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A Lunar Laser Ranging Retroreflector Array for the 21st Century

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Abstract

To date, lunar laser ranging to the Apollo retroreflector arrays, which are still operational after four decades, has produced some of the best tests of General Relativity. Since the ground Observatories have improved their accuracy by a factor of 200, the lunar hardware, due to the lunar librations, now limits the ranging accuracy. The Lunar Laser Ranging Retroreflector Array for the 21st Century program plans to deploy new packages that will improve the ranging accuracy by a factor of ten to one hundred in the next few years.

Keywords: Lunar Laser Ranging; Apollo Retroreflectors; General Relativity; Strong Equivalence Principle; Selenophysics; Lunar Core; Optical/Thermal Simulation

1. Introduction and Motivation

One may ask why we should we care about gravity? For the past five centuries, gravity has been the central feature in our understanding of the external universe in what is now called astrophysics and cosmology. Tyco Brahe, Kepler, Newton and Einstein - all these great minds have described and analyzed both the observations and the theory describing gravity.

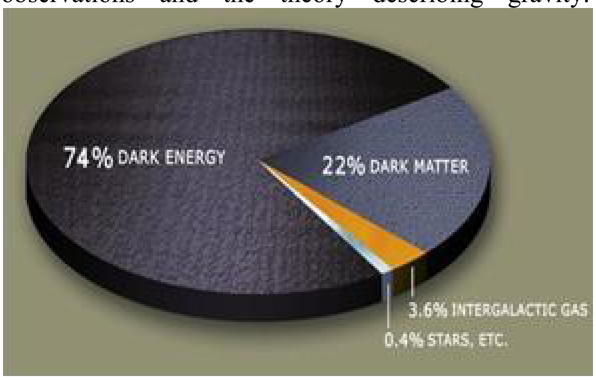

Figure 1 Illustration of the various major contents of the currently known Universe. This illustrates the importance of the Dark Energy and Dark Matter.

Therefore today we should now have a complete understanding of these phenomena. However, today as we look out to the cosmos, the components of the universe known to Newton and Einstein makes up less than 1% of the universe. Dark Matter and Dark Energy dominate the observed universe as illustrated in Figure 1 and we have yet to understand them. Even worse, in the last century Quantum Mechanics has accurately explained the behavior of the microscopic world and has been tested with phenomenal accuracy. And yet we know that Einstein's General Relativity and Quantum Mechanics cannot both be correct. For all of these reasons we must keep pushing on more tests of General Relativity, testing to the limit of available technology.

2. Background of Lunar Laser Ranging

Back in the days of the Apollo Missions, a group, initially centered under Robert Dicke at Princeton University and then led by the University of Maryland, College Park, investigated the possibility of using laser ranging to the moon to address critical questions in General Relativity and Lunar physics. At this time,

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two critical events entered the consideration. The first was the invention of the laser. The second was John F. Kennedy's announcement of landing men on the moon. A concept using retroreflectors was developed and analyzed. This special set of mirrors was then fabricated, carried to the moon and deployed by the astronauts [1],[2]. The "Lunar Laser Ranging Observatory" was developed using the 107" telescope at the McDonald Observatory in Texas [3] to fire short laser pulses to the mirrors, which then send the light directly back to the observatory. By timing the interval between transmission and return we were able to determine the distance with an uncertainty of ~300 mm. All the other Apollo experiments left on the moon required power and communication. As a result, they shut down after a few years, however, these retroreflectors are still operating and ranging to them continues to this day. The analysis of these data continue to generate new discoveries about gravity and lunar physics.

3. Operational Procedure

The process of Lunar Laser Ranging (LLR) consists, first, of placing on the lunar surface the retroreflectors. These are special prisms that can receive a laser pulse from the earth and send it directly back in the same direction as it came with no delay and in a well collimated manner. As a result the return light signal reaching earth is strong enough to be detected.

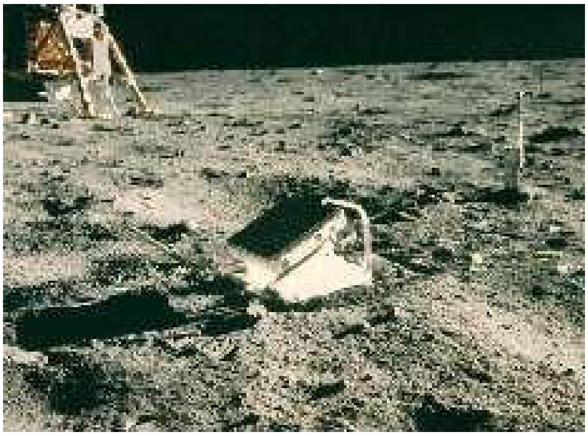

Figure 2 The retroreflector array as placed on the lunar surface by Neil Armstrong during the Apollo 11 Mission.

