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MoonLIGHT-R:

MOON LASER INSTRUMENTATION FOR GENERAL RELATIVITY HIGH-ACCURACY TESTS

An ASI study for a robotic mission on the Moon

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ABSTRACT

New robotic lunar landings may take place during next decade. The Italian Space Agency (ASI) has requested proposals for interesting and compelling physics experiments to be performed with the severe weight, size, power and deployment restrictions inherent to lunar sorties.

MoonLIGHT-R is a proposal for improving by a factor 1000 or more the accuracy of the current Lunar Laser Ranging (LLR) experiment, performed since 1969 with retro-reflector arrays deployed by Apollo 11, 14 and 15. LLR is the only Apollo experiment still taking data today. Achieving this goal requires a new, different thermal, optical and mechanical design of the retro-reflector array and detailed simulations and experimental tests. MoonLIGHT-R is a light, compact, very-long lasting, maintenance-free and completely passive payload.

MoonLIGHT-R will perform accurate tests of General Relativity (GR) already with the existing ILRS systems (like ASI-MLRO)[1]. This accuracy will get better and better as laser technologies improve over the next few decades, like they did relentlessly since the invention of the laser in the '60s. A specific cosmological model, which explains the acceleration of the Universe via modified GR at very large distances, can be fully tested by measuring an anomalous precession of the Moon perigee. A high scientific return is guaranteed.

We are committed to the space-climatic and laser-optical simulation (and, at a later stage, experimental characterization) of the new LLR array using the LNF Space Climatic Facility (SCF). The payload construction and deployment is an opportunity for the national industries.

Preliminary space-climatic simulations and payload specs are presented in this LNF report.

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[1] ILRS = International Laser Ranging Service; ASI-MLRO = ASI - Matera Laser Ranging Observatory.

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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 with a robotic probe. 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 or a robot 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 deployment risk 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 (LLRA) which is still functioning 37 years later; and other Apollo missions deployed their own still-functioning arrays.

A manned version of the MoonLIGHT study, whose internal INFN name is MoonLIGHT-M, has been presented by the authors of this report together with other US collaborators to NASA, answering the call "Suitcase Science to the Moon" on October 2006. The proposed LLRA will be hand-carried and placed on the Moon by astronauts as part of the human exploration program. The MoonLIGHT-M proposal can be found among the references.

We have the maximum possible experience in this area: on of the Co-Principal Investigators (DGC) 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. The new basic design is shown in Fig. 1.

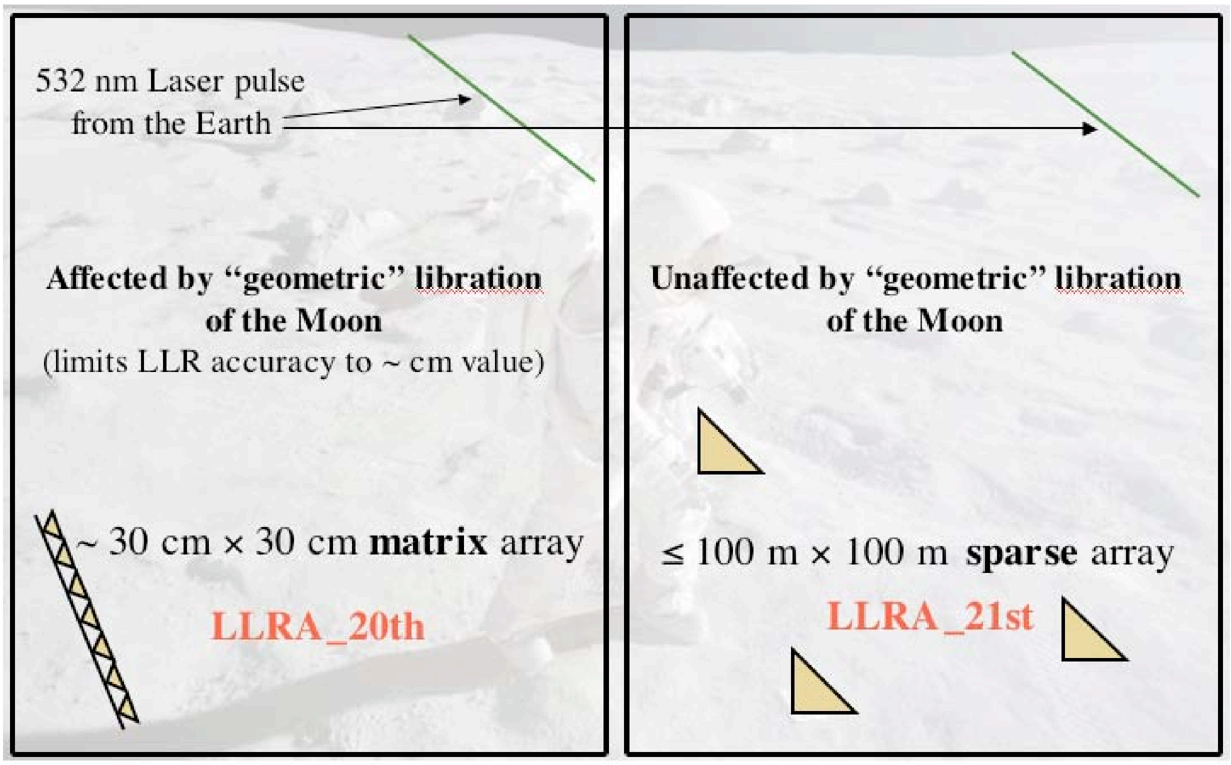

Figure 1. The MoonLIGHT concept: a large sparse array instead of a small tight arrangement.

