A LUNAR LASER RANGING ARRAY
FOR
THE 21ST CENTURY

A Proposal Submitted by

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1. SCIENTIFIC/TECHNICAL/MANAGEMENT

A. Overview and Background

We propose to place one or more improved retroreflector arrays on the Moon. Such arrays are perfect for lunar "suitcase science:" they are small, lightweight, completely passive requiring no power at all, and maintenance-free. Once an astronaut has successfully deployed an array, it need never be tended again. The useful lifetime of the array will be decades to a century or more. Furthermore, the risk to an astronaut is low: so low that the riskiest manned mission of all, Apollo 11--the very first manned mission to the Moon--deployed an LLR array which is still functioning 37 years later; and other Apollo missions deployed their own still-functioning arrays.

We have the maximum possible experience in this area: the Principal Investigator was part of the team which built and tested the very first LLRA which Apollo 11 took to the Moon, as well as the two succeeding Apollo arrays. These arrays have provided fiducial marks on the Moon for the last 37 years. The improvement in the reference accuracy was a factor of about 10,000 with respect to ranging to the surface of the Moon, which prior to the LLRA's was kilometers. The scientific results of this improvement in General Relativity, Geodesy, Geophysics and other fields have resulted in 2,000 papers and 10,000 references.

Until the past year, our design of the Apollo-era arrays provided reference points that were far more accurate than the ground-based technology used to interrogate them. Since Apollo 11, the accuracy of the single shot measurements has gone from 20 cm to ~4 cm. Today the linear dimension of the array, combined with the (geometric) lunar librations, results in a return pulse that has a full with at half maximum (FWHM) of about 8 cm. This improvement by a factor of 5 has come about due to intense research and great technology advances in lasers, in the understanding of lasers, in orbital modeling programs, and in detector and timing electronics.

At present without hardware improvement, one can only progress by using very large numbers of single shots to r.m.s. the errors down. This is being done successfully by the APOLLO program at Apache point, which hopes to eventually obtain millimeter accuracy with many thousands of shots in a given normal point.

The goal of our proposal is to provide an improved array that offers the possibility of another factor of 10,000 improvement in the range, down to the micron level. The basic design of our array is 8 single retroreflectors spread out over tens of meters. Each retroreflector sits in its own housing, unconnected to the other retroreflectors. This will allow identification of which retroreflector returns which photon, which is not possible with the meter-sized arrays currently on the Moon.

How do we get to our desired accuracy? The design of the Cube Corner Reflector (CCR) and the design of the housing are critical. Under our program, notional architectures will be fabricated and tested in an optical interferometric/thermal-vacuum facility, which is the Space Climatic Facility (SCF) at INFN in Italy. The Italians have agreed to make the tests in the SCF without cost to NASA. We believe we can reach the micron level with good thermal/mechanical design and detailed testing.

The most critical challenge is the “mounting” to the interior structure of the Moon. We will necessarily be on the regolith and subject to the thermal motions as the Sun rises and sets. Thus a strong component of our program will be addressing methods of deployment that minimize this effect, which will be the actual limiting accuracy of the facility. This intimately involves acceptable methods of deployment within the constraints of a first landing. We have astronaut Roberto Vittori on our team, who will address the astronaut side of the trade-offs between methods of deployment that minimize ranging errors and methods of deployment that minimize astronaut time and skill.

B. Relation of Goals to NASA

The NASA strategic goals relevant to the present investigation are the following:

Strategic Goal 3: Develop a balanced overall program of science, exploration, and aeronautics consistent with the redirection of the human spaceflight program to focus on exploration.

Subgoal 3C: Advance scientific knowledge of the origin and history of the solar system, the potential for life elsewhere, and the hazards and resources present as humans explore space. Mars and the Moon are important research targets...

The proposed LLRA will be hand-carried and placed on the Moon by astronauts as part of the human exploration program, so that the science package directly addresses the human exploration component of NASA’s mission..

A major scientific advance that can be supported with the Lunar Laser Ranging Array for 21st Century is the investigation of the role of dark matter. In a recent paper, G. Dvali has shown that our improved accuracy potential can address the acceleration of the universe on a “local” scale, that is, in the distance to the moon. This would be an extremely interesting investigation, since about 85% of the mass of the Universe must be accounted for in some form of dark matter.

Lunar Laser Ranging (LLR) has for decades provided the very best tests of a wide variety of gravitational phenomena, probing the validity of Einstein's theory of general relativity. The lunar orbit is obviously influenced by the gravity fields of the Earth and Sun, but also is sensitive to the presence of many other solar system bodies. This makes the dynamics of the lunar orbit complex, but the system is relatively pure in that non-gravitational influences (solar radiation pressure, solar wind, drag) are negligible. This makes the Earth-Moon distance a useful tool for testing the nature of gravity, constraining potential deviations from general relativity.

LLR currently provides the best constraints on:

* The Weak Equivalence Principle (WEP) at a level of 10^{-13}

* The Strong Equivalence Principle (SEP) at a level of $4x10^{-4}$

* Time-rate-of-change of Newton's gravitational constant, G, to a part in 10^{-12} per year

* Geodetic precession at a level of 0.35%

* Deviations from $1/r^2$ gravity at 10^{-10} times the strength of gravity

The equivalence principle states that any mass, independent of composition, will react (accelerate) in precisely the same way when placed in a gravitational field. This is the same as saying that the inertial mass and gravitational mass of any object are precisely the same. The equivalence principle is fundamental to general relativity, allowing gravity to be treated as an aspect of the geometry of spacetime. In general, scalar additions to general relativity -- motivated by string theories or quantum gravity—produce a violation of the equivalence principle and also lead to secular changes in the fundamental constants. Scalar fields are also frequently invoked to account for the apparent acceleration of the expansion of the universe. Thus tests of the equivalence principle are a vital part of understanding the interface between gravity and quantum mechanics, and in probing our cosmological fate.

The equivalence principle comes in two flavors. The WEP relates to the composition of an object, in effect probing electromagnetic, strong nuclear, and weak nuclear energy contributions. The SEP extends to include gravity itself. The Earth-Moon system allows a test of the strong equivalence principle in a way that laboratory tests cannot, in that the contribution of gravitational self-energy to the total mass-energy budget is $5x10^{-10}$ for the earth, but only 10^{-27} for typical laboratory masses. LLR allows us to ask the questions: "Do the Earth and Moon fall at the same rate toward the sun?; Does the gravitational self-energy of the Earth fall toward the Sun at the same rate as the less gravity-burdened Moon?; Does gravity pull on gravity in the same way it pulls on ordinary matter?" The Earth-Moon system is currently the best laboratory for answering these questions. If the SEP were to utterly fail--that is, gravitational self energy failed to gravitate--the Moon's orbit would be shifted by 13 meters. Current LLR constrains this shift to be less than 5 mm, constituting a $4x10^{-4}$ constraint on violation of the SEP.

