THERMAL/OPTICAL ANALYSIS OF CUBE CORNER RETROREFLECTORS FOR THE LUNAR ENVIRONMENT

Giovanni O. Delle Monache[1], Douglas Currie[2], Simone Dell' Agnello[1], Bradfor Bher[2]

1 INFN-LNF Frascati Italy

2 University of Maryland College Park MD

ABSTRACT

Over the past 40 years, the Lunar Laser Ranging Program (LLRP) to the Apollo Cube Corner (CCR) Retroreflector Arrays (ALLRRA) has supplied almost all of the significant tests of General Relativity. This is the only Apollo experiment that is still in operation. Initially the ALLRRAs contributed a negligible fraction of the ranging error budget. Over the decades, the ranging capabilities of the ground stations have improved by more than two orders of magnitude. Now, 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 Array technology. The investigation of this new technology, with Professor Currie as Principal Investigator, is currently being supported by two NASA programs and by the INFN-LNF in Frascati, Italy. Thus after the proposed installation during the next lunar landing, the new arrays will support ranging observations that are a factor 100 more accurate than the current ALLRRAs. 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 at Frascati and at the University of Maryland. To perform these simulations, we use Thermal Desktop®. This analysis yields a three dimensional matrix describing the temperature distribution in the CCR for a given configuration and set of parameters. A program developed at the University of Maryland using IDL of RSI Inc. converts the three dimensional temperature matrixes into a two dimensional phase front which captures the error induced by the temperature gradients. Results of an integrated model which contains a housing design, a model for the behavior of the regolith and the coupling of these effects are presented. The model has been parameterized to agree with the Heat Flow Experiment (HFE) deployed during the Apollo 15 mission by means of a Thermal Desktop® model of the Regolith down to 3 m depth developed by correlation to Apollo data and related articles. In addition this Regolith model is used to investigate current optical performance of Apollo 11 ALLRRA during eclipse, to evaluate degradation by possible lunar dust deposition. Preliminary results on Apollo 11 "dusted" ALLRRA model are presented.

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.

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 (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 10–100 mm, depending upon the mission and mode of emplacement. This may be considered in terms of a Phase I program that addresses deployment on the surface of the regolith that will support single photoelectron ranging accuracies of better than 1 mm. A Phase II program would involve anchoring the CCR to the regolith at a depth of about one meter so that thermal effects in the regolith would not affect the ranging. The Phase II emplacement would support ranging accuracy approaching 10 mm, but it will be many years before the ground stations can take advantage of this accuracy.

This program currently addresses the primary component (i.e., the CCR and the housing) regarding the use of next generation retroreflectors. The details of the mounting and the emplacement procedures will depend upon the mission. For a manned mission (our initial objective), we have considered an array of five CCRs, separated by ten or more meters. These would be anchored to the sub-surface regolith (i.e., at a depth of one meter) to escape the diurnal vertical motion of the surface due to solar heating. We also consider robotic missions (ILN, Lunette and X-Google) where, depending upon the available mass and mobility of a possible rover, the configuration may consist of a single or multiple CCRs and/or with surface or anchored emplacements.

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.

TECHNICAL CHALLENGES OF THE LLRRA-21

The primary technical objectives of the design of the LLRRA-21 that follow from the scientific objectives are to (1) provide sub-millimeter accuracy of ranging data, (2) provide adequate laser return to earth-based ground stations and (3) to be stable over the long term – decades – with respect to the deep local regolith.

The fabrication of a CCR that would support the LLRRA21 concept has not been achieved in the past. This requires a CCR that is much larger than any previous CCRs (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 with the required homogeneity, the fabrication and polishing

Figure 1Flight Certified 100 CCR fabricated to the specifications with Apollo

procedures and the measurement methods. In addition, our tolerances on the back surface angles (i.e., 0.2 arcsec) are more restrictive by a factor of 2.5 than the previous state-ofthe-art for laser ranging CCR fabrication. To address this, we have commissioned the fabrication of a 100 mm 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. Two of the angles are a factor of two better (i.e., less than 0.1 arcsec) than our 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) in all three directions, (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 demonstration CCR has been fabricated of SupraSil 1 as were the Apollo CCRs. For the next generation of CCRs for LLRRA-21, concerning (1) for the flight CCRs, we plan to use SupraSil 311 which has even better homogeneity, i.e., $5n<10^{\sim 6}$ Concerning (2) the radiation resistance, the SupraSil 311 specification by Hereaus indicates that there is no visible degradation of the visible transmittance after exposure to Co^{60} radiation at a level of 0.063 Mrad/h for 98 h. Concerning (3) the low absorption of solar radiation that produces thermal gradients that in turn distorts the retroreflected beam, the measured transmission of SupraSil 311. This is then combined with detailed ray traces of the light paths through the CCR that indicates that 3.5% of the solar radiation is absorbed. Fig. 1 is a photograph of this 100 mm CCR and one of the Apollo 11 CCR spares.

SOURCES OF THERMAL GRADIENT WITHIN THE CCR

One of the most critical challenges is the issue of 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 at Frascati and at the University of Maryland. To perform these simulations, we use Thermal Desktop. 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 matrixes 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 (FFDP) which defines the strength of the signal that will be seen as a laser return at the ground station.

Thermal Desktop® allows the user to define absorption of surfaces as function of the radiating wavelength, but cannot simulate absorption in the volume of transparent materials. In the lunar CCR, 100 mm diameter, this is a small amount of heat, of the order of 0.4 W at lunar noon. Nonetheless, due to the sensitiveness of the optical performances of the material, must be considered in the heat load budget.

For this reason the University of Maryland has developed software which calculates the heat load absorbed by a CCR along the lunar orbit, able to account for the interaction of the CCR with the structure of the experiment concerning the solar radiation.