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. While MoonLIGHT-R is an analysis study, for MoonLIGHT-M the LNF group has 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. In MoonLIGHT-M, this will be addressed by the US collaborators expert in this field[2]. For MoonLIGHT-R this will be care of the national industries under the supervision of ASI. We will necessarily be on the regolith and subject to the thermal motions as the Sun rises and sets. The deployment will have to minimize this effect, which will be the actual limiting accuracy of the facility. The basic requirement is that the installation must be stable at the level of 10 μm.

Finally, we have astronaut Roberto Vittori on our team, who can address the differences, advantages and disadvantages between the robotic and manned versions of MoonLIGHT. Ultimately, his contribution will be important to find out which one of the two approaches, MoonLIGHT-R or MoonLIGHT-M will be more likely to be successful from a technical point a view.

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[2] W. D. Carrier III, MoonLIGHT-M proposal.

B. Physics Measurements

A robotic lunar landing would represent a major milestone in the history of space exploration of ASI. Such an event would also be a unique opportunity for Fundamental Physics measurements with the MoonLIGHT-R payload.

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 specific model predicts an anomalous precession of the Moon perigee by ~1mm, as opposed to current lunar ranging accuracy of ~1cm, and can be fully tested by MoonLIGHT-R. 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:

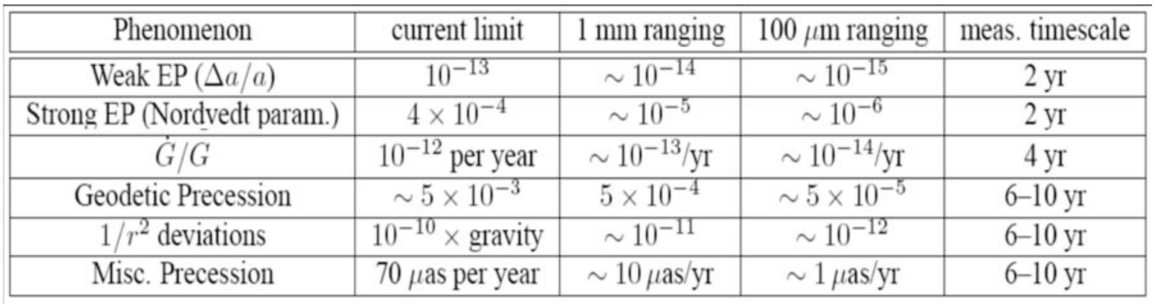
- The Weak Equivalence Principle (WEP) at a level of 10^{-13}
- The Strong Equivalence Principle (SEP) at a level of $4\text{x}10^{-4}$
- Time-rate-of-change of Newton's gravitational constant, G, to a part in 10^{-12}/year
- Geodetic precession at a level of 0.35%
- Deviations from $1/r^2$ gravity at 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 $5\text{x}10^{-10}$ 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 $4\text{x}10^{-4}$ constraint on violation of the SEP.

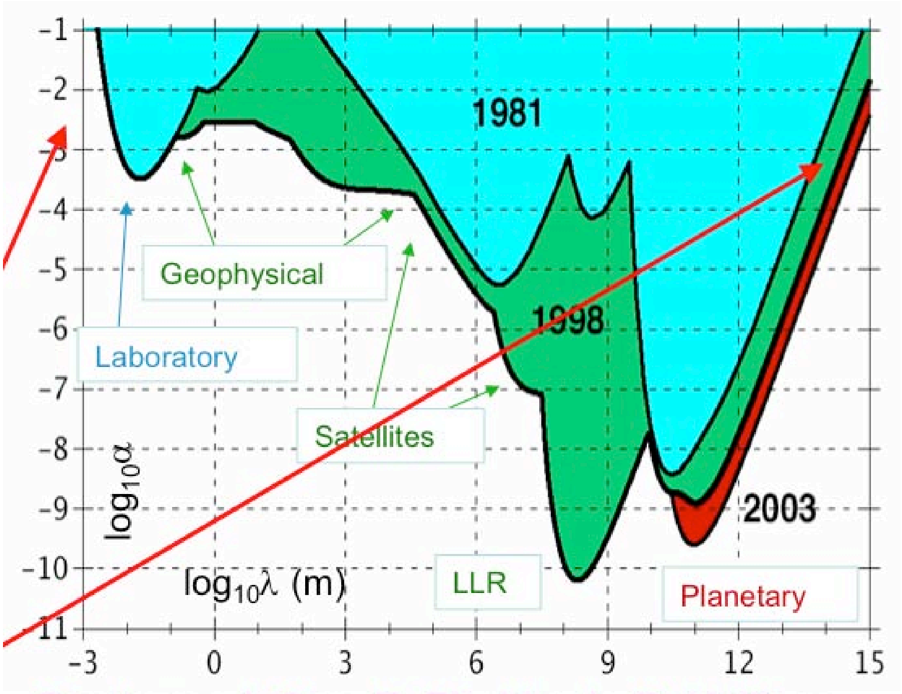
LLR can also constrain new theoretical paradigms. An example is an idea to account for the apparent acceleration of the universe by allowing gravitons to leak off of our 4-dimensional spacetime "brane" into another bulk dimension, thus weakening gravity over cosmological scales. Though small, such a 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 expected improvements on the General Relativity measurements discussed above with MoonLIGHT are shown in Table 1[3], together with their measurement time scale. Figure 2[4] shows the current status of the limits on non-Newtonian gravity, parametrized in the form of an additional Yukawa-like potential: $\alpha \times$ (Newtonian-gravity) $\times\, e^{-r/\lambda}$.