Thus the retroreflectors are a very effective device to assure a useful signal level on earth. At an observatory on earth, a laser system transmits a short pulse in time that is spatially coherent. This very narrow laser beam is then collimated and pointed with a telescope system. Initially these were large astronomical telescopes, but today they may also be smaller telescope dedicated to satellite and lunar ranging. This short pulse (<1 nanosecond, where a nanosecond of delay of the pulse return represents 15 centimeter of range) is then directed toward the moon. A small portion of the light returns to earth and is collected by the telescope. This time interval of ~2.5 seconds between transmission and return is precisely measured and stored for processing.

These measurements are taken frequently. Originally, at a rate of three times a day, but at a lower rate today. This time series of measurements is then compared to the current best model of the lunar orbit and the librations of the moon. A model of the orbit and the physical librations has been developed by the Jet Propulsion Laboratory (JPL) and accounts for the effects of the other planets and other bodies in the solar system. The differences between the measured and modeled ranges (a.k.a. the residuals) are then analyzed to address the various signatures that are seen in the time series. Specific signatures can be connected with the specific parameters entering the model and used to adjust the values of the orbital and librational parameters to obtain a more accurate model, reduce the magnitude of the residuals and provide more accurate values for the physical parameters associated with the signatures. Thus the new values of the parameters related to General Relativity and the structure of the moon are determined.

4. What has the LLR Program Accomplished

A primary objective of the Lunar Laser Ranging (LLR) experiment is to provide precise observations of the lunar orbit and librations that contribute to a wide range of science investigations. This time series of the highly accurate measurements of the distance between the Earth and Moon provides unique information used to determine a variety of properties of gravitation, relativity and lunar physics.

Some of the results are that gravitational energy has the inertial properties of mass, that the change of gravity over the past four decades project to the past to show that the change since the big bang is less than ~1 percent.

4.1 *Gravitation and Relativity Physics*

Equivalence Principle

The LLR measurements can determine if the observations are in accordance with the Equivalence Principle (EP), that is, are both the earth and the moon are falling towards the Sun at the same rate, despite their different masses, compositions, and gravitational self-energies. Current LLR solutions give -1 +/- 1.4 times 10^{-13} for any possible inequality in the ratios of the gravitational and inertial masses for the Earth and Moon, Δ(M_G/M_I). This result, in combination with laboratory experiments on the Weak Equivalence Principle, yields a Strong Equivalence Principle (SEP) test of Δ(M_G/M_I)SEP = -2.0 +/- 2.0 x 10^{-13}. Such an accurate result allows other tests of gravitational theories. The result of the SEP test translates into a value for the corresponding SEP violation parameter η of 4.4 +/- 4.5 x 10^{-4} where $\eta = 4\beta-\gamma-3$ and both β and γ are the parametrized post-Newtonian (PPN) parameters. The parameter β is determined to be β-1 = 1.2 +/- 1.1 x 10^{-4}. Focusing on the tests of the EP, we can discuss the existing data, and characterize the modeling and data analysis techniques. The robustness of the LLR solutions is demonstrated with several different approaches that are discussed in [4] .

Changes of the Gravitational Constant

Einstein's general theory of relativity does not predict a variable gravitational constant G, but some other theories of gravity do. Among the most promising extensions of relativistic gravity beyond General Relativity are the scalar-tensor theories. These theories can imply small violations of the equivalence principle as well as a time-varying gravitational "constant", two quantities that LLR determines very well. Different aspects of metric theories of gravity can described using the Parametrized Post-Newtonian (PPN) β and γ parameters. These PPN parameters have a unit value for General Relativity, but a deviation from unity at levels of 10^{-5} to 10^{-7} has been predicted by Damour and Nordtvedt [5] and Damour, Piazza, and Veneziano [6]. The great stability of the lunar orbit allows LLR to use the orbital motion to make accurate tests of the gravitational physics. The following discussion addresses the role of the LLR tests of the equivalence principle, and its implication for the PPN parameter β, and for the variation of the gravitational constant. The following papers address the LLR solution results using LLR data through April 2004 [7],[8].