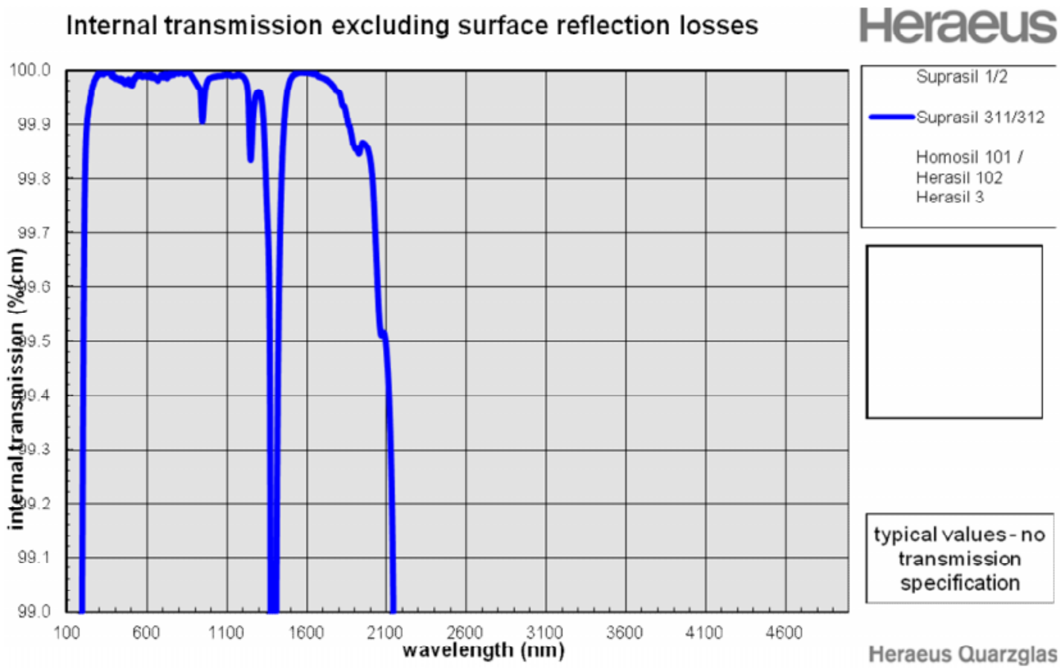


Figure 2 Suprasil 311/312 internal trasmission vs. wavelenght

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 heat is deposited in different proportions in different parts of the CCR. To address this, we must analyze each narrow spectral band (1 nm) of the solar radiation separately and then sum over the wavelength bands to determine the heat deposition at each node of the CCR model. Thus for each narrow band, we must determine the amount of energy in the AMOS2 solar spectrum. We then use the band-by-band absorption data from Heraeus to determine the "decay depth" in the fused silica. The dependence of the decay depth on wavelength is illustrated in Fig. 2. Using Beer's law and the solar spectrum, we may 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 file to the Thermal Desktop in order to compute the thermal gradients.

If the CCR is at a temperature that is different than the housing temperature there will be a flow of heat passing into (or out of) the housing to the tab of the CCR and then into the CCR. This in turn will cause a flow of heat within the CCR which produces irregularities in the temperature and then in the indices of refraction of the fused silica. This causes a degradation of the retroreflected beam and a reduction of the return signal to the ground station.

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 the 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. This consists of 1 mm ''pins'' that provide a line contact, rather than the two dimensional contact of existing CCR mountings.

In the case of the Apollo CCR arrays, the back surfaces of the CCR view the aluminum surface of the pocket in 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 has 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 low emissivity, (i.e., 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 the initial thermal/optical/ vacuum tests to evaluate the effectiveness of this solution. Fig. 3 is a photograph of the inner thermal shield that was used in the April 2010 thermal/optical/vacuum tests.

THERMAL MODEL OF THE LUNAR REGOLITH

Thermo-physical properties of Lunar Regolith have been investigated in the past by data processing of Apollo Heat Flow Experiment (HFE), part of the Apollo Lunar Surface Experiments Package (ALSEP). The HFE has been installed during Apollo 15, Apollo 16 and Apollo 17 missions; Apollo 16 did not produce data due to experiment failure. Heat probes have been inserted in holes drilled on the surface, and T measurement taken to determine Lunar Heat flow as well as regolith thermo-physical properties.

To simulate the regolith a 1-D model have been made using Thermal Desktop®. A Lunar block of 1x1x3 m3 is exposed to Solar flux according to the Lunar orbit. Thermo-optical properties and thermo-physical properties have been derived from the work by Keihm, Peters, Langseth and Chute. Lunar heat flow data from Keihm which refer to the Apollo 17 data. The block is divided into 13 sub-blocks to allow proper definition of properties which depend on temperature and distance from the surface. Each sub-block is modeled with several subdivisions in order to correctly simulate sharp effects produced by severe T gradient during the lunar day near the surface. Lunar infrared emissivity of 1 and solar absorptivity of 0.93 were used in the model accordingly to the Keihm paper despite measurement of emissivity on returned Apollo 15 soils yielded an average value of about 0.95 over the 6-12 band. Density profile as a function of depth is reported on Keihm paper based on soil-mechanics data. These values have not been authentically modeled because the results are not much affected by them.