Phenomenon	current limit	1 mm ranging	100 μm ranging	meas. timescale
Weak EP ($\Delta a/a$)	10^{-13}	$\sim 10^{-14}$	$\sim 10^{-15}$	2 yr
Strong EP (Nordvedt param.)	4×10^{-4}	$\sim 10^{-5}$	$\sim 10^{-6}$	2 yr
$\dot{G}/G$	10^{-12} per year	$\sim 10^{-13}$/yr	$\sim 10^{-14}$/yr	4 yr
Geodetic Precession	$\sim 5 \times 10^{-3}$	5×10^{-4}	$\sim 5 \times 10^{-5}$	6–10 yr
$1/r^2$ deviations	$10^{-10} \times$ gravity	$\sim 10^{-11}$	$\sim 10^{-12}$	6–10 yr
Misc. Precession	70 μas per year	$\sim 10\ \mu$as/yr	$\sim 1\ \mu$as/yr	6–10 yr

Table 1. Expected physics reach of MoonLIGHT.



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

Figure 2. Current limits on non-Newtonian gravity ($\alpha \times$ (Newtonian-gravity) $\times\, e^{-r/\lambda}$). At the Earth-Moon distance LLR gives a limit on α around 10^{-10}. With MoonLIGHT-R this limit will reach 10^{-12} (out of scale). Untested regions are present at λ<1 mm and λ>10^6 m (red arrows).

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[3] Source: T. Murphy, MoonLIGHT-M study proposal (see References of this Report).

[4] Source: S. Reynaud, “Quantum to Cosmos” conference (http://physics.jpl.nasa.gov/quantum-to-cosmos/.

C. Other Scientific Goals

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.

D. 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. This is shown schematically in Fig. 3.

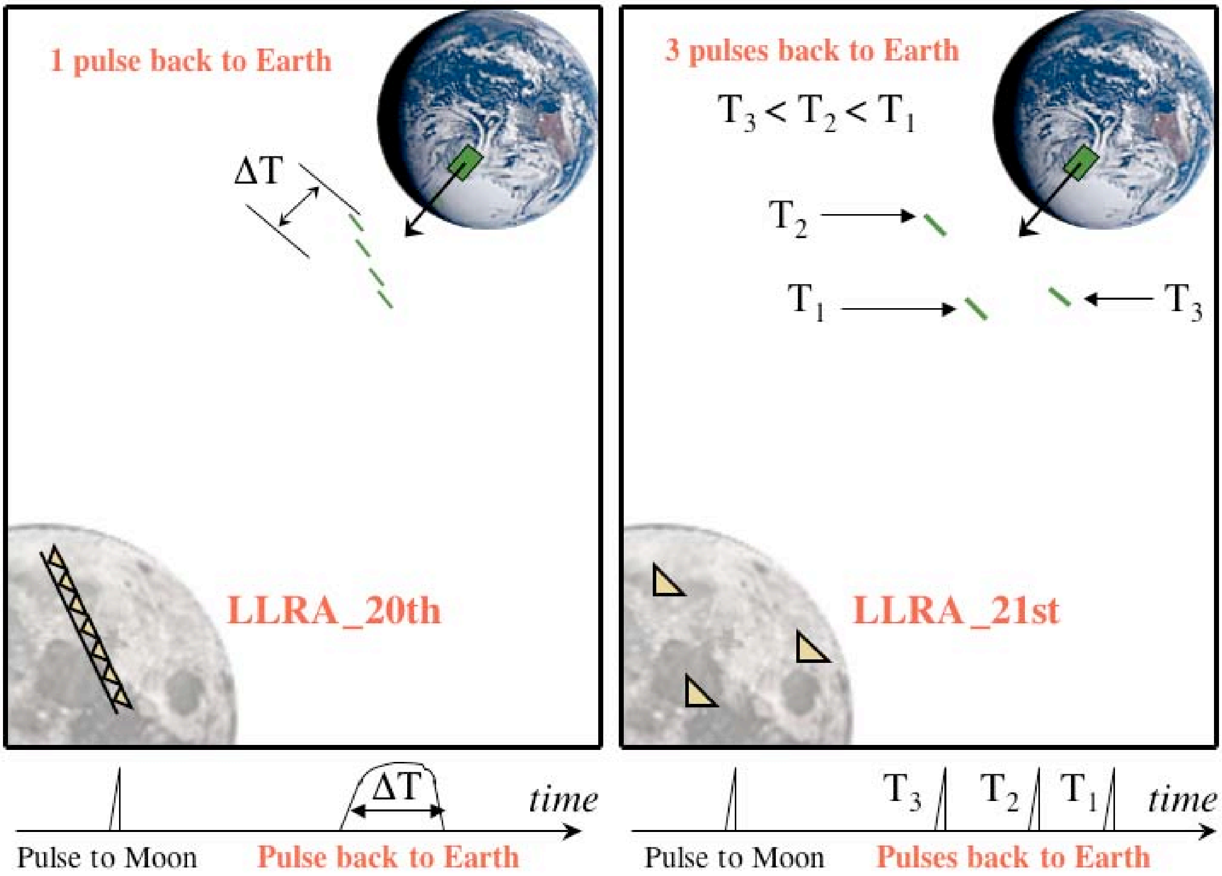


Figure 3. Separate detection of retroreflected pulses with MoonLIGHT. This is not possible with the 20st century LLRA due to the Moon geometric librations.