A changing G would alter the scale and periods of the orbits of the Moon and planets. LLR is sensitive to this change of G (G^{dot}/G) at the 1 AU scale of the annual orbit about the Sun [8]. No variation of the gravitational constant is discernible, with G^{dot}/G = (4±9)x10^{-13}/yr. This is the most accurate result published to date. This uncertainty corresponds to ~0.6% of the age of the universe. The scale of the solar system does not share the cosmological expansion. The sensitivity of changing G depends on the square of the LLR time span so significant improvements are expected when future data accumulate.

Variation in the Speed of Light

Considering the possible variation of the speed of light provides an illustration of the power of the LLR results to constrain alternate theories of gravitation. In the lunar anomaly paper [9] it is proposed that the speed of light c is slowing with time. Although a slowing speed of light would cause an increase in the apparent lunar distance (which is seen), it would not change the tidal acceleration in orbital longitude, already conflicting with the observational results given earlier. Still, an apparent non-tidal increase in distance or scale is a testable prediction. LLR data was analyzed to seek any rate of change of the round-trip time of the laser pulse, the “range”, that was distinct from lunar tidal acceleration and recession [8], [10]. Apart from tidal recession, [8], [10] found a limit for the absolute value of any anomalous distance rate of <3.5 mm/yr; a limit that converts to |scale rate| = $|(\delta c/\delta t)/c| < 0.9\times10^{-11}$ /yr. This limit is smaller than the prediction in [9] of –2.4x10–11 /yr for (δc/δt)/c, or +9 mm/yr in apparent distance. Thus we see that, at least for the values for the change in the velocity of light stated in [9], the LLR results have indicated that this is not a valid description of gravity.

Gravitational and Relativity Objectives

The objective of these measurements and this analysis is to address the various theories that have been formulated to explain Dark Matter and Dark Energy. For example these include the Bran-Dicke theory, the Galileaon theory, braneworld scenarios, f(G) where G is the Gauss-Bonnett terms, Hooraxa-Lefshitz theory, MOND and TeVes theories. Reviews of these theories may be found in references [11]. While most of these papers address the magnitude of the constraints that the LLR measurements imply for the theory, the most interesting results will be to address if these theories can explain the magnitude of the observed Dark Matter and/or Dark Energy within the current LLR constraints. The theories that remain viable will be addressed by ranging to the next generation retroreflector that are proposed here.

4.2 *SelenoPhysics Results*

We now consider two of the various discoveries provided by the LLR program concerning the lunar interior and crust.

Inner Molten Core and Oblateness of CMB

By the observation of the dissipation of the free librations, a liquid inner core was discovered in 2002 [12]. Further, the detection of the oblateness of the fluid-core/solid-mantle boundary (CMB) is independent evidence for the existence of a liquid core. In the first approximation, CMB oblateness influences the tilt of the lunar equator with respect to the ecliptic plane [13]. Parameters for CMB flattening, core moment of inertia, and core spin vector, are introduced into torque T_{cmb} in the numerical integration model used for lunar orientation and partial derivatives. Equator tilt is also influenced by moment-of-inertia differences, gravity harmonics and Love number k_2, solution parameters affected by CMB oblateness. Solutions can be made adjusting the core and mantle parameters.

The torque from an oblate CMB shape depends on the product of the fluid core moment of inertia and the CMB flattening, fCf = (Cf–Af), where the pole and equator fluid core moments are Cf and Af. Both are uncertain and there is no information about flattening apart from these LLR solutions. The LLR solution gives $f = (Cf–Af)/Cf = (2.5\pm1.4)x10^{-4}$ [12] ,[14]. For a 370 km core radius the flattening value would correspond to a difference between equatorial and polar radii of about 90 m with a large uncertainty. The f uncertainty seems to imply weak detection at best, but the derived oblateness varies inversely with fluid core moment, as expected theoretically, so a smaller fluid core corresponds to a larger oblateness value. The product $fCf/C = (Cf–Af)/C = (1.7\pm0.5)x10^{-7}$ is better determined than f alone. Core flattening appears to be detected and the foregoing product is more secure in a relative sense than the value of f itself. In the solution the corrections to core moment and CMB flattening are from the DE430 ephemeris [14], [12].

Free Librations

The differential equations for lunar rotation have normal modes, three for the mantle and one for the fluid core. Dissipation has been recognized by LLR from both tidal flexing and the fluid/solid interaction at the core/mantle boundary. Dissipation introduces a phase shift in each periodic component of the forced physical librations. It might be expected that the free physical librations associated with these normal modes would be imperceptible since the damping times are short compared to the age of the Moon.