LLR can also constrain new theoretical paradigms. An example is an idea to account for the apparent acceleration of the universe by allowing gravitons to leak off of our 4-dimensional spacetime "brane" into another bulk dimension, thus weakening gravity over cosmological scales. Though small, such a process would have an impact on the lunar orbit--causing it to precess by effectively invalidating the $1/r^2$ force law of gravity. LLR needs to see a factor of 15 improvement to reach this level of sensitivity to new physics.

The LLRA will also help in understanding the hazards posed by impacts to human habitation on the Moon, and to the Earth in general (e.g., Buratti and Johnson, 2003). In particular, we would like to know the impactor flux in near-Earth space. Most of the dangers to astronauts and buildings would be from secondaries thrown out by a distant impact.

Impacts will excite the Moon's free librations. These librations take some time to die away; the amount of time depends on the Moon's internal properties. Hence the free librations provide some "memory" of past impacts. This is unlike current real-time optical observations of the Moon, which must see the impact the instant it occurs. Whether an impact is optically seen depends on whether the equipment is switched on and the phase of the Moon. The impact must also occur on the near side, so that the optical program covers only half the lunar surface.

On the other hand, due to "memory," the librations do not have to be monitored in real-time to detect impacts, and the "observed" impacts are not confined to the near side. However, the impactors have to be fairly large to excite detectable librations. In addition to measuring the present librations more accurately, which gives us information on the size and flux of past hits, we intend to compute how large an impact must be to make a change in the librations, and thus detect impacts which occur during the lifetime of the LLRA. This lifetime is long; we expect to get laser returns over decades to centuries. We will compare our estimate of the flux to those obtained by other means.

Determination of the frequency dependence of the Lunar tidal quality factor Q was one of the most important items of the first Lunar-ranging project carried out by the JPL team of Williams et al (2001). As expected, it turned out to be proportional to the tidal frequency taken to some fractional power. Surprisingly, this exponential turned out to be negative, about -0.2. Later efforts in data processing, undertaken by the JPL team, lead to a somewhat different value, about -0.07, which still was negative. (Williams *et al.,* 2006).

Intensive research independently carried out by several teams through the past twenty years has demonstrated that within the geophysically interesting range of frequencies the seismological quality factor of the Earth must scale as the frequency taken to a positive power. (The sign may change for time scales longer than the Maxwell time, which is about 100 yr and is far beyond the scope of our discussion.) These studies, performed for vast terrestrial seismological basins, have favoured the values for this power, that lay between 0.2 and 0.4 (Shito et al 2004, Stachnik et al 2004). On general grounds, one should expect that the frequency dependence of the tidal quality factor, both for the Earth and the Moon, would be qualitatively similar to that of the seismological Q. This means that either the JPL data were not sufficiently accurate or that our knowledge of the internal structure of the Moon needs a further study (existence of a molten core being one possibility; e.g., Yoder, 1981; Bills, 1995). One way or another, this gives us an impetus to use the new Lunar-ranging data to once again determine the frequency dependence of the Lunar tidal quality factor.

C. General Concept

The general concept of the LLR_21st is to consider a number (notionally eight) large single Cube Corner Retroreflectors (CCRs). Each of these will have a return that, with a single photoelectron detection system such as current APOLLO system located at the Apache Point Observatory can be used to determine the range to the limit determined by the librational effects of the current arrays and the laser pulse length. By using single CCRs, the return is unaffected by the libration. That is, there is no increased spread of the FWHM due to the CCR and the librational effects. We plan to use eight such single reflectors spread over tens of meters. The return from each of the CCRs will be registered separately and can be identified by comparison with the nominal lunar orbit and earth rotational parameters.

D. Notional Design and Alternatives

We currently envision the use of 100 mm CCRs composed of T19 SupraSil I from Heraeu-Ameresil of Germany. This is the same material used in LLRA_20th and both LAGEOS satellites. This will be mounted in an aluminum holder that is thermally shielded in order to maintain a relatively constant temperature through the lunar day and night. It is also isolated from the CCR, so the CCR receives relatively little thermal input due to the high temperature of the lunar day and the low temperature of the lunar night.

E. Thermal Simulation and SCF Facility at INFN

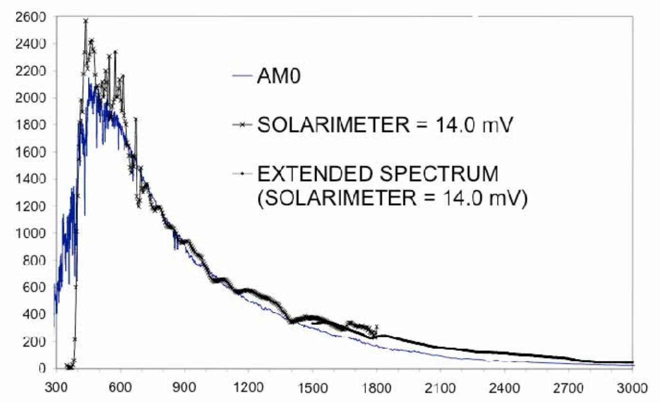


Figure 1: AM0 spectrum (W/m^2/nm x10^3) as a function of wavelength (nm) measured with the SCF simulator. Lamp currents are around 36 A (tungsten) and 29 A (HMI).

In order to conduct the thermal modeling and thermal/vacuum/optical testing (TVOT) we will use the newly inaugurated Space Climatic Facility (SCF) at the LNF/INFN in Frascati, Italy. This facility was originally developed for the LARES experiment, a LAGEOS-like satellite to measure a variety of General Relativistic Effects, especially the Lense-Thirring Effect (the gravi-magnetic effect caused by the mass current generated by the rotation of the Earth). This facility is described under "4. Facilities and Equipment."