E. CCR Notional Design Options

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. The holder will then be installed on the isothermal rock, with a single leg or tripod. An INVAR alloy should be considered to limit variations of the CCR position to 10 mm, depending on the results of the thermal simulations. A drawing of the CCR and a possible mechanical support structure is shown in Fig. 4. The mounting of the CCR inside the box is not shown. KEL-F could be used for this mounting (its used in LAGEOS) due to its good insulating, low out-gassing and non-hygroscopic properties.

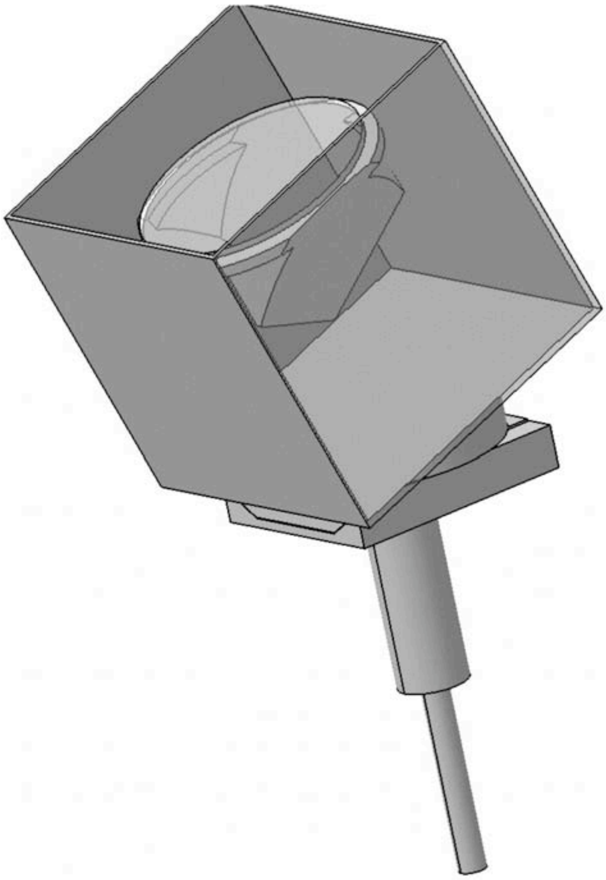


Figure 4. A 100 mm CCR and support structure.

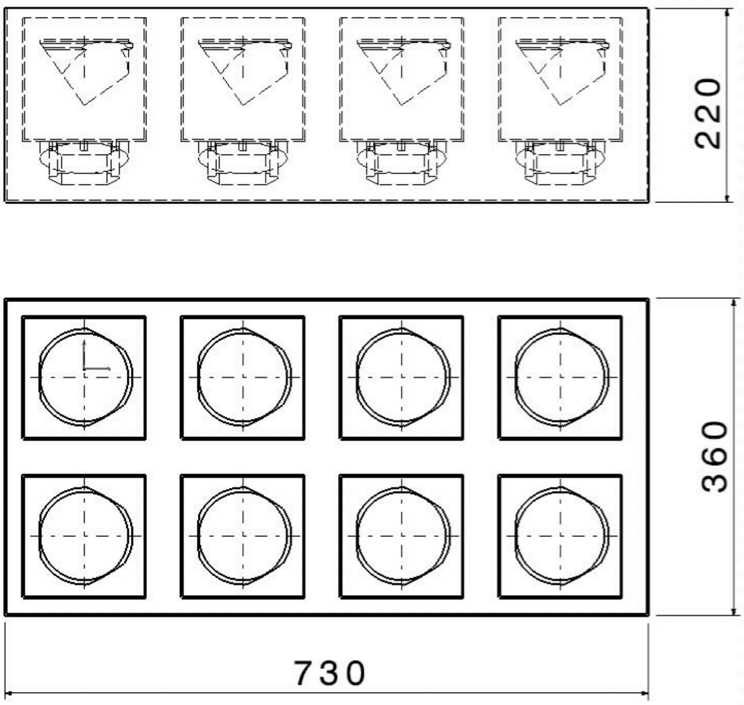


Figure 5. Possible size of the “Suitcase Science to the Moon” for a MoonLIGHT array made by eight cubic boxes of 140 mm side and CCRs of 100 mm diameters.

F. Thermal Simulation and SCF Facility at INFN-LNF

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 in detail under "4. Facilities and Equipment."

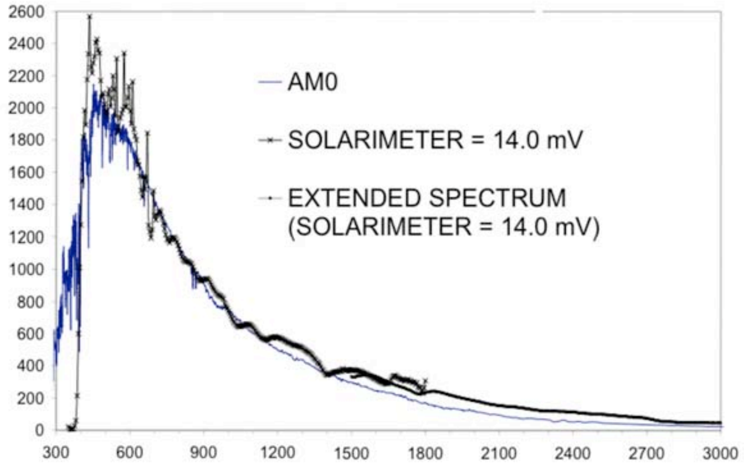


Figure 6. AM0 spectrum (W/m^2/nm x10^3) as a function of wavelength (nm) measured with the SCF simulator. Lamp currents are around 36 A (tungsten) and 29 A (HMI).