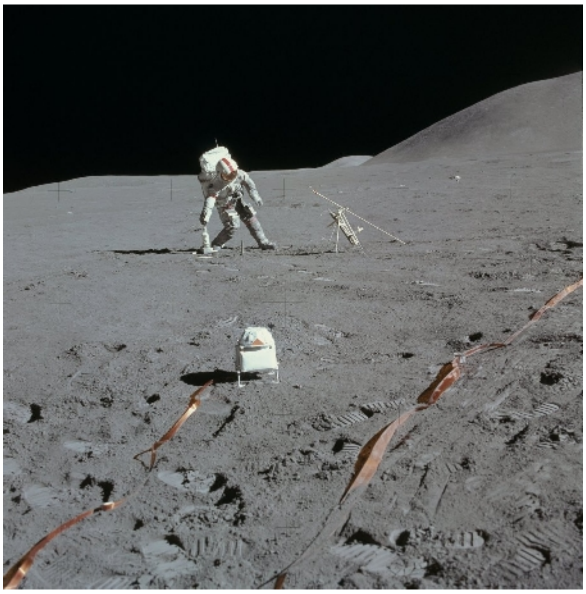


Figure 3 : Apollo 16 HFE deployment

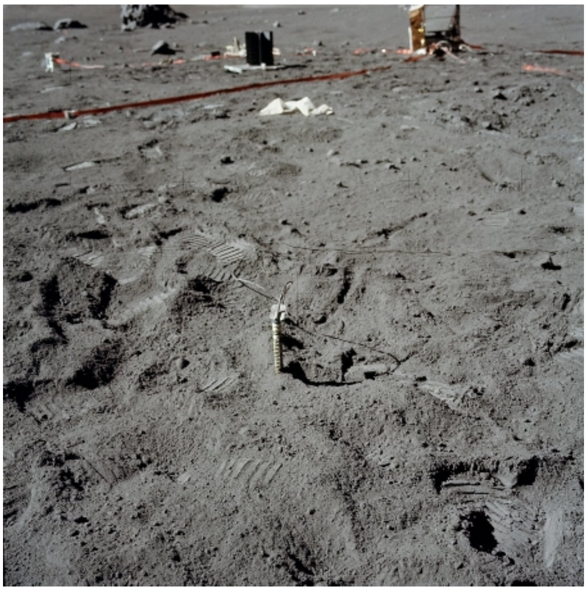


Figure 4 Apollo 16 HFE deployed

Data about heat capacity as a function of temperature have been taken from Robie's measurement on Apollo 11 samples. At least square fit was made to the data points. The properties which must be carefully modeled in order to match results as shown later on the paragraph is the thermal conductivity. According to Linsky it can be modeled as $K(z,T)=A(z) + B(z,T)*T^{\wedge 3}$; 13 different curves for K=K(z,T) have been defined for each block of the model.

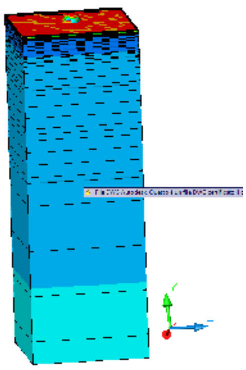


Figure 5 Thermal Desktop 1-D model of 1x1x3 m^3 regolith block

A full orbital transient analysis for the block is run in two steps; in the first one a large number of lunations is set in order to reach steady state. Due to the large amount of data only the final temperature data set is saved. In the second step the data set saved is used as start condition to run one more lunation, whose results are saved along the lunar period and presented in fig. XXX. Analysis have demonstrated that 2000 lunations are enough to reach steady state, but since the model does not require lot of CPU time a 20.000 lunations run has been used for initial condition.

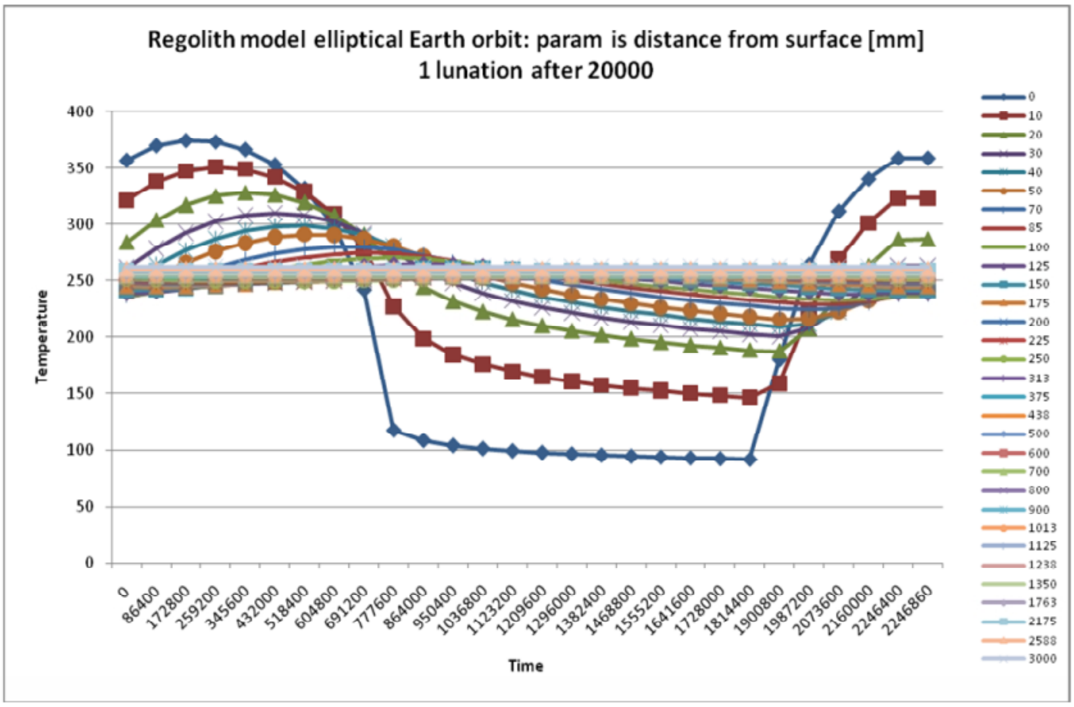
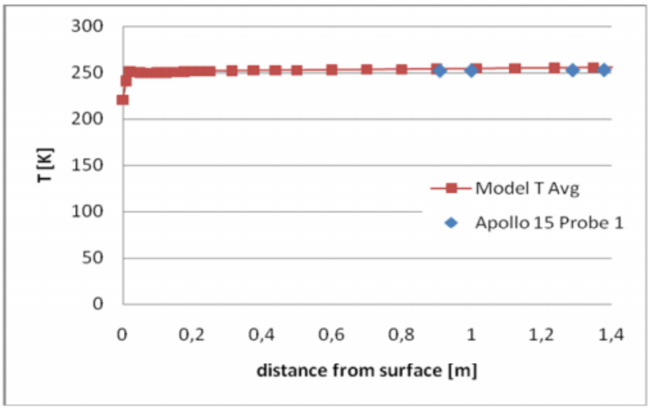


Figure 6: Regolith T evolution over one lunation at different depths

Selenographic latitude of the Hadley-Rille site has been considered for correction of the solar heat flux on the model. Data obtained for $T_{avg.}$ vs. depth has been compared with those of the Apollo 15 PSR for probe 1

Data obtained from the model for $T_{difference}$ vs. depth has been compared with those from the model of Keihm et. All. In both cases there is evidence of good match between model and experimental/simulated data.



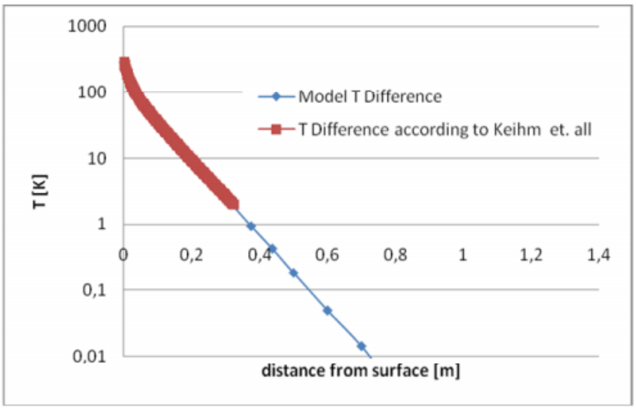


Figure 7 : T_{avg} comparison with Apollo 15 data **Figure 8 T_{dif} comparison with Keihm et. all**

RESULTS OF THERMAL SIMULATION

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.