The SCF includes both a Sun and Earth simulator. The Sun simulator (from www.ts-space.co.uk) provides a 40 cm diameter beam with close spectral match to the AM0 standard of 1 Sun in space (1366.1 W/m^2), with a uniformity better than ±5\% over an area of 35 cm diameter. The spectrum is formed from the output of two sources, namely an HMI arc lamp (UV-V), together with a tungsten filament lamp (Red-IR). The quartz halogen lamp (with the tungsten filament) has a power of 12 KW, while the metal halide lamp has 6 KW power. These two sources are filtered such that when the two beams are combined with a beam splitter/filter mirror, the resulting spectrum is a good match to AM0 in the range 400-1800 nm (see Fig. 1). The spectrum has also been measured from λ = 1500 nm up to 3000 nm and found to be in reasonable agreement with the AM0 over this extended range

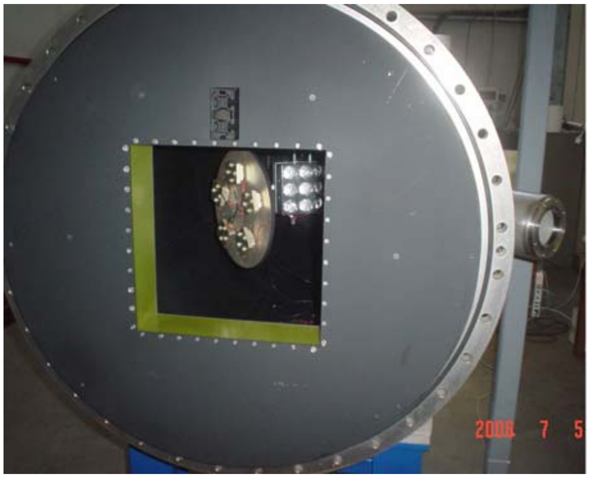
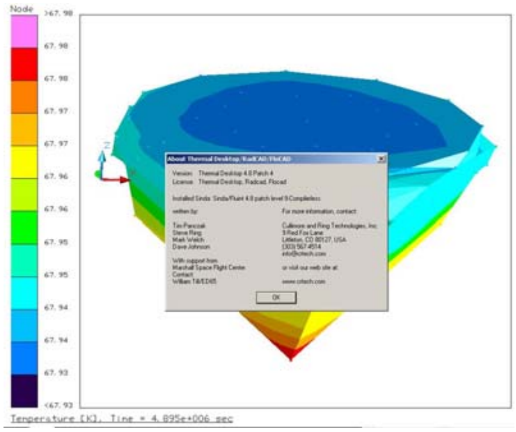


Fig. 2: Earth simulator.

The absolute scale of the solar simulator intensity is established by exposing the beam to a reference device, the *solarimeter*, which is a standard www.epply.com thermopile. The solarimeter is basically a calibrated blackbody, accurate and stable over 5+ years to ±2%. It is used over long times to adjust the power of the lamps and compensate for the their ageing. During continuous operation, the beam intensity is monitored and controlled by means of a feedback PID photodiode which reads a portion of the beam with a small optical prism.

The Earth simulator [for the LAGEOS altitude] (Fig. 2) is a 30 cm diameter disk painted with Aeroglaze Z306, kept at the appropriate temperature (250 K) and distance from the satellite prototype in order to provide the CCRs with the same viewing angle in orbit (~60^{o} for LAGEOS).

Thermal Simulation Package



Version: Thermal Desktop 4.8 Patch 4
License: Thermal Desktop, Radcad, Flocad

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With support from
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For more information, contact:
Cullimore and Ring Technologies, Inc

or visit our web site at
www.crtech.com

Figure 3: Software version and CCR temperature profile for a Moon climatic simulation.

The INFN-LNF group has been using, since the beginning of 2005, a specialized software for satellite thermal simulation purchased from the US firm "Cullimore & Ring Technologies" (see http://www.crtech.com/). The software currently used is version 4.8 (see Fig. 3) and it includes the following packages: (i) Thermal Desktop, the CAD-based geometric thermal modeler, (ii) RadCad, the radiation analysis module, (iii) Sinda-Fluint, the solver and orbital simulator. This package will be indicated as TRS in the following. TRS simulations can handle models with up to 20000 nodes. It can also handle the orbital motion of the Moon and Earth satellites as well as satellite spin. Typical software updates occur once per year and they are included in the yearly maintenance package.

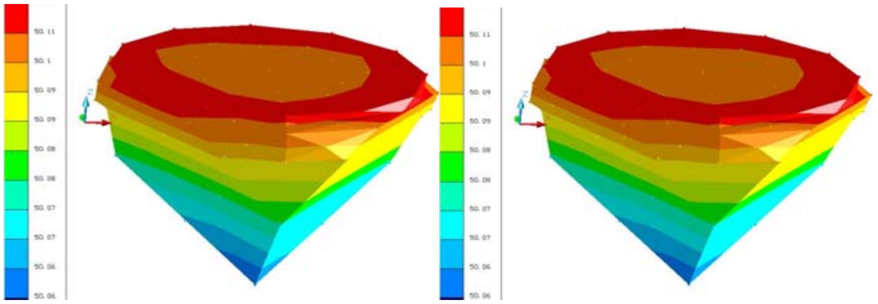


Figure 5: CCR temperature profile for the Moon climatic simulation: highest temperature point (left, time ~ 1st week) and lowest temperature point (right, time ~ 4th week). This CCR finite element model has 110 nodes.

TRS will be used for the simulation of the climatic conditions of the CCR on the Moon. Fig. 4 shows the variation of the temperature of two nodes of the CCR finite element model, one on the front circular face and one at its opposite corner. For this simulation we assume the input solar flux shown in Fig. 4 and that the CCR is surrounded by an Al box whose temperature is fixed at 10 K. Therefore only radiative heat exchange is modeled.

The thermo-optical parameters chosen for the CCR are: IR emissivity = 82 %, solar absorptivity = 3%. The Al IR emissivity is 20%. The value of the Al solar absorptivity is not relevant since the Al temperature is held fixed at 10 K. The CCR temperature profile is shown in Fig. 5. While this specific simulation (with one single CCR in a simplified Al box) can be done with an ordinary PC in a few hours, more complex configurations and with several thousands of nodes (and orbital motions) require a high performance PC.