The SCF includes both a Sun and an Earth simulator. The Sun simulator (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. 6). 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. 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.

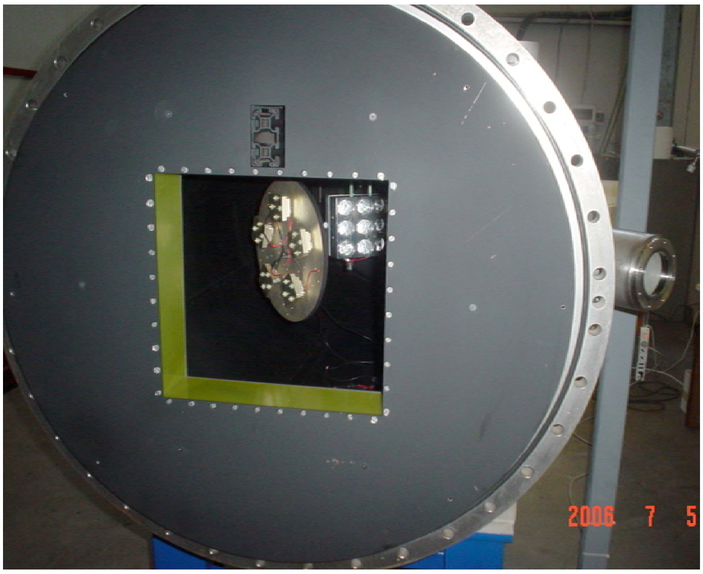
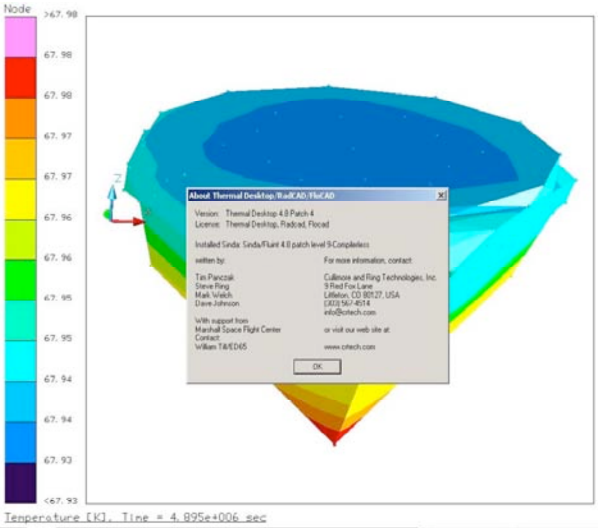


Figure 7. The SCF Earth simulator

The Earth simulator [for the LAGEOS altitude] (Fig. 7) 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 (for example this would be ~60° for LAGEOS).

Thermal Simulation Package

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" (http://www.crtech.com/). The software currently used is version 4.8 (see Fig. 8) 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.



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

Installed Sinda: Sinda/Fluint 4.8 patch level 9-Compilerless

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www.crtech.com

Figure 8: Software version and CCR temperature profile for a Moon climatic simulation.

TRS will be used for the simulation of the climatic conditions of the CCR on the Moon. Fig. 9 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. 9 and that the CCR is surrounded by an Al box whose temperature is fixed at 10 K. Therefore only radiative heat exchange is modeled.

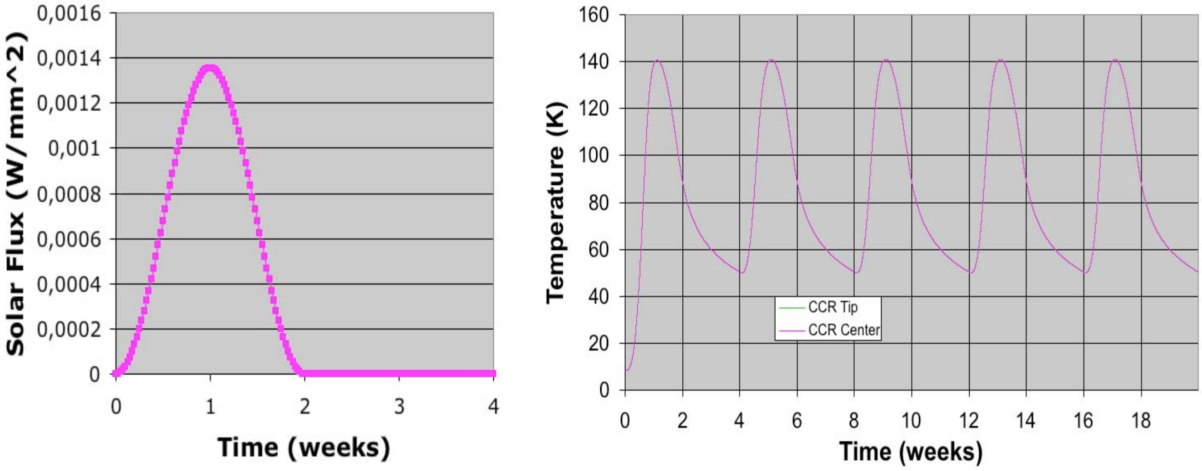

Figure 9: Solar flux in the CCR climatic simulation (left) and temperature variation of the CCR in the Moon climatic simulation (right).