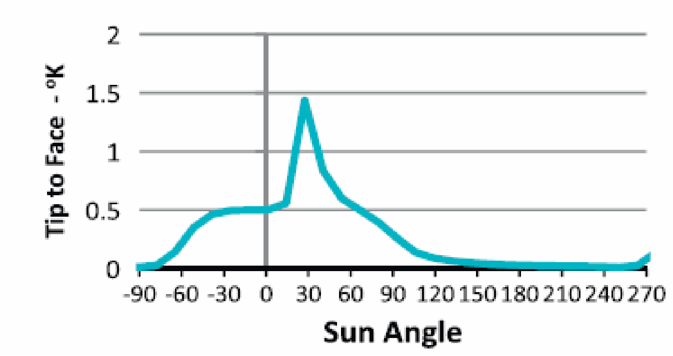


Figure 9 :CCR tip to face T variation for sun shade shown in fig. to the right

Figure 10 hardware implementation of LLRRA-21 with 100 mm high shade

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). For various sun angles, one obtains different magnitudes and distributions of the temperatures, as illustrated in Fig. 4. It is this gradient that will change the index of refraction and thus disturb the strength of the return beam to the earth. Fig. 5 is a plot of the variation of the gradient, through a full lunation, which is below 0.5 K for all but one or two days of the month. For most of the lunation, the worst of the performance is indicated in Fig. 6. For one or two days the performance is worse. Although this would be an acceptable situation, we believe that by modifying the sun shield and with a better selection of the shape and metal surfaces of the inner thermal shield, this can be brought below 0.7 K. We are still proceeding to optimize this design further. In addition, there are optical design procedures for the CCR that

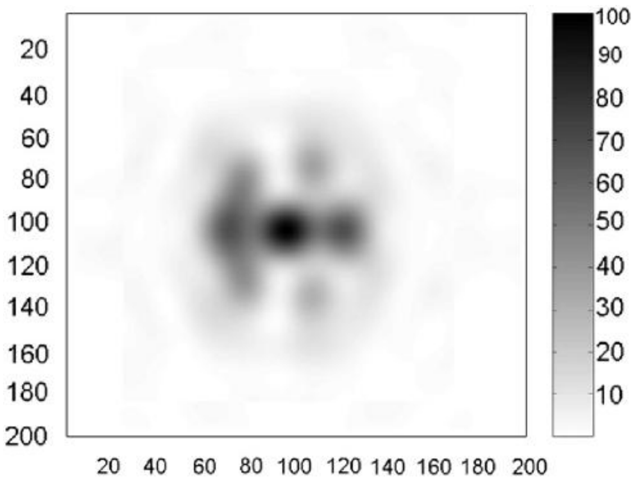


Figure 11 Sample of FFDPs obtained during the April 2010 test at INFN LNF

allow us to further reduce the effective temperature difference from the tip to the face. As a result, we have demonstrated (in computer simulation) that the thermal effects of the solar absorption, the mount conduction and the radiative exchange with the pocket can be controlled to a sufficient degree. Using Code V, we may simulate the FFDP that is expected for a given axial thermal gradient. Thus the pattern for a CCR with the measured back surface offset angles and a thermal gradient of 0.5 K (the worst gradient in the computer simulation of all the thermal effects except for one or two days) is shown in Fig. 6. With the modified design, the signal return for various ground station latitudes and the expected selenographic coordinates will be computed for the full lunation cycle. This will be done with a sequence of programs, now being tested, which consist of a custom IDL program, Thermal Desktop by C&R Technologies program, Code V by OA Associates, and finally another custom IDL program.

