportunities have arisen. The International Lunar Network 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 Lunar Laser Ranging.

In addition, a Phase Study for the Italian Space Agency for the MAGIA mission [11,12], which is a lunar orbiter, has been completed. The MAGIA spacecraft would include our LLRRA-21. It is awaiting a down selection in preparation to funding for the flight.

16. 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 Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati (INFN-LNF). We also wish to thank the support of the Italian Space Agency (ASI) during the 2007 lunar studies and the 2008 Phase A study for the proposed MAGIA mission. The first author would also like to acknowledge helpful conversation with Jack Schmidt, Ken Nordtvelt and Ed Aaron.

17. References

1. Bender, P. L.; Currie, D. G.; Dicke, R. H.; Eckhardt, D. H.; Faller, J. E.; Kaula, W. M.; Mulholland, J. D.; Plotkin, H. H.; Poultney, S. K.; Silverberg, E. C.; Wilkinson, D. T.; Williams, J. G.; Alley, C. O. *The Lunar Laser Ranging Experiment* Science, Volume 182, Issue 4109, pp. 229-238, 1973

2. Currie, D. G.; Dell'Agnello, S.; Delle Monache, G.; Murphy, T.; Vittori, R.; Carrier, D.; Cantone, C.; Garattini, M.; Boni, A.; Martini, M.; Lops, C.; Intaglietta, N.; Bellettini, G.; Tauraso, R.; March, R.; Bianco, G.; Rubincam, D. *A Lunar Laser Ranging Retro-Reflector Array for NASA's Manned Landings, the International Lunar Network and the Proposed ASI Lunar Mission MAGIA* Sixteenth International Workshop on Laser Ranging Instrumentation Poznan Poland, October 13-17, 2008

3. Ratcliff, J. T.; Williams, J. G.; Turyshev, S. G. *Lunar Science from Laser Ranging - Present and Future* 39th Lunar and Planetary Science Conference, (Lunar and Planetary Science XXXIX), held March 10-14, 2008 in League City, Texas. LPI Contribution No. 139, p.1849

4. The MAGIA prime contractor is Rheinmetall talia SpA; the MAGIA PI is Angioletta Coradini of INAF-IFSI.

5. Williams, J. G.; Boggs, D. H.; Ratcliff, J. T. *A Larger Lunar Core?* 40th Lunar and Planetary Science Conference, (Lunar and Planetary Science XL), held March 23-27, 2009 in The Woodlands, Texas, id.1452

6. Williams, J. G.; Turyshev, S. G.; Boggs, Dale H. *Lunar Laser Ranging Tests of the Equivalence Principle with the Earth and Moon* International Journal of Modern Physics D, Volume 18, pp. 1129-1175 (2009).

7. Rambaux, N.; Williams, J. G.; Boggs, D. H. *A Dynamically Active Moon - Lunar Free Librations and Excitation Mechanisms* 39th Lunar and Planetary Science Conference, (Lunar and Planetary Science XXXIX), held March 10-14, 2008 in League City, Texas. LPI Contribution No. 1391, p.1769

8. Williams, J. G.; Boggs, D. H.; Ratcliff, J. T. *Lunar Tides, Fluid Core and Core/Mantle Boundary* 39th Lunar and Planetary Science Conference, (Lunar and Planetary Science XXXIX), held March 10-14, 2008 in League City, Texas. LPI Contribution No. 1391., p.1484

9. Nordtvedt, K. *Lunar laser ranging: a comprehensive probe of post-Newtonian gravity* Gravitation: From the Hubble Length to the Planck Length. Edited by Ignazio Ciufolini, Eugenio Coccia, Vittorio Gorini, Roberto Peron, Nicola Vittorio. ISBN 07503 0948 2. Published by Institute of Physics Publishing, the Institute of Physics, London, 2005, p.97

10. Murphy, T. W.; Adelberger, E. G.; Strasburg, J. D.; Stubbs, C. W.; Nordtvedt, K. *Testing Gravity via Next-Generation Lunar Laser-Ranging* Nuclear Physics B Proceedings Supplements, Volume 134, p. 155-162.

11. Nordtvedt, K. *Testing the Equivalence Principle with laser ranging to the Moon* Advances in Space Research, Volume 32, Issue 7, p. 1311-1320.

12. Dvali, G.; Gruzinov, A.; and Zaldarriaga, M. *The Accelerated Universe and the Moon* Physical Review D, vol. 68, Issue 2, id. 024012

13. ASTM E40090 *Solar Constant and Zero Air Mass Solar Spectral Irradiance*

14. Private Communication

15. Dell'Agnello, S.; Currie, D.; Delle Monache, G.; Vittori, R.; Bellettini, G.; March, R.; Tauraso, R.; Boni, A.; Cantone, C.; Garattini, M.; Lops, C.; Martini, M.; Prosperi, C. *Fundamental Physics with the ASI Lunar Mission MAGIA (Phase A Study)* NLSI Lunar Science Conference, held July 20-23, 2008 at NASA Ames Research Center, Moffett Field, California, LPI Contribution No. 1415, abstract no. 2146.

16. ASI call document DC-PRZ-2007-002, *Invitation to the Presentation of Proposal for Small Missions.*

17. Prete, F. *Contact Structural Analysis of the MoonLIGHT Laser Retro-reflector Assembly with ANSYS* Bachelor Thesis (unpublished), Dipartimento di Meccanica e Aeronautica, University of Rome “Sapienza”

18. Minghiglioni, A. *Modal Analysis of the MoonLIGHT Laser retro-reflector Assembly with ANSYS* Bachelor Thesis (unpublished), Dipartimento di Meccanica e Aeronautica, University of Rome “Sapienza”