Optical Performance of Thermal Simulation

The thermal simulation is performed with Radcad and FloCad. Using many nodes, this will address the detailed geometry of the CCR, including the offset angles of the back faces and the figured front surface of the CCR. This produces a four dimensional matrix illustrating of the performance of a particular notional design for a particular scenario of solar illumination and thermal impact of the warm lunar surface on the package. This is run for a number of months to establish equilibrium. In order to illustrate this procedure, we have defined a simple configuration (100 mm CCR contained in an aluminum box.) The CCR is illuminated by the Sun, rising to provide full illumination at "noon" and then setting. This is shown in Figure 4. As one can see, this case has no long term effects that require many months. Each month is essentially the same thermal record. The selection of a particular three dimensional matrix out of the four-dimensional stream represents the thermal condition of the CCR at a particular time. In order to evaluate the optical performance and thus the expected return from a laser illumination, we need to convert the temperatures to changes in the index of refraction and then perform ray traces, or more precisely, wave front modifications to evaluate the output wave function. This in turn can be transformed to obtain the far field diffraction pattern (as measured on the optical table) and the intensity at the velocity aberrated point. This is the same analysis that was performed by the PI for the APOLLO arrays. To accomplish this, we will use conventional ray tracing software (Zemax) to predict the wavefront emerging from the corner cube being fabricated for this proposal. The methodology will be as follows: the temperature variations in the CCR at various stages in the diurnal lunar cycle will be provided by thermal modeling performed at LNF/INFN in Frascati. This is in the form a three dimensional map of the index of refraction. By tracing a given ray through the CCR, we will determine the phase variation due to the temperature variations along a given ray, and interaction with the optical figure variations

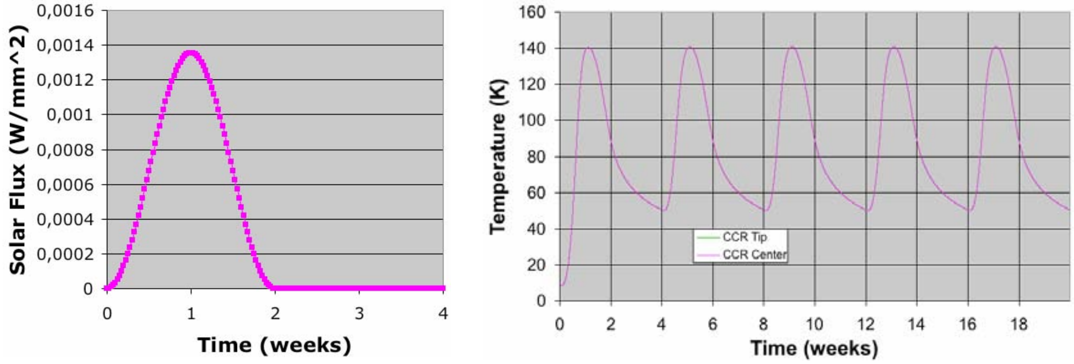


Figure 4: Solar flux in the CCR climatic simulation (left) and temperature variation of the CCR in the Moon climatic simulation (right).

Figure 6: Photo of GPS3 Array.

Figure 7: GPS3 Test Configuration with Dave Arnold, Doug Currie and Giovanni Delle Monache.

of the entrance face and the total internal reflection of the back surfaces of the CCR. These calculations will be done using wave optics (scalar diffraction theory) and are well within the capabilities of modern optical modeling software packages.

The three "GPS" CCR arrays were obtained to be installed on the U.S. GPS Satellites. Two were installed on GPS 35 and GPS 36. GPS3 is the third identical array that was loaned to our program by C. O. Alley of the University of Maryland. These arrays are similar to the arrays on GLONASS. The performance of these arrays is particularly interesting in view of the anomalous behavior that has been seen in the magnitude of the returns obtained from GPS35 and GPS36. That is, the laser return vanishes when the solar input to the array is reduced. In Figure 6, we see the mounting for a preliminary test of the thermal behavior of the GPS3 array.

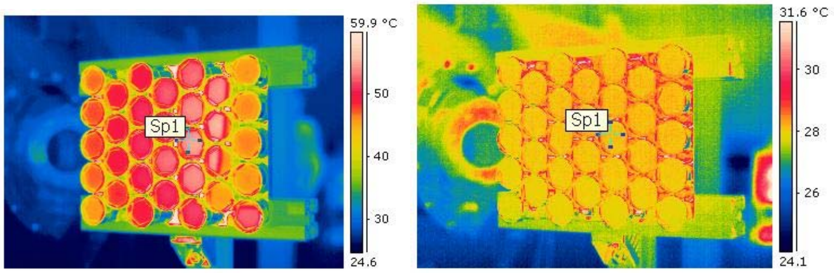


Figure 8A:Warmest condition. Figure 8B: Coolest condition. Infrared images of the GPS3 array at recorded different times during the tests. The high thermal resolution of the IR camera allows very precise determination of the temperatures at various points in the array.

The array was then "solar" illuminated, and after equilibrium of the CCRs was reached, the solar illumination was terminated. Figures 8A and 8B illustrate the infrared images of the array. The fine temperature sensitivity allows us to measure small temperature differences, even of the fused silica where thermocouples are not effective. Figure 9 illustrates the temperature as a function of time for the central CCR.

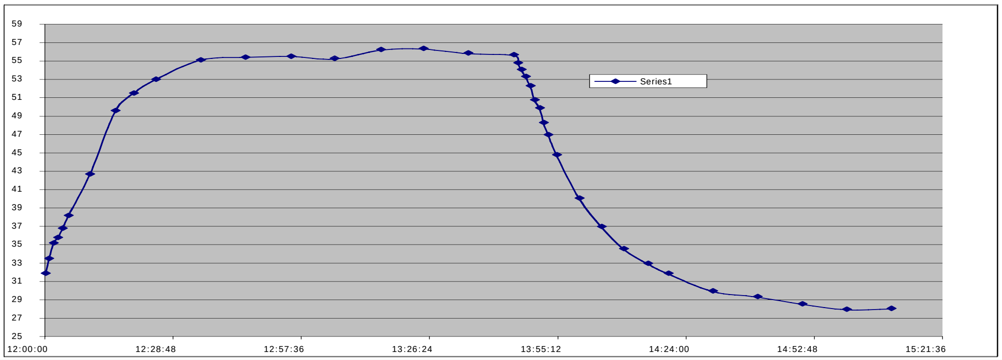


Figure 9: Temperature in ^{o}C as a function of time in hours, minutes and seconds. Solar simulator turned on at 12:00:00 and then turned off at ~13:50:00. This illustrates the heating primarily due to absorption of visible light by the aluminum backing and cooling, primarily due to the infrared emission by the front face of the CCRs.

F. Mechanical Support

The CCR enclosure must be sufficiently strong to handle launch conditions and still thermal isolate the CCR from the surroundings. Various candidates will be designed and modeled as a part of this program.