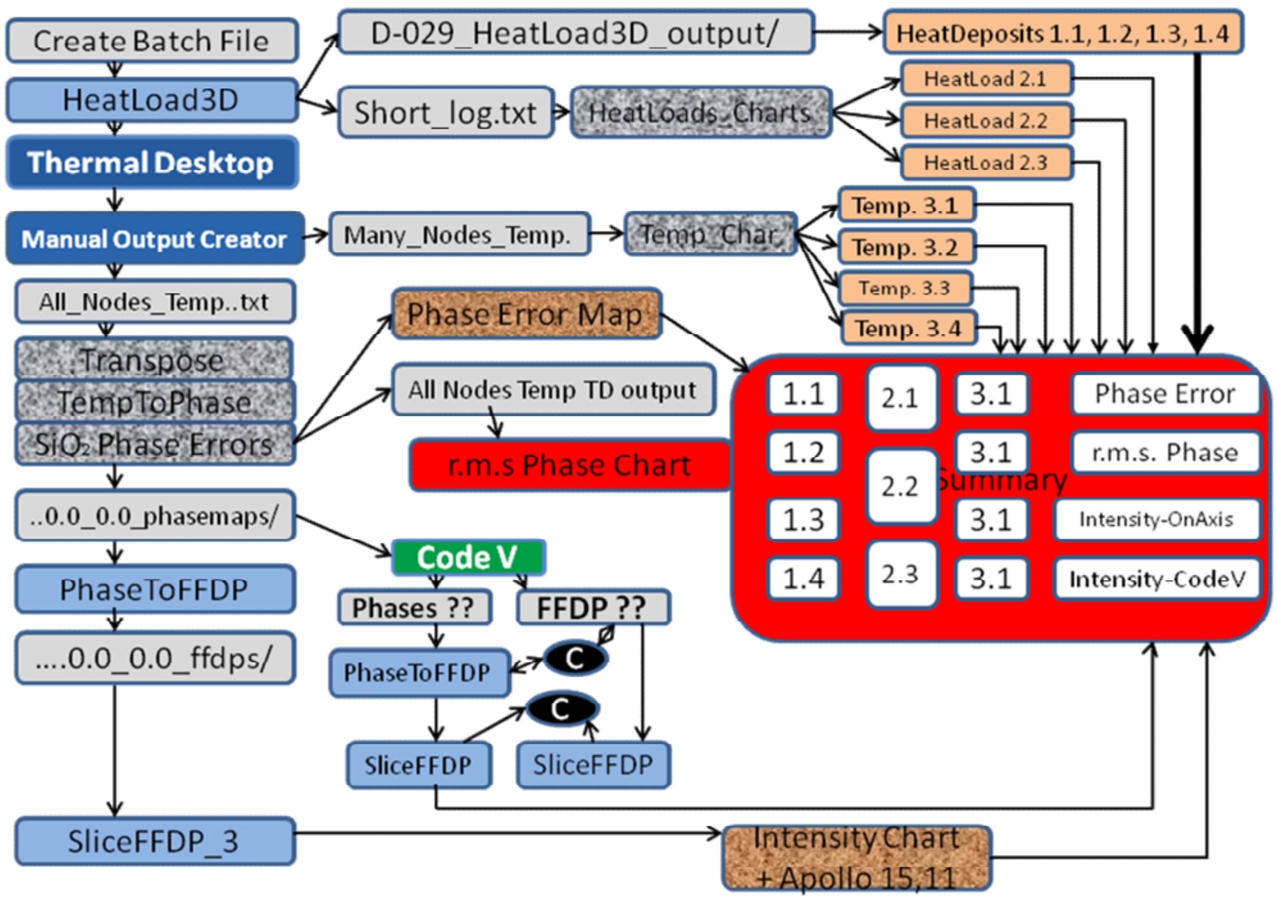


Figure 12 The structure and interconnections of the IDL, Thermal Desktop and Code V programs

SIGNAL STRENGTH

We address the dependence of the signal strength on the thermal gradient, a two step procedure. First the curvature of the wave front due to the axial thermal gradient is computed. This relates the curvature (or peak to peak value) of the curvature to the TtFF temperature difference. Then the on-axis degradation is computed using the wave front curvature with Code V. The result is shown in Fig. 6. This is combined with the reduction in the central intensity due to the TIR. This is somewhat conservative since it does not take into account the surrounding lobes from the TIR. The axial gradient is different for the surface emplacement (Fig. 7) and for the anchored emplacement (Fig. 8). It also varies throughout the lunar cycle. However, at this point, we have taken a typical value of 0.5 K. In this case, the result of the thermal degradation is to reduce the signal by about 20%. Thus the return of a single 100 mm CCR is about 4.8% of the theoretical Apollo 15 array of 300 CCRs. However, taking into account the dust issue (see next session) the return will be about half of the current operational return of the Apollo 15 array.

Recent analysis of the returns obtained by the Apollo station indicate that the rate of single photoelectron return is about a factor of ten less than the expected return rate. While the reason for this is still under investigation the two main candidates are dust raised by the rockets used for the launch of the Lunar Excursion Module as the astronauts left the surface of the moon, or the accumulation of levitated dust on the front surface of the CCR over the decades. Concerning a robotic mission (which will be the first set of missions), the dust will be raised on landing. Our current design will have a “dust cover”in place during landing. Therefore this problem will not arise (since the Lander will obviously not take off as did the LEM).

Concerning the accumulation of the dust, the sunshade will significantly reduce in the quantity of dust that reaches the surface of the CCR. In addition, we are investigating a “dust filter” that may further reduce the dust reaching the CCR. In any case, this should not be a significant problem during the first decade of operation. Thus we may expect over the first decade an increase in the signal by about a factor of ten. Thus, the single 100 mm CCR will have about 48% of the rate of return of the 300 CCRs in the Apollo 15 array in its current condition.

In the analysis of the previous section, in order to address a surface emplacement, we have assumed certain parameters for the regolith and other effects, etc. However, we now address an anchored emplacement, in which one must develop an integrated model which contains 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. This has been parameterized to agree with the heat flow experiment deployed during the Apollo 16 mission. The results of one such run are shown in Figure 13, 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. The solar blanket isolates the regolith from the direct thermal input of the sun. In turn, this shields the support rod from the temperature extremes it would encounter in the unshielded regolith. See Figure 13 for the effects under and beyond the blanket.

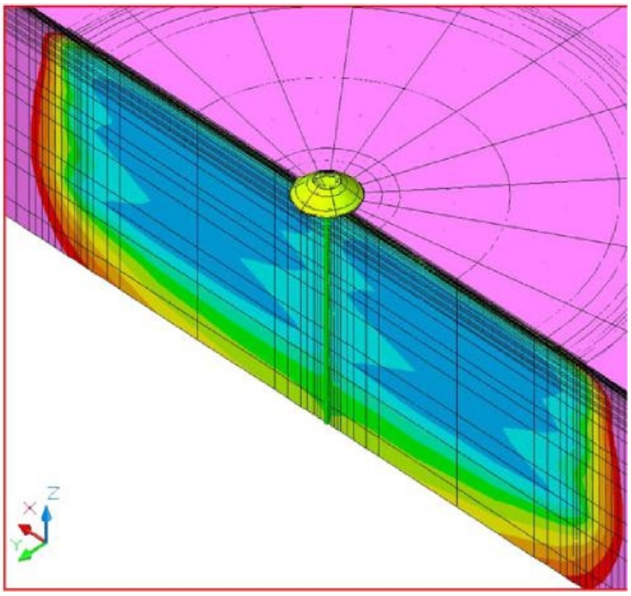


Figure 13 Cross section of LLRRA-21 (anchored deplying configuration).

Various runs have been made to evaluate the advantages. In particular, this uses the earlier “mushroom”(i.e., descriptive of the shape of the design) design of the housing and uses an aluminum support rod. The circular region surrounding the housing is a thermal blanket to reduce the temperature variations surrounding the support rod. In fact, the plot of the temperature gradient across the CCR shown in Figure 9 was derived by this “whole”model. Again, Figure 13 is one frame in a sequence that covers an entire lunation. The evaluation of a single lunation is performed after evaluating many successive lunations (~1000) in order to reach the "final state"distribution.

To attain the required mechanical stability w.r.t. the center of mass of the moon, we must address the temperature distribution in the regolith, the effects of the thermal blanket and the effects of heat conduction in the support rod. A locking depth is chosen to reduce thermal motion. The blanket further reduces the thermal effects and the effects on the support rod. This simulation cycles through the lunation and annual cycles.

CURRENT HOUSING DESIGNS

We are successively refining our design based upon maximizing the overall performance by jointly optimizing the behavior with respect to the various are successively refining our designs based upon optimizing the behavior with respect to 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 with the thermal vacuum measurements. This addressed both the design for the manned emplacement and the use of the 100 mm solid CCR package on various robotic missions such as the ILN, Lunette and possible X-Google missions.