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. 10. 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.

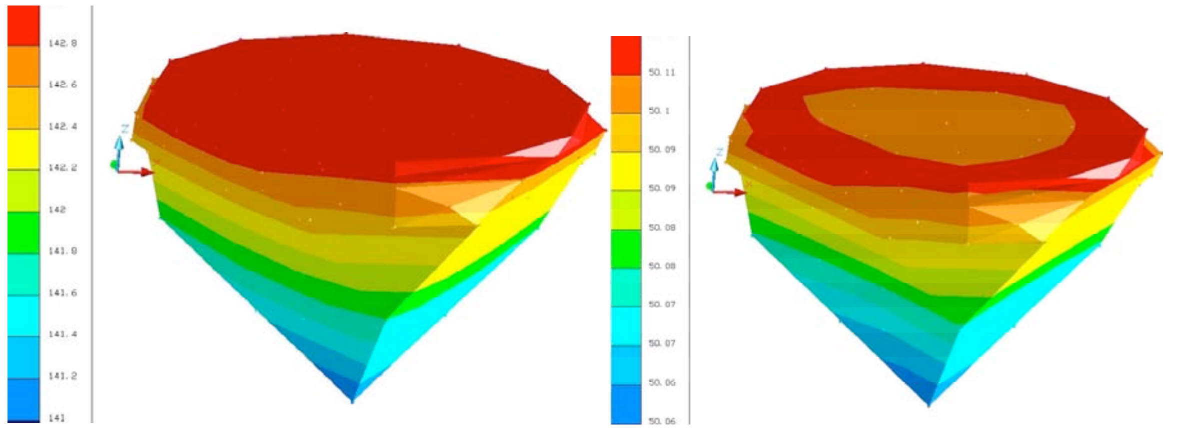

Figure 10: CCR temperature profile for the Moon climatic simulation: highest temperature point (left, time ~ 1st week) and lowest temperature point (right, time ~ 4th week). This CCR finite element model has 110 nodes.

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 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 9. 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, CodeV) 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 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.

Example of Thermal Measurement with a GPS Array

Three "GPS" CCR arrays were obtained to be installed on the U.S. GPS Satellites. Two were installed on satellites 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 11 and 12, we see the mounting for a preliminary test of the thermal behavior of the GPS3 array performed at INFN/LNF. The array was then "solar" illuminated, and after equilibrium of the CCRs was reached, the solar illumination was terminated. Figures 13A and 13B 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 14 illustrates the temperature as a function of time for the central CCR.

Figure 11: Photo of the GPS3 array.

Figure 12: GPS3 test with (left to right) Dave Arnold, Douglas Currie and Giovanni Delle Monache.

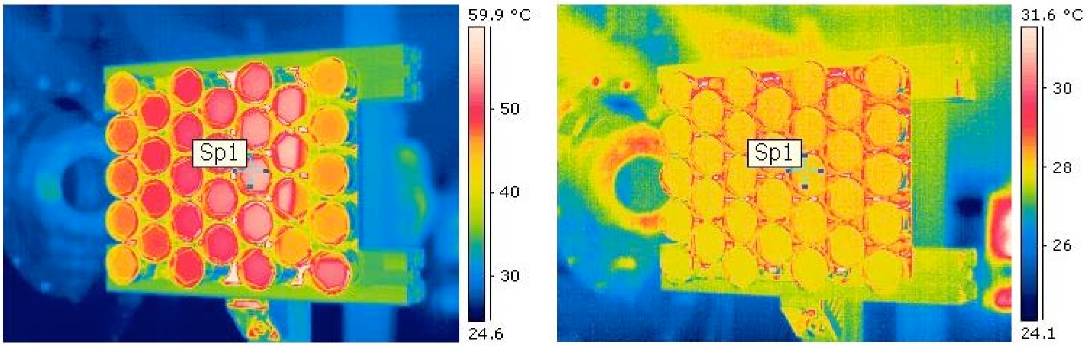

Figure 13A:Warmest condition. Figure 13B Coolest condition.
Infrared images of the GPS3 array at recorded different times during the tests.
The high thermal resolution of the IR camera allows very precise determination of the temperatures at various points in the array.

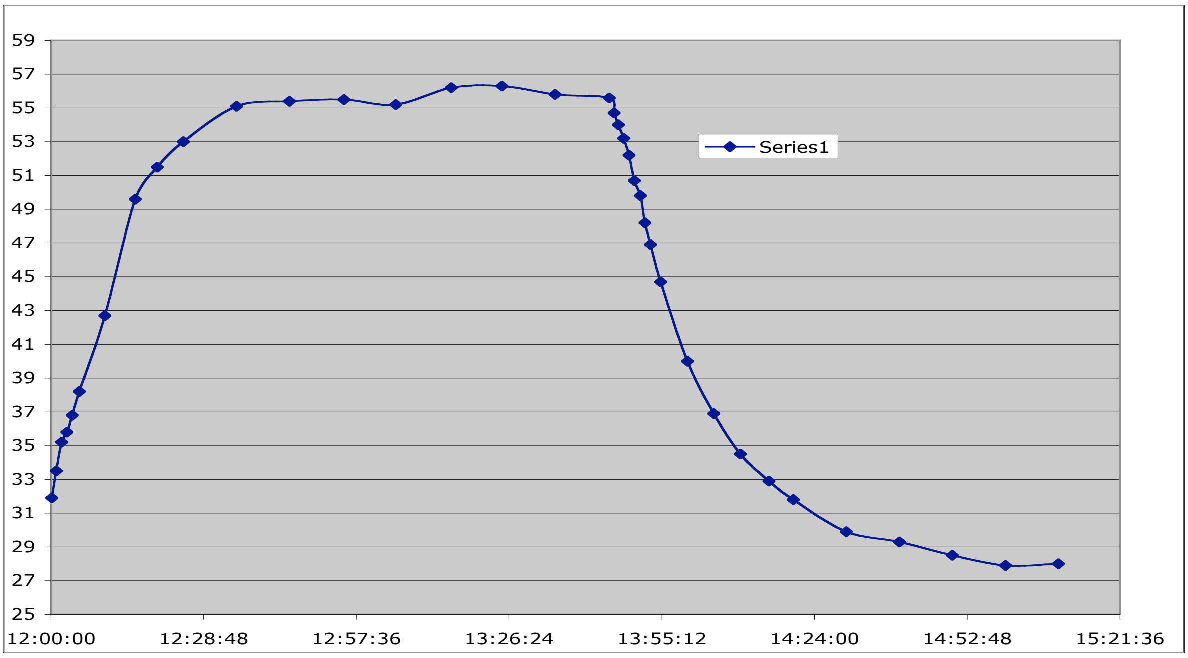

Figure 14 Temperature in ºC as a function of time in hours, minutes and seconds. Solar simulator turned on at 12:00:00 and then turned off at ~13:50:00. This illustrates the heating primarily due to absorption of visible light by the aluminum backing and cooling, primarily due to the infrared emission by the front face of the CCRs.

G. Interface Between CCR Package and Lunar Surface

This section is discussed in detail in the MoonLIGHT-M proposal (see references).

H. Deployment Configuration, Procedures, and Conditions

This section is discussed in detail in the MoonLIGHT-M proposal (see references).

I. Ground-Based Technologies

This section is discussed in detail in the MoonLIGHT-M proposal (see references).

L. Development Requirements

This section is discussed in detail in the MoonLIGHT-M proposal (see references).

M. Preliminary Thermal Simulation 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 and is shown in Fig. 15. The red and orange curves represent the a 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.

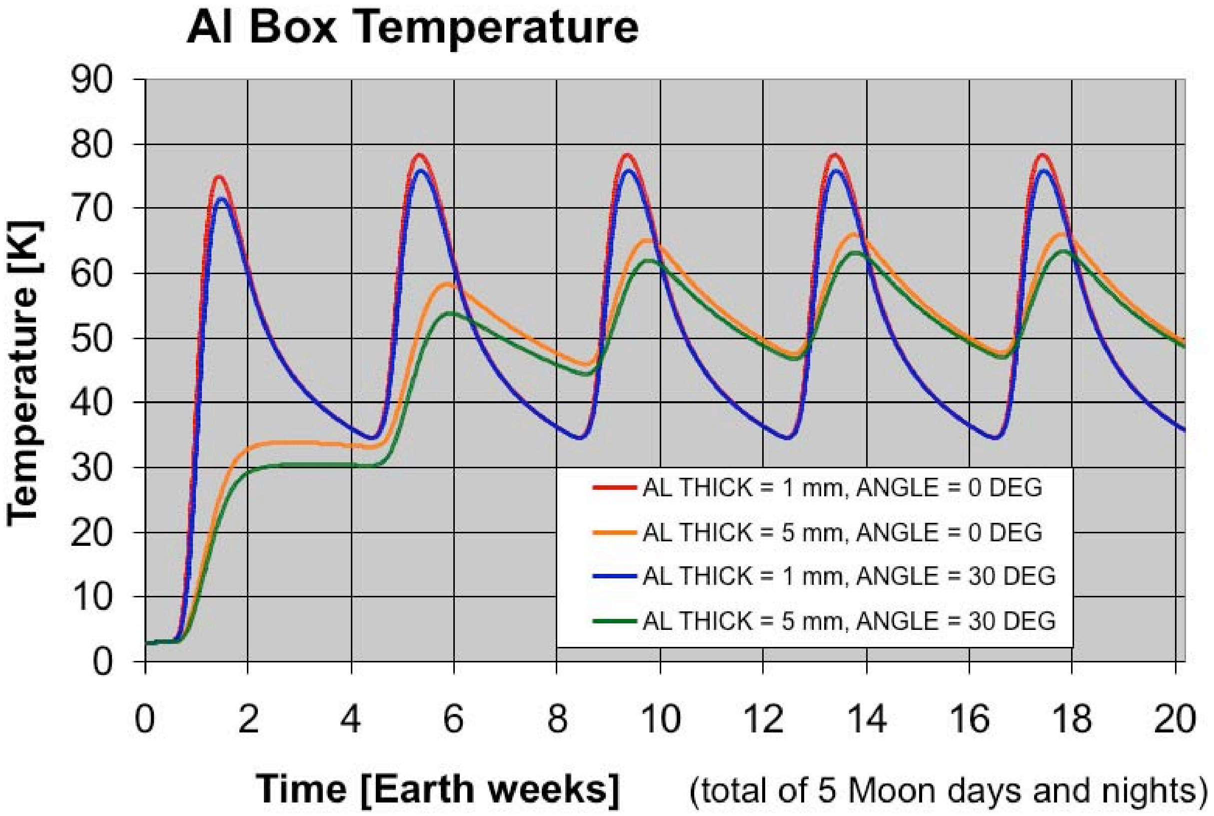

Figure 15. Temperature variation of the Al box containing the CCR.