G. Interface Between the CCR Package and the Lunar Surface

The behavior of the lunar regolith is critical to the ultimate performance of LLR_21st Century. The upper 5 to 10 cm of the lunar soil are loose, grading rapidly to a very densely packed condition (Lunar Sourcebook, pp. 494-500). The dense soil will be very good for establishing a firm foundation. But the loose soil will complicate initial positioning of the template; and the dense soil will result in soil particles coming up the hole during drilling and potentially interfering with the template. The heating of the regolith will cause expansion and thus motion much greater than the few microns that would be the case for a fixed attachment. Not only is there the lunar diurnal variation in temperature but also a significant annual variation. Our notional design, to be investigated in the program, is to anchor the CCR to a layer in the regolith that is nominally isothermal. At a depth of 30-40 cm, the diurnal change is less than three degrees. Thus we will use a template that is aligned using the Sun shadow to align the CCR to the center for the librational pattern for the center of the Earth. Since this is to maximize return rather than minimize the effects of libration on the delay across the array, the tolerances are less precise than that which was needed for the APOLLO arrays. With the template in place, we will use the drill to create three holes in the regolith that are 50 centimeters in depth. This is sufficient to reach a layer that does not change its temperature from lunar hour to lunar hour. Thus we will not be affected by the irregular thermal effects in the regolith. Our idea is thus similar to the stability of an oil drilling platform: the ocean surface goes up and down, but the platform safely rests on the solid bottom.

H. Deployment Configuration, Procedures, and Conditions

The CCRs will be carried out in two "parcels." Each parcel carries four of the arrays. At each deployment site, a template is place on the regolith. Using a sun dial, the template is oriented so the normal to the CCR will point towards the center of the Earth at the center of the librational pattern. Then three holes about 2 cm in diameter are drilled. Then the template is removed and the CCR mounting, which has three "legs" that fit in the holes, is placed in position. This repeated for the other seven CCRs.

Also of critical importance is to address the possible role of dust. Measurements of the magnitude of the laser returns from the APOLLO arrays by Thomas Murphy indicate that the magnitude of the returns is smaller by a factor of twenty. This did not seem to be the case for the first years, as the returns at McDonald were reasonable close to predictions. However, this will be investigated in more detail. Since it occurs for all of the arrays, a nearby meteorite does not seem to be the cause. The most interesting candidate is the possibility of electro-statically levitated dust. Understanding this issue is critical for the design and role of the next generation array. We will review in detail the calculations of the APOLLO returns. As feasible within the available support, we will also address the various indicators that may bear on this issue. These include the magnitude of the returns from the early McDonald Observatory shots, the returns of the current French and US lunar ranging, the behavior of the solar cells and the received power of the Surveyor space craft, and finally the condition of the Surveyor camera that was brought back to Earth on the APOLLO program. The PI participated in the initial inspection of this camera at the Johnson Space Craft Center on the return of the camera. The results of these reviews will be incorporated in the design to minimize the effect.

I. Astronaut Requirements

This program will define the method of deployment and address the difficulties and the procedures to ameliorate any problems. This portion of the program will be led by Astronaut Roberto Vittori. He has access to the details of the issues in the deployment of the APOLLO arrays and is familiar with the mobility aspects of the current generation of space suits.

J. Ground-based Technologies

We will review the current status of the ground-based systems. This will assess the increase in accuracy that will be immediately available with the new array (if it were deployed this year). We will also review the expected improvements in the ground based system to be expected over the next fifteen years, to determine the accuracy to be expected at the time of launch. Finally, we will outline the critical improvements in ground –based technology that would support the increased accuracy of the lunar facility.

The error budgets of the three active lunar ranging stations are all dominated by the libration-induced tilt angle of the reflector arrays. Measuring 100--300 ps RMS, typical laser pulse widths of ~100 ps FWHM (= 40 ps RMS) are of little consequence in a quadrature sense. Therefore current stations are not rewarded by pushing for shorter-pulse lasers.

Lasers pulsing in the picosecond regime are limited by peak power, at roughly the 1 GW level. Thus a 100 ps laser can produce about 100 mJ per pulse. If the lunar reflectors were designed to permit resolution of the individual corner cubes, reducing the pulse width by a factor of two would also reduce the energy per pulse by the same factor, but one would only need one-fourth of the photons to achieve the same statistical error. Thus the time needed to require a fixed precision scales linearly with the pulse width.

Taking APOLLO (the Apache Point Observatory Lunar Laser-ranging Operation) as an example, a large libration angle currently requires about 2500 photons to be collected for one-millimeter range precision. Under typical conditions, this takes about 20,000 shots, or 1000 seconds at 20 Hz. A sparse array would immediately reduce the requirement to the system performance of 150 ps RMS, requiring less than 500 photons (thus 200 seconds). Given the incentive to reduce the total system error (which includes laser, timing electronics, etc.), this time can be reduced by a factor of four for each factor-of-two improvement in timing performance, and by a factor of two for each factor-of-two improvement in laser pulse width. Clearly the potential for sub-millimeter range performance becomes practical, thus driving station development in these directions.

Signal Loss and Mitigation

Recent analysis from the newly operational APOLLO (Apache Point Observatory Lunar Laser-ranging Operation) station suggests that the signal strength from the moon is a factor of 10-20 below expectations. All appropriate checks of ground station throughput and outgoing beam profile leave little room for anything but a degradation of the APOLLO Lunar Laser Ranging Arrays (LLRAs). Moreover, scaling between the three operational LLR stations indicates that all three experience a common missing factor--further advancing the idea that the LRRAs are the problem. Signal strength from the three Apollo reflectors is consistent with the expected 1:1:3 return strength, so that if degradation has occurred it is not a localized phenomenon.

It is difficult to make plans for mitigation of this degradation if one does not know its cause. The most likely culprit is dust. Electrostatic levitation at the < 1 meter level has been observed on the lunar surface--presenting "fuzzy" local horizons. Dust was also thought to be responsible for the appearance of crepuscular rays observed before sunset from the Apollo 17 lunar orbiter at an altitude of 100 km. Theories of a dynamic dust fountain by Timothy Stubbs et al. can account for dust at these heights, and also predict horizontal transport around the lunar terminator. This last feature of the theory is consistent with the Apollo 17 dust detector left on the surface, which saw substantial increases in low-velocity dust activity (largely horizontal) at lunar sunrise and sunset.

Because the corner cubes are dielectrics, they too will acquire a charge of the same sign as that of the dust under solar radiation (day) and solar wind (night). So they could come into equilibrium with the dust, repelling dust at a rate equal to new dust accumulation. But this equilibrium may still involve substantial dust coverage of the corner cube. In addition to the obvious obstructive nature of the dust, the thermal properties of the array are compromised by the presence of low-albedo material on the surfaces of the cubes.

Additional possibilities involve dust transported ballistically from meteoric impacts, or dust from the interplanetary medium (especially when the earth-moon system passes through a comet debris tail). These forms of dust have enough velocity to pit the surface of the reflector (larger than the dust grain itself). In addition to the permanent scattering loss, the surface of the glass becomes partially absorbing, which results in thermal deformation of the cube under solar illumination.