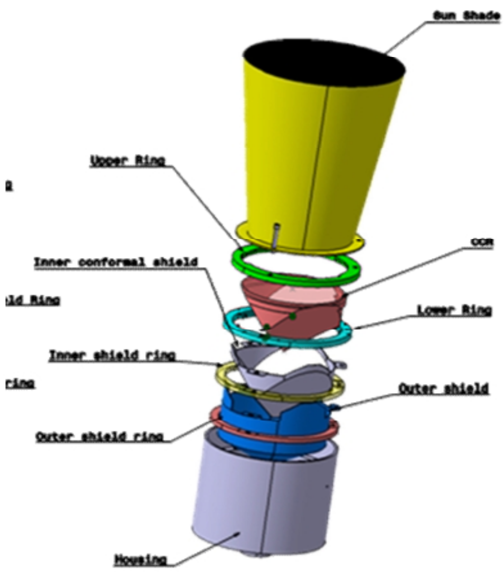


Figure 14 hardware implementation of the current LLRRA-21 package design. This unit, with the sun shade, was tested in the thermal/ optical/vacuum system in Frascati in April 2010.

Other designs have been addressed for the Italian Space Agency MAGIA mission, lunar orbiter mission for gravity and gravitational red-shift measurements which will carry our 100 mm CCR into lunar orbit (if and when it receives final approval).

THERMAL VACUUM CHAMBER TESTING

Up to this point, the discussions have addressed concepts for the LLRR-21 and thermal and optical computer simulation developed to validate the design concepts. We now address the thermal/optical/vacuum testing to further validate the design issues. To accomplish this, we need to provide two classes of measurements in the SCF. The first is the thermal behavior of the test configuration. A solar simulator that has a good representation of the AM02 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. 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).

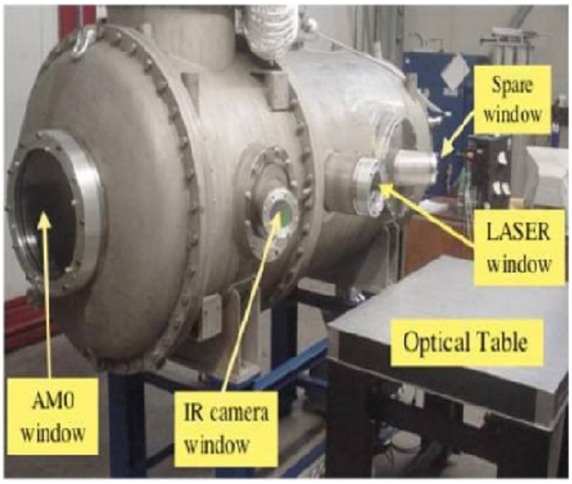


Figure 15 SCF indicating the windows for various functions.

Figure 16 Instrumented CCR prepared for the April 2010 test

CHALLENGES AND OBJECTIVES

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

(1) Continue simulations to optimize thermal performance, i.e. minimize the TtFF gradient

  a. Evaluate further modifications of the housing structure and the support rod.

  b. Investigate optical procedures to minimize the beam spreading for a TtFF gradient.

  c. Optimize the offset of the back faces to minimize the impact of velocity aberration.

(2) Continue further thermal vacuum testing of designs at SCF 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

Figure 17 "Jigsaw" Sun shade: geometry and thermo optical properties optimized to reflect back to space as much sun radiation as possible

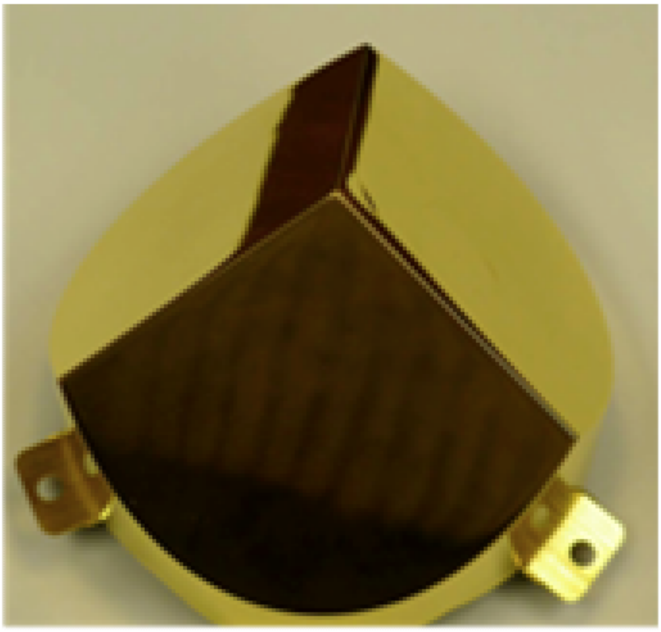


Figure 18 Inner conformal shield: to limit green house thermal budget in the CCR cavity

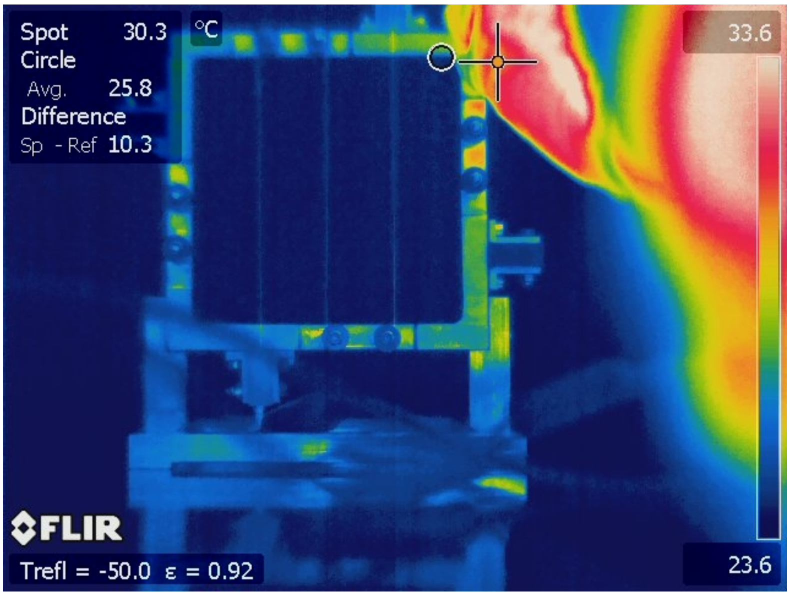


Figure 19 New concept of IR simulator for CCRs

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CONTACT

Giovanni O. Delle Monache

Cryogenic Group Head - Accelerators Division

INFN LNF Via E. Fermi 40 00044 Frascati (RM)

Voice +39 0694032544

FAX +39 0694032256

email: dellemon@lnf.infn.it

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APPENDIX A: MODELING OF SOLAR FLUX ABSORBED BY THE IR SHIELD IN CASE OF TOTAL INTERNAL REFLECTION (TIR) LOSS

The CCR of the Moonlight experiment is uncoated type because of the Moon distance. Coated CCR's suffer from considerable thermal gradient when illuminated by the sun even if the coating material is chosen with very low solar absorption.