However, substantial motions are found for two of the modes [15], [16], [17], [18], [19], [20] and we have to ask what is the source of this stimulation? Reported in [20] are the results from the recent effort that analyzed the DE421 numerically integrated physical librations. The free physical librations depend on the initial conditions for the Euler angles and spin rates, which are adjusted during the LLR fits. The integrated Euler angles were fit with polynomials plus amplitudes and amplitude rates for trigonometric series. More than 130 periodic terms were recognized in two latitude libration angles, while longitude libration yielded 89. The free libration terms were identified among many forced terms.

The longitude mode is a pendulum-like oscillation of the rotation about the (polar) principal axis associated with moment C. The period for this normal mode is 1056 d = 2.89 yr and the amplitude is 1.3" (11 m at the equator). The damping time is $2x10^4$ yr. The lunar wobble mode is analogous to the Earth's polar motion, that is, the Chandler wobble, but the period is much longer and the path is elliptical. Observed from a frame rotating with the lunar crust and mantle, the rotation axis traces out an elliptical path with a 74.6 yr period. The amplitudes are 3.3" x 8.2" (28 m x 69 m). The computed damping time is about 106 yr. The two remaining free modes are retrograde precession modes when viewed from a nonrotating frame in space. The mantle free precession of the equator (or pole) has an 81 yr period. An amplitude of 0.03" is found for this mode, but there is uncertainty because the LLR fit for the integration initial conditions appears to be sensitive to the lunar interior model. The expected damping time is $2x10^5$ yr. The fluid core free precession of the fluid spin vector has an expected period >100 yr; it would be 300 yr for the DE430 integration. The period depends on the CMB flattening previously discussed under Core Oblateness. Based on the trigonometric analysis, this mode must have a small amplitude.

5. Optical Libration Problem

As discussed above, the retroreflector arrays left by the astronauts of the Apollo missions have been responsible for a large number of new science results, in gravity, relativity and selenophysics. One might ask why the push for a new set of retroreflectors when we are still generating new science with the Apollo arrays.

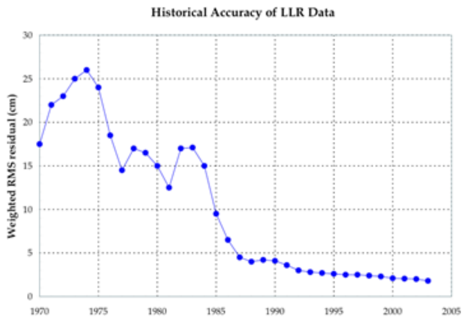

Figure 3 Plot showing the agreement between the ranging observations and the best fit model. In the recent decades this fit has an r.m.s value of ~19 mm.

During the past four decades, the laser ranging observatories on the ground have improved measurement accuracy by more than a factor of 200. As a result, our current limiting accuracy is defined by the Apollo arrays in conjunction with the optical lunar librations. Optical librations are the changes in the apparent direction to the earth as seen from the moon due to the eccentricity and inclination of the lunar orbit. The Apollo retroreflectors each consist of a panel with 100 or 300 38 mm CCRs. During the monthly optical libration pattern, the angular offset of the normal to the panel with respect to the direction to the earth becomes as large as 8˚ in longitude and 7˚ in latitude. Thus, as the moon rotates, the panel is tipped

Figure 4 The 100 mm CCR fabricated to demonstrate the capability to meet the required specifications next to one of the CCRs from the Apollo project.

with respect to the normal to the direction to the earth. Intuitively, this means that we do not know whether a photon was reflected by a CCR at the furthest corner of the panel or the nearest corner. This results in an r.m.s. uncertainty of 24 mm for the Apollo 11 and 14 retroreflector arrays and 46 mm for the Apollo 15 reflector. For unfavorable optical librations the uncertainty can be as large as 70 mm for the Apollo 15 array. On a more practical level, the result of the optical librations is to produce a spread in the temporal width of the return pulse, so it is not effective to install a laser with an extremely narrow pulse. Today, the only method of obtained millimeter ranges is to have a large astronomical telescope and to record thousands of returns. This results in fewer observation sessions per month and means that laser observatories with smaller aperture telescope cannot achieve the millimeter results. Primarily for these reasons, the agreement between the observations and the best fit model has reached a plateau of ~20 mm over the past two decades. To address an improvement by a factor of ten to one hundred, NASA and the NASA Lunar Science Institute have supported our development of the next generation of retroreflector, the "Lunar Laser Ranging Retroreflector Array for the 21st Century (LLRRA-21).

5.1 Solution to Optical Libration Problem

The LLRRA-21 is based upon a single large solid Cube Corner Reflector. The fact that there is a single CCR rather than an array of smaller CCRs means there is no ambiguity as to where the return comes from, and thus it supports the use of a much shorter laser pulses to obtain a much more accurate timing of each return photoelectron. The LLRRA-21 will be ready for flight within the next year. This should improve our ability to address critical science questions concerning gravity, relativity and the properties of the moon by a factor of 10 to 100, depending upon the method of deployment on the lunar surface.

5.2 Challenges Involved for a Large Solid CCR

While, as mentioned, the use of a single large solid Cube Corner Reflector is a theoretical solution to the optical libration problem, there are significant technical challenges to accomplish this in a practical manner in the challenging environment of the lunar surface. We will discuss the three most important challenges: the fabrication of the CCR, the optico-thermal distortion due to the harsh lunar environment and the stability of the emplacement on the lunar surface.

Fabrication of Large Cube Corner Reflectors

The angular tolerances required for the fabrication of the 100 mm CCR are a factor of ~2.5 more stringent than the normal state of the art for the fabrication of the 500 original Apollo CCRs and the thousands of CCRs currently used in satellites. To address the feasibility of meeting these requirements, we have fabricated a 100 mm CCR for which the requirements of an accuracy of 0.2 arc second were met and exceeded. On the other hand, we have found that the technology for measuring the angles of such a prism requires a deeper investigation. Extensive data is being collected and discussions with the manufacturer of the interferometers are proceeding to address this issue.

In addition, for the size of the 100 mm CCR, the homogeneity of fused silica material is a challenge. A measurement program is also underway to address this issue.

Thermal Control to Reduce Thermal Gradients

The high temperatures during lunar day, reaching ~400^{o}K, cause the housing to be much hotter than the CCR. As a result of the radiation transfer to the back of the CCR, there are significant thermal gradients within the CCR. Due to the temperature dependence of the index of refraction, this results in gradients in the index of refraction within the CCR. These in turn result in the degradation of the collimation of the return beam going back to the observatories on earth, which reduces the observed signal level. Thus the harsh environment of the lunar surface, where the temperature can range from 100K to nearly 400K means that thermal control is extremely important. This is far more important than in the case of earth orbiting satellites and more even, due to the larger size of the LLRRA-21 CCR, then that for the Apollo arrays.

Emplacement Goals for Long Term Stability

The final major challenge addresses the ability to maintain a known defined relation between the optical center of the CCR and the Center of Mass (CoM) of the moon. This is important since the tests of General Relativity involve the motion of the CoM of the moon on the orbit, that is, the motion of the CoM moon along a geodesic as addressed by General Relativity. However, the harsh thermal environment of the lunar surface makes this a challenge. To address this, we consider three different deployment approaches:

Deployment on the Lunar Lander

The deployment of the LLRRA-21 on a lunar lander is the most likely expectation in the near future. This has the advantage of requiring the minimum of auxiliary equipment and minimizes the required mass for the transport. On the other hand, it suffers from the change in height due to the thermal expansion and contraction of the lander itself. This will limit the accuracy for a single photoelectron return to a few millimeters or greater depending upon the structure of the lander and the mission. While some of the science is affected by this, other science elements can benefit in that such an emplacement will allow millimeter ranging by additional stations. This will assure a continuing observation program over the next few decades. In order to reach the millimeter level, one will require ten or more returns to obtain a one millimeter normal point. Such a deployment is being developed with several flight candidates that could provide the ride to the moon. For example, the Moon Express team is developing a lander shown in Figure 5. Since the LLRRA-21 must be pointed back toward the earth to within 1 or 2 degrees and since the lander landing orientation will not have this accuracy, we need a dedicated pointing mechanism. Such a mechanism is being developed at the University of Maryland and at Sant'Anna University in Italy. Figure 13 illustrates the conceptual design currently being developed.

Figure 5 A *model of our Lunar Laser Ranging Retroreflector for the 21st Century mounted on the instrument platform of the model of MoonEx1 is shown. In the background are Joe Lazio, Deputy PI of LUNAR, Jack Burns, PI of LUNAR, Doug Currie, PI of LLRRA-21, Bob Richards, COO of Moon Express and Alan Stern, Chief Scientist of Moon Express.*

Deployment on the Lunar Surface

The second method of deployment is to place the package directly on the regolith. This will result in a reduced effect of the thermal motion but still be subject to the thermal motion of the regolith, which is a significant portion of a millimeter. This will require a careful thermal design of the support so that it does not contribute to the thermal motion. A candidate for this type of deployment is shown in Figure 6. This method of deployment requires the lander have an articulated arm in order to deploy the surface-mounted LLRRA-21.

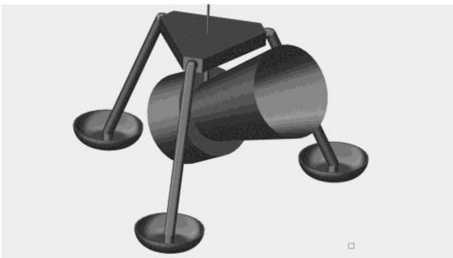

Figure 6 Artist's concept of the current design for the surface deployment possibility. The indicated "tripod" is composed of silicon carbide to achieve a very low coefficient of thermal expansion. In addition, a special coupling between the tripod and the LLRRA-21 counteracts the residual coefficient of thermal expansion of the silicon carbide.

Anchoring the CCR to the Deep Regolith

In order to escape the problem of the vertical thermal motion of the regolith, we note that at a depth of 0.5 to 1.0 meters, the temperature remains essentially constant during a lunation. Therefore, if we were to anchor the LLRRA-21 to this depth we could deploy the LLRRA-21 in a manner to escape the day to night vertical motion of the regolith. The CCR would then be attached to this deep anchor by a support rod composed of a low thermal expansion material such as INVAR or silicon carbide. However, the process of drilling of the hole for the support rod and anchor would appear to be a non-trivial challenge. During the Apollo mission, drilling was quite difficult (see Figure 7 with Jack Schmidt and Gene Cernan on Apollo 17). This was primarily because previous drilling methods attempted to compress the regolith. In general, the mechanical properties of the regolith strongly resist such compression. However Kris Zacny at Honeybee [21] has developed a technique

Apollo 17 Spill

Figure 7 Drilling operation by Jack Schmidt and Gene Cernan which illustrates the challenges of conventional drilling in the regolith regolith.

– pneumatic drilling – in which the support rod is hollow and gas is sent down the hollow core. When the gas exits the hole in the tip, it blows the regolith particles out of the newly formed hole. This technology has already been tested using a 100 mm

Honeybee Lab Test

Figure 8 Demonstration that the pneumatic drilling technique needs only the weight of the CCR to excavate a hole in compacted JSC1a lunar regolith simulant.

CCR with compacted JSC1a lunar regolith simulant. (Figure 8). Further tests of the pneumatic drilling have been conducted with the compacted JSC1a in vacuum and at lunar gravity. In order to address the feasibility of implementing such a drilling technique during an actual lunar landing, Zacny has developed a conceptual design for the deployment of the pneumatic drill with a CCR on the lander being developed by the Astrobotics Team (Figure 9) [22]

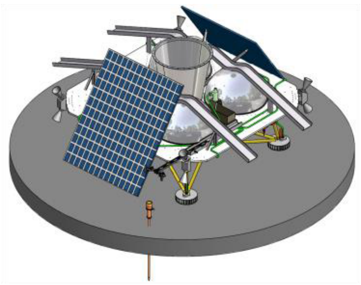

Figure 9 Artist's concept of the Astrobotics lander showing the deployment mechanism on the lander and the deployed LLRRA-21 in the anchored mode.

6.0 Current Status of LLRRA-21 Program

6.1 LLRRA-21 Design

The preliminary design of the LLRRA-21 package has been completed. This design is illustrated in Figure 10. The sunshade, in yellow at the top, blocks the direct sun into the CCR for most of the lunar day. It also reduces the exposure of the CCR to dust that could accumulate on the front surface of the CCR, reducing the return signal. Such a problem has greatly reduced the magnitude of the return signal but not the accuracy of the Apollo arrays. The CCR is shown in red. Below the CCR are two thermal shields of very low emissivity, to prevent radiation emitted from the internal surface of the housing from being absorbed by the CCR and generating thermal gradients. The interior surface of the inner thermal shield is shaped like an open CCR and has a silver coating to effectively reflect most of whatever solar radiation breaks through the total internal reflection back to space. Finally, the housing encloses the CCR and the thermal shields and serves as the interface to the lander/pointing mechanism. The current prototype is shown in Figure 11. This illustrates the stepped sunshade that significantly reduces the solar heating of the CCR and the thermal shields.

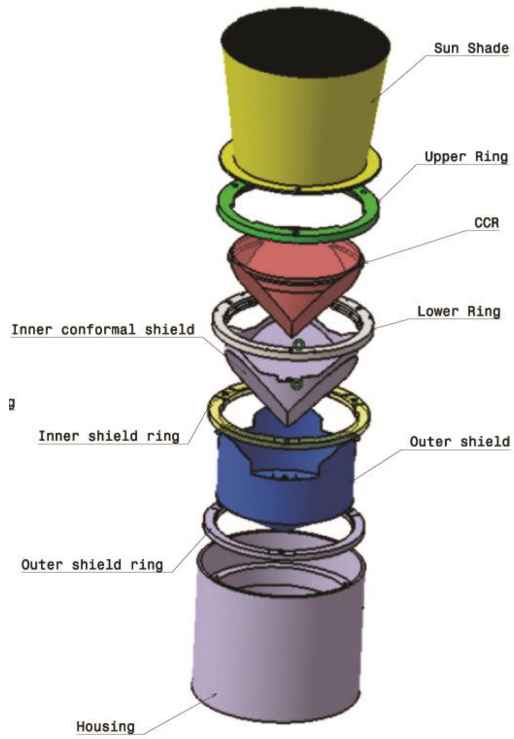

Figure 10 Artist conception of the current design of the LLRRA-21. The details are discussing in the adjoining text.

6.2 Solar/Thermal/Vacuum/Optical Simulation

In order to understand the thermal issues and in order to optimize the thermal performance a detailed set of programs has been developed to simulate the performance of the LLRRA-21 in the thermal environment of the lunar surface. These programs successively determine the heat loads, due to the solar radiation within the 3D volume of the CCR using IDL [23] programs developed at the University of Maryland. The commercial program "Thermal Desktop" [24] is then used to convert these heat loads into temperature distributions,. Themal Desktop accounts for the external solar inputs to the exterior surfaces of the LLRRA-21, the radiation exchange with the regolith as the latter changes temperature and the other radiation and conduction exchanges, both internal and with space that occur throughout a full lunation. The another set of IDL programs converts the 3D temperature distributions into changes in the index of refraction and finally the optical output in the form of a phase error map and finally to signal level that would be seen by the observatories back on Earth.

At present, the simulation programs are being used to select thermal coatings to optimize the performance. As a portion of this project, the thermal performance of the Apollo arrays is being developed to understand the effects of dust and other degrading processes. In the case of the Apollo arrays, we have observational data on the performance throughout a lunation and also during a lunar eclipse.

6.3 LLRRA-21 Brass Board Prototype

In order to understand the details of the challenges of fabricating the real hardware, we have developed a full prototype model of the LLRRA-21. This has also provided the basis for developing the procedures and mechanical jigs required for the assembly. This has been done using the primary components that are fully flight qualified. This is shown in Figure 11 although this is not the unit that would be expected to fly.

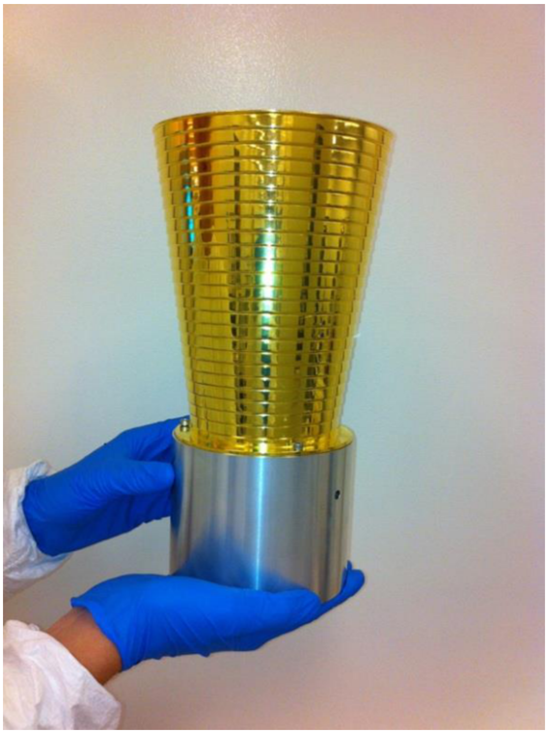

Figure 11 Prototype of the LLRRA-21 with stepped sunshade, housing and 100 mm CCR. This will be used in the Phase 2 thermal vacuum testing in the SCF in Frascati, Italy

6.4 Thermal Vac Testing of LLRRA-21

In order to address the validity of the thermal simulation, a series of thermal/vacuum/optical tests have been performed. These have been performed at a special facility, the **S**atellite/lunar laser ranging **C**haracterization **F**acility (SCF) at the Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati (INFN-LNF) in Frascati, Italy. This SCF has been created especially for testing retroreflector packages [25],[26]. It consists of a solar simulator, fused silica input window, a window for the laser illumination and optical evaluation of the CCR while under test conditions and an infrared transmitting window to allow an infra-red (IR) camera to evaluate the temperature distribution while the test is being conducted. The IR measurements allow a cross calibration with thermocouples that are distributed on the CCR and the other components of the package. Over the past year, the original chamber where the earlier tests were conducted has been upgraded and is now operating in a clean room facility suitable for testing flight hardware as seen in Figure 12. Figure 13 is an infra-red image of the CCR during one of the test indicating the temperature distribution across the front face of the CCR.