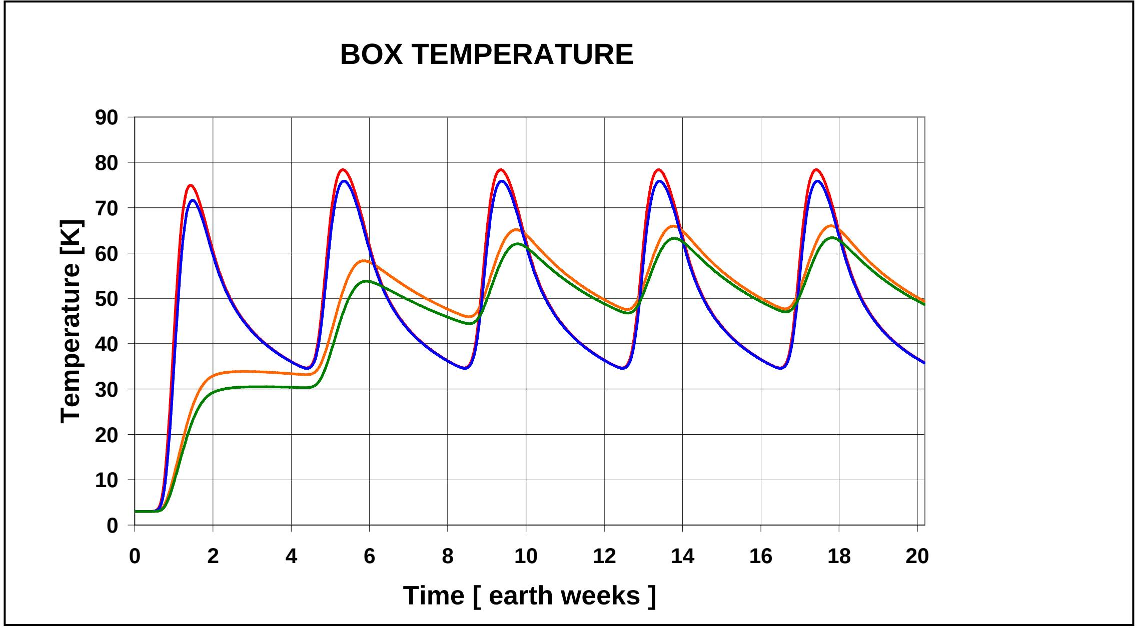
It may be interesting to explore the placement of a shield around a new reflector array that restricts the solid angle visible to the reflector to a small region around the mean earth direction. Unless the reflector is placed near the sub-earth point on the lunar surface, such a shield would eliminate vertical access, and likely mitigate electrostatically-driven dust contamination. A multi-layer aluminized Mylar construction would reduce thermal load onto the reflector. If the shield were in the form of a dome, the surrounding lunar surface could also be largely protected from the thermal load of the sun, reducing regolith expansion and keeping the array in a more nearly isothermal state. A carefully designed opening could limit sun illumination angles to those that would experience total reflection by the corner cube, thus lowering the heat load to the holding apparatus.

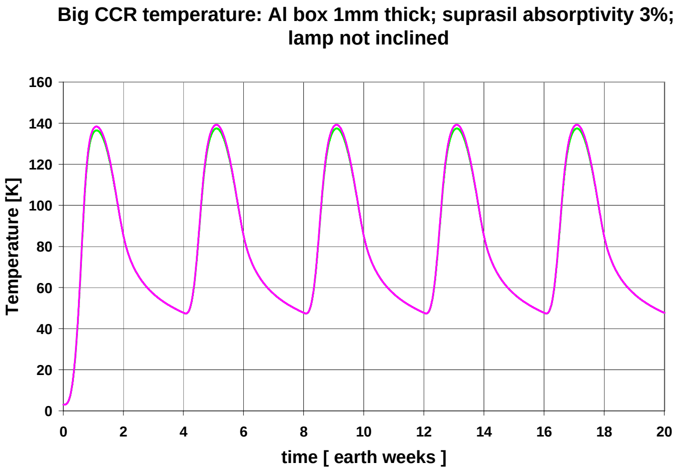
K. Development Requirements

As seen at the present time, the primary aspect that will have to be addressed is to obtain a better modeling of the regolith. This will be followed by a review of the lunar drill programs that have been supported by NASA and the selection among these programs.

L. Recent Results

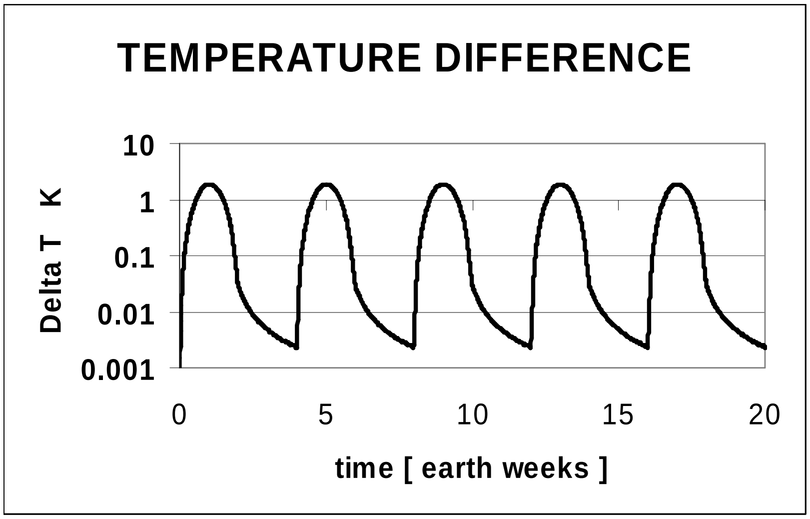
In order to illustrate the analysis procedures, we have defined a notional package to house the CCR and used the thermal simulation program to simulate the illumination of the CCR and package. The package is a square box with the CCR mounted in a recessed manner. The illuminating light arrives at a fixed angle with an intensity that varies sinusoidally during the day. This proceeds through five lunar days. The red and





orange curves represent the zenith sun illumination for a box wall of 1 and 5 mm respectively and the blue and green curves represent the same for an illumination off 30 degrees to investigate the solar break through of TIR reflection.

For the CCR inside the box, we consider the case of the zenith illumination and the 1 mm box. In this case, we plot the temperature of the center of the front face (red) and the back tip (green) of the CCR. This shows the rapid heating with the inset of illumination and the slower radiative cooling during the lunar night. Finally, we look at the temperature difference from the center of the front face to the tip. This is the best representative of the thermal distortion of the return beam to the earth. For this, we have the "TEMPERATURE DIFFERENCE" plot. Note that this is a very preliminary result. While the demonstration that the temperature difference is less than two degrees indicates that the optical performance of the CCR package should be quite good, most of this temperature difference is due to the current version of the software causing the optical energy to be absorbed on the surface rather than in the volume of the CCR. Using the proper software additions, we expect that the differences will be further reduced by a factor of two or three. On the other hand, the current simulation does not include the modeling of the supports of the CCR. This will require many more nodes and longer runs.



M. Program Plan

The NASA Kickoff Meeting will take place in Washington or at the University of Maryland in College Park, depending upon the preference of NASA personnel. During the kickoff meeting, the detailed roles of the participants will be defined and tasks assigned. This will be a video conference among the PIs and CoIs. If necessary, the administrative aspects of the meeting will continue after the end of the formal kickoff meeting. In this meeting, the notional design will be formally defined and the different aspects needing analysis will be assigned.

An internet site will be developed that will allow documents and PowerPoint presentations to be hosted, so that they are available to the entire team.

During the next four months (Work Period 1) the participants will proceed with the assigned tasks. This will include the preparation of internal reports, review of nominal design defined in the Program Kickoff Meeting, various simulations of the nominal design to be conducted at LNF/INFN at Frascati, the procurement of a large (100 mm) single test CCR, creation of thermal model, and the preparation of the mounting to receive the CCR for thermal vacuum testing in the SCF at LNF/INFN. Toward the end of Work Period 1, the participants will upload a review of their current status to the LLR web site for review by other participants.

At the end of Period 1, a second Video Workshop will take place. The participants will be at there home facilities. Each participant will then present the results of the initial Work Period. The comments during the discussion associated with each presentation will then be used to define the areas to be addressed by each participant during Work Period 2.

During Period 2, which will also last for four months, further analysis will be conducted, especially on the points brought out by the team during the presentations and in the working group sessions. In addition, the CCR will be received; the mounting possibly changed based upon Workshop 1, and thermal vacuum tests performed. The latter will address the effects of passage from lunar day to lunar night and the reverse. Interim reports and PowerPoint presentations will be uploaded to the web site during Work Period 2. The result of Work Period 2 will be a draft final report and draft final PowerPoint presentation for NASA.

A second video conference will then be conducted. The various chapters or portions of the final draft report will be presented by the responsible individuals. As a result of these presentations, modifications of the draft report and presentation will be prepared.

Work Period 3 will be one month in duration. During Work Period 3 the changes in the draft final report that were addressed in the third Video Conference will be incorporated into the final report and the PowerPoint presentation by the individual participants. This will then be presented to NASA personnel, with the primary participates involved in the presentation.

N. Team Responsibilities

Professor Currie will organize and monitor the development of the program as described in this proposal. This monitoring will include the coordination of the efforts of various team members, despite the physical separations. He will conduct two visits to LFN/INFN in order to coordinate the simulation, optical and thermal-vacuum testing work at Frascati with the rest of the program. He will also work specifically on the optical table definition, implementation and operation. He will also participate in the technical developments of the definition, evaluation and testing of the notional design.

Simone Dell'Agnello will supervise the work will take place in by LNF/INFN in Frascati, Italy. His support and the support of his team will be provided by INFN. The tasks to be accomplished in Frascati will include the thermal simulations and the thermal vacuum tests. Dr. Dell'Agnello will also participate in concept design.[*]

Colonel Roberto Vittori, a member of the Italian Astronaut Corp who has flown on the International Space Station and participated in the University of Maryland/ University of Roma SPQR experiment, will address the issues of astronaut capabilities, methods and risk as they apply to the deployment of various notional designs of the LLR array on the lunar surface. This will especially address issues of limited abilities of the astronaut in the lunar space suit.[*]

W. David Carrier III will be responsible for addressing the mechanical and thermal properties of the lunar regolith, the methods for coupling of the array to the deeper, more stable, layers of the regolith, the optimal methods for drilling into the lunar regolith and for modeling the thermal response of the regolith.

David P. Rubincam will be responsible for lunar libration analysis in terms of the array's sensitivity to impacts, and to the internal structure of the Moon.

Arsen R. Hajian will perform the optical analysis using Zemax. He will report on the final wavefront characteristics of the thermally distorted CCR based on the 3D index map of the index of refresction provided by LNF/INFN. This will include the effects of the phase shifts induced by TIR and the offset angles of the back faces.

Giovanni Delle Monache will be responsible for oversight of the thermal analysis and for the conduct of the thermal vacuum tests.[*]

Claudio Cantone will be responsible for the thermal modeling and the comparison of the results of the thermal vacuum tests and the modification of the thermal models based upon the comparison with the actual measurements.[*]

Marco Garattini will perform experimental work for the thermal vacuum tests.[*]

Nicola Intaglietta will perform CAD drawing and mechanical installations.[*]

[*] These tasks will be accomplished at no cost to NASA.

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3. FACILITIES AND EQUIPMENT

A schematic view of the Space Climatic Facility (SCF) is shown below. The size of the steel cryostat is approximately 2 m length by 1 m diameter. The inner copper shield is painted with the Aeroglaze Z306 black paint (0.95 emissivity and low outgassing properties) and is kept at T = 77 K with liquid nitrogen. When the SCF is cold, the vacuum is typically in the 10^{-6} mbar range. A support fixture on the ceiling holds the prototype spacecraft in front of the Earth infrared simulator (inside the SCF). The solar simulator is outside, behind a quartz window (40 cm diameter, 4 cm thickness), which is transparent to the solar radiation up to 3000 nm. A side flange with a Germanium window allows to take thermograms of the prototypes with a FLIR infrared digital camera.

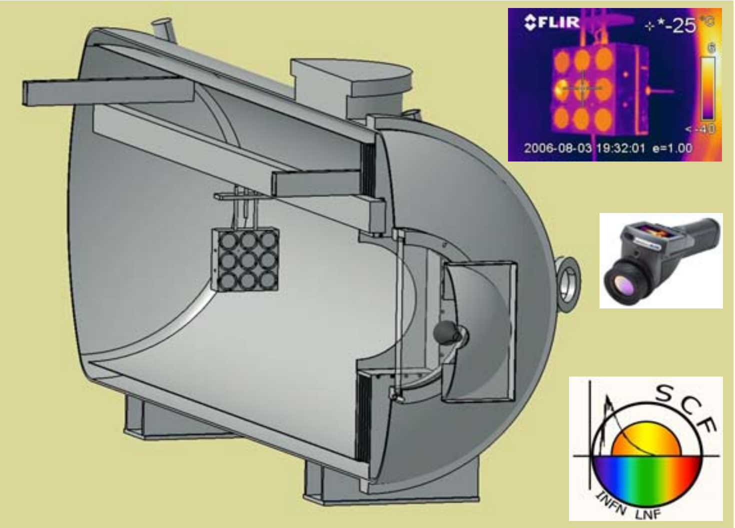

Figure 10: INFN/LNF Space Climatic Facility

The IR camera in use at the SCF, a ThermaCAM® EX320 by FLIR Systems (http://www.flir.com), has a true, built-in 320 x 240 pixel array, field of view/min focus distance 25° x 19° / 0.3 m and thermal sensitivity 80 mK. Since its factory absolute temperature accuracy is 2 K, PT100/PT1000 temperature probes with 4-wire readout are used to establish the correct temperature scale. The camera focal plane array detector is an uncooled Vanadium Oxide microbolometer with spectral range 7.5 ÷ 13 μm.

Figure 10: Sketch of the LNF Space Climatic Facility with the LAGEOS 3x3 CCR array built at LNF. The top right inset figure is a temperature photo taken with the IR camera (right middle inset), through the side tunnel of the cryostat. Bottom right is the SCF logo.
Figure 11: ThermaCAM EX320 IR camera.

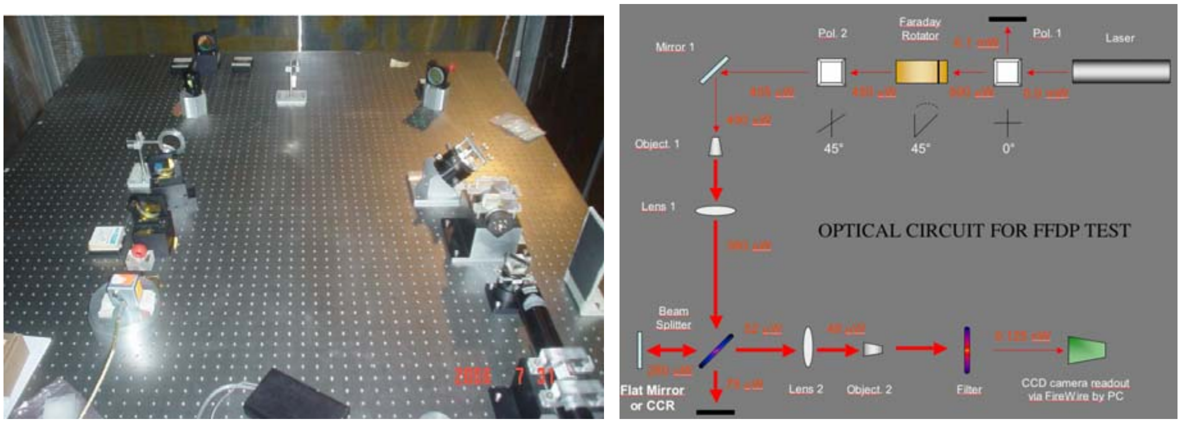

Figure 12: Far Field Diffraction Pattern measurement.

In order to evaluate the performance of the CCRs, the optical table shown above has been set up at INFN/LNF. At present, it is being used to determine the far field diffraction pattern. This is being used as a general evaluation of the optical performance and expected return at the velocity aberrated angle. It will soon be configured to also perform interferometric measurements of the phase or wave front. This will allow evaluation of the optical parameters of the CCRs. Finally, a similar configuration to evaluate the far field pattern will be developed in conjunction with the thermal/vacuum chamber

On the optical bench, we measure the intensity distribution of the return from the retro-reflector. This is the far field pattern. This pattern is then recorded on a CCD camera that then performs an analysis indicating the return as various offset angles to evaluate the effects at the velocity aberrated angle.

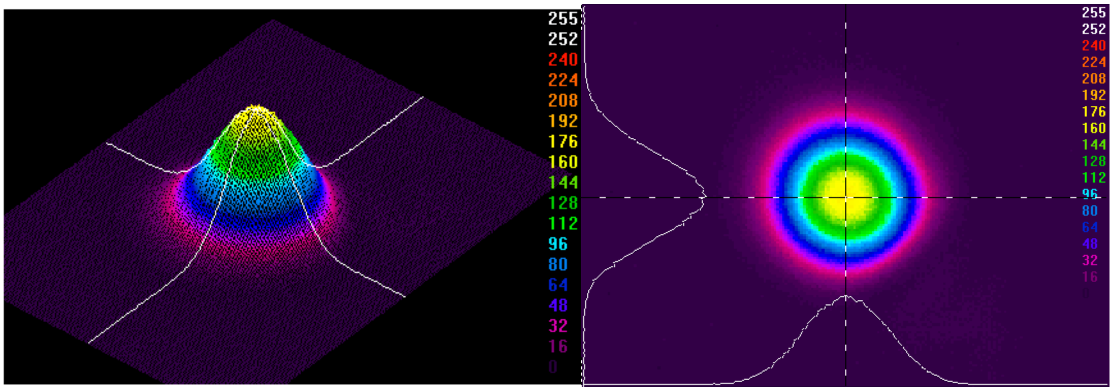

Figure 13: Intensity of Far Field Diffraction Pattern.

Software

The optimization and evaluation of the thermal design of the CCR, the CCR support and the deployment package will require many runs. At present, experimental simulation runs discussed in the text of the proposal, with a relatively small number of nodes require one to a few days of CPU time. Thus we need a dedicated system to perform these calculations to an accuracy that can then be entered into ZeMAX to evaluate the end-to-end performance to be expected. Thus the cost of a license and one year of maintenance is included in the budget.

Hardware

The full size (100 mm) CCR will be installed in a nominal package similar to the package proposed for the lunar deployment. This will then be used for thermal testing in the SCF (i.e. the thermal-vacuum facility at INFN) in order to validate the computer modeling of the thermal performance of the CCR and package under lunar conditions.

For the above reasons, we need a dedicated PC with high end capability to accomplish the simulations. Thermal simulation software will be installed on this PC.

Travel

Most of the communication and workshops will be conduced by telephone and video conferencing. However, to coordinate the work between the US segment and the Italian segment, the PI will make two trips to Frascati. The PI will also address the configuration of the optical test table and details of the thermal simulation. In addition, there are two trips for David Carrier to come to the University of Maryland for the workshops and working sessions on the details of the regolith issues, the design of the interface to the regolith and the drilling procedures.

Use of European Personnel, Equipment, and Facilities

These will be at no cost to NASA.