TIR is guarantee in a coated CCR providing that the radiation enter the reflector within limited angles from the Zenith. Figure 20 shows the reflection pattern of an Apollo era CCR. Parameter is zenith angle, and it is plotted along a radius, corresponding to the solar incident angle; the azimuthal angles corresponding to the rotation of CCR are plotted counterclockwise in a usual polar plot.

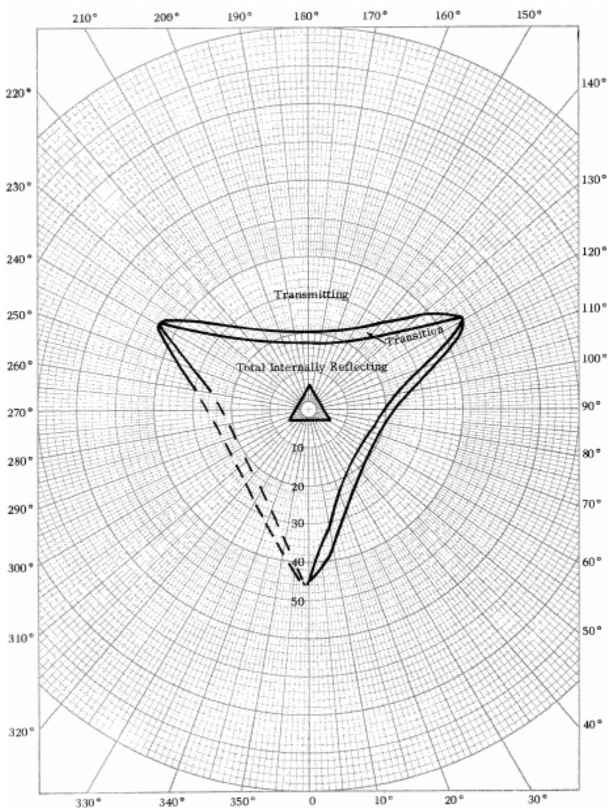


Figure 20 Reflection patterns of Apollo CCR prototype

From the previous figure we can conclude that, depending from azimuth orientation, if the Sun inclination is not between +/- 22 deg and -/+47 deg the radiation is not reflected, passes the CCR and is absorbed by the containing cavity (IR shield) according to its thermo-optical properties.

This effect must be considered in the thermal analysis because the amount of heat absorbed by the IR shield even kept as low as possible by proper choice of the thermal control coating is of the same order of magnitude of the one absorbed in the volume of fused Silica.

In order to investigate this effect we made use of special feature of Thermal Desktop®, which can perform thermo-optical analysis of transmissive materials, even if limited to surfaces. In fact the software can simulate the TIR properties of a CCR.

The analysis has been set in such a way to not interfere with the volumetric load in the reflector; for this reason we use a separate model for the radiation absorbed by the IR shield.

The CCR is modeled without volume; CCR surfaces can be divided in polished surfaces (PSs) (one entrance and three reflecting surfaces) and grinded surfaces (GSs).

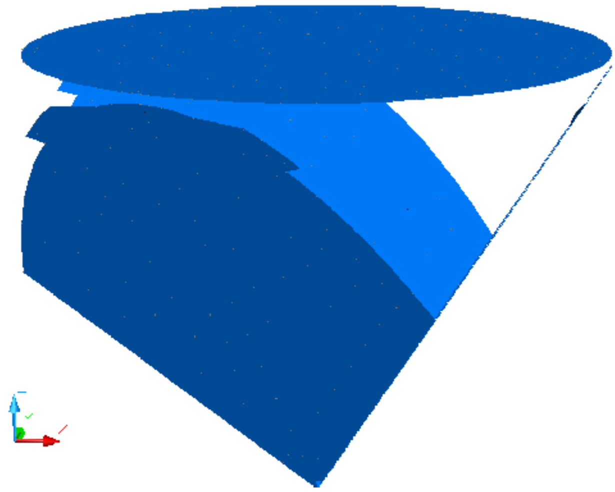


Figure 21 CCR PSs

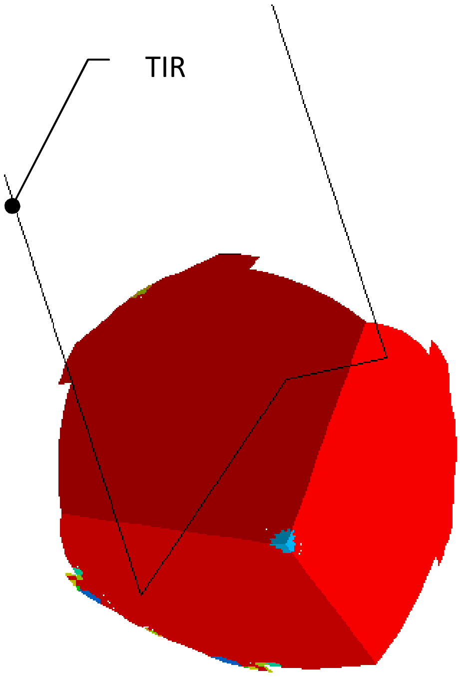
For the PSs index of refraction is defined for both inner and outer side; as a conservative approximation a solar absorption of 0% is defined and considered constant all around the orbit.

The GSs are made inactive in the model; this is another conservative approximation necessary to get rid of uncertainties about solar absorption of grinded/coated surface, which probably will be dropped considering a possible shading element mounted in such a way that limits solar radiation from entering the CCR when the sun is far from the zenith. Shall this be the case this analysis must be repeated with the shade.