For the CCR inside the box, we consider the case of the zenith illumination and the 1 mm box. In this case, we plot in Fig. 16 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.

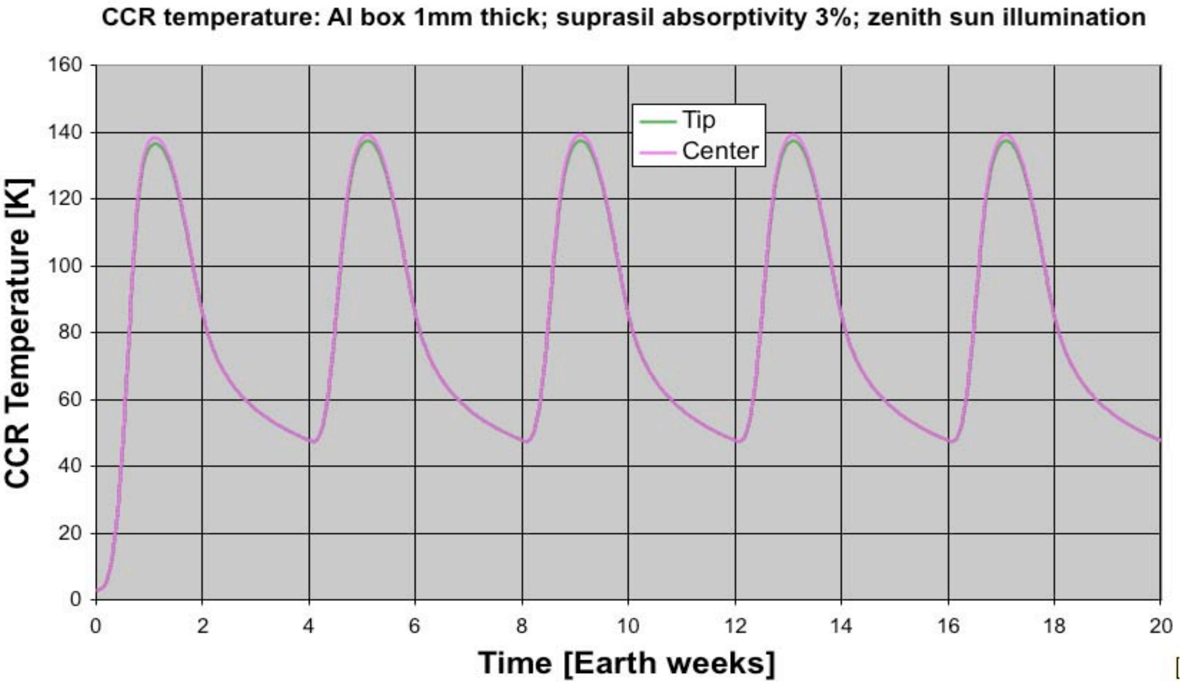

Figure 16. Temperature variation of the CCR. The difference between the "center" (on the front face) and "tip" (on the back) is barely visible on this scale.

Finally, we look at the temperature difference from the center of the front face to the tip (see Fig. 17). This is the best representative of the thermal distortion of the return beam to the earth. 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.

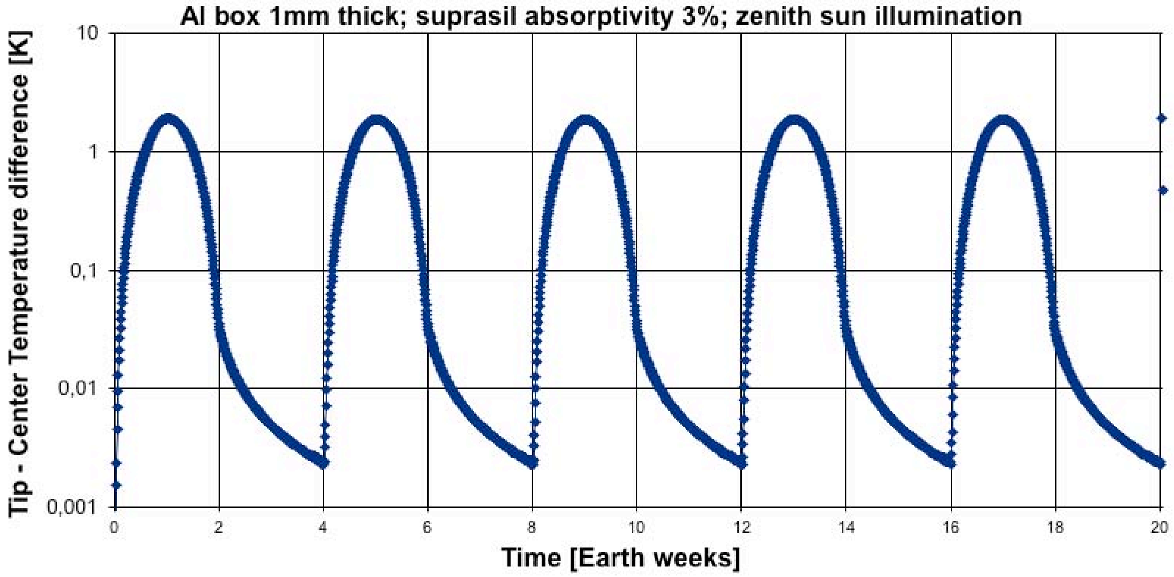

Figure 17. Temperature difference between CCR front ("center") and back ("tip")

Finally, a possible thermal configuration of the CCR deployment on the Moon is shown in Fig. 18.