Figure 12 Thermal vacuum chamber to be used in the Phase 2 thermal vacuum testing of the LLRRA-21 at the new SCF facility consisting of a large clean room with two thermal/vac chambers.

7.0 But how do we get to the moon?

In response to the Google Lunar X Prize (GLXP) [28] a large number of commercial groups have started plans to accomplish a soft lunar landing. Included are

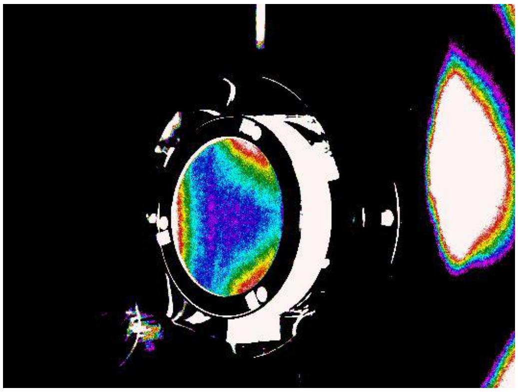

Figure 13 Infrared image of the 100 mm CCR under thermal vacuum test. Temperature variation illustrates the effect of tab conduction and radiation from thin regions.

several groups that have a commercial transportation objective. In particular, the current candidates that we are working with are Moon Express [29] and Astrobotics [22]. We have been discussing detailed interface issues with the Moon Express Team for mounting on the lander and, as mentioned earlier, created a design concept for an anchored emplacement. With Moon Express, located at the NASA Ames Reach Center in Mountain View CA we are planning a landing before the end of 2015. We have also a signed agreement with the Japanese group that is considering a retroreflector for SELENE-2 [30],[29].

Working with these commercial groups, Moon Express, Astrobotics and SpaceX is a refreshing experience. They have the youth, enthusiasm and excitement that I enjoyed in NASA in the early days.

8.0 Conclusions

In conclusion, the LLR program using the Apollo retroreflectors has demonstrated the feasibility of a space program with a lifetime of many decades and a ranging program that has been the source of unique results in the fields of gravity, relativity and selenophysics. Although Apollo retroreflectors continue to operate and provide unique new science results, they now limit the accuracy of the single photoelectron returns. A next generation of retroreflector has been described that is nearly ready for deployment on the lunar surface. The next generation retroreflector, the LLRRA-21, will support improvements in ranging accuracy, and the resultant scientific results, by factors of ten to one hundred, depending upon the method of deployment. Thus the scientific objective is to provide constraints on the theories that are proposed to accommodate an inclusion of the properties of Dark Matter and Dark Energy. This in turn will identify the theoretical directions that will further the development of an understanding of these mysterious phenomena that lie beyond our current understanding.

Abbreviations

Af	-- equator fluid core moments of ineretia
Apollo	-- NASA missions to the moon of 1969 - 1974
APOLLO	-- Apache Point Observatory Lunar Laser-ranging Operation
CCR	-- Cube Corner Reflector
CoM	--Center of Mass (of the Moon)
Cf	-- pole fluid core moment of ineretia
CMB	-- Core-Mantle Boundary
CoM	-- Center of Mass
ESA	-- European Space Agency
F	-- Core Mantel Flattening
GLXP	-- Google Lunar X Prize
GRACE	-- Gravity Recovery and Climate Experiment
GRAIL	-- Gravity Recovery and Interior Laboratory
IAS	-- Italian Space Agency
INFN	-- Istituto Nazionale di Fisica Nucleare
INFN-LNF	-- INFN-Laboratori Nazionali di Frascati
IR	-- Infra-Red
ISAR	-- Interferometric Synthetic Aperture Radar
JPL	-- Jet Propulsion Laboratory
LLR	-- Lunar Laser Ranging
LLRRA-21	-- Lunar Laser Ranging Retroreflector Array for the 21^{st} Century
LUNAR	-- Lunar University Network for Astrophysical Research
NASA	-- National Aeronautics and Space Administration
SCF	-- Space Climatic Facility
UMCP	-- University of Maryland at College Park

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