Figure 22 shows the post processing of one ray shot from the solar radiation at zenith. The ray trace is the real one computed by the Monte-Carlo solver built in the software. Figure 23 shows the same ray when the Sun is far from the zenith. This part of the radiation is not reflected back, but is absorbed by the IR shield. The model is run over one lunation, and the heat load data for each node of the shield is stored to be applied in the whole model together with the volumetric orbital loads, thus simulating the real effect of TIR loss.

Figure 24 shows the total heat load on the IR shield along the orbit with gold as thermal control coating. Values on the whole Moonlight model can be easily adjusted for different materials. Plot shows qualitative match with Figure 20. The analysis has been optimized regarding the number of rays to be shot by the solver and the time resolution for the orbital positions.

The plot in Figure 24 refers to a CCR whose axis lays exactly on the Sun direction. This condition is hard to be met both for precision of the experiment alignment and for experimental site designation.



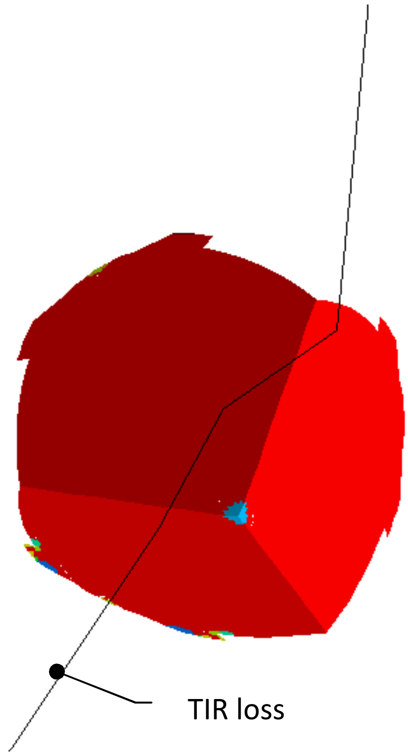


Figure 22 Thermal Desktop TIR ray trace **Figure 23 Thermal Desktop TIR loss ray trace**

In fact the behavior showed in plot is lost as soon as the CCR axis is rotated by more than 2.25 deg with respect to Sun direction as showed in Figure 25.

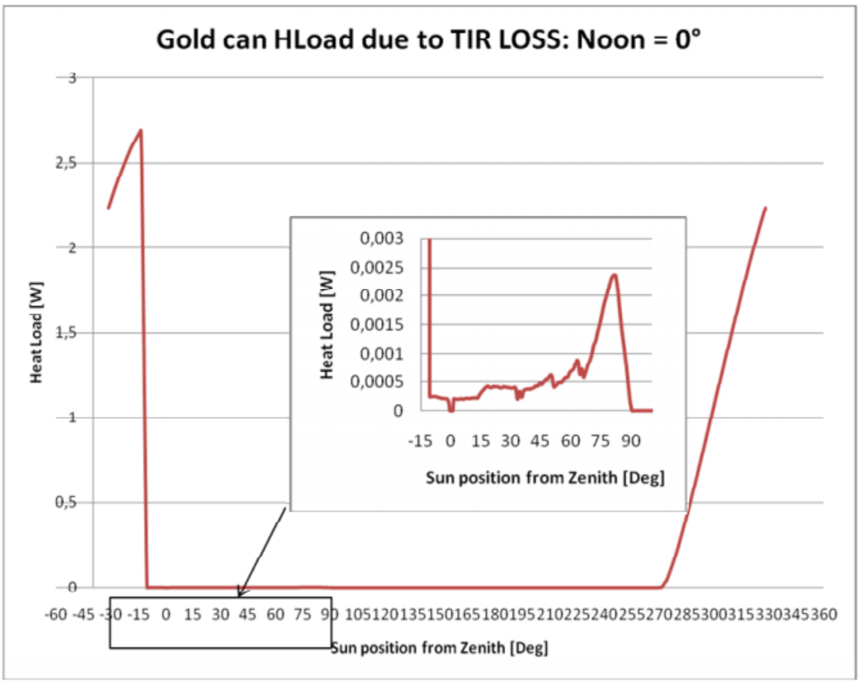


Figure 24 Total heat load on the IR shield along the orbit with gold as thermal control coating

Thus the use of a resested mounting is to be considered necessary unless the site and the precision of the positioning system can avoid this second zone for which TIR is lost considerably.

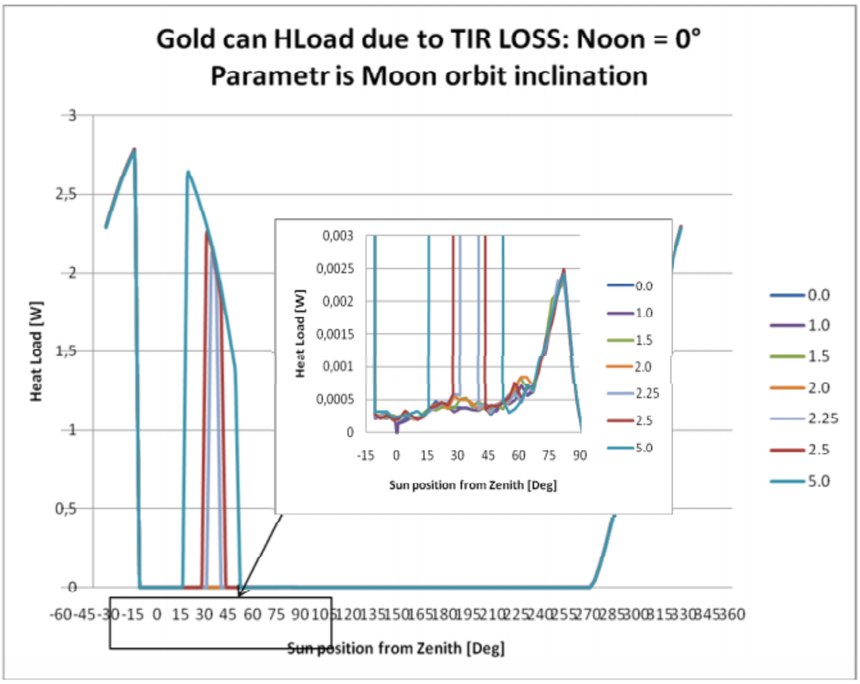


Figure 25 heat load on the IR shield along the orbit at different orbit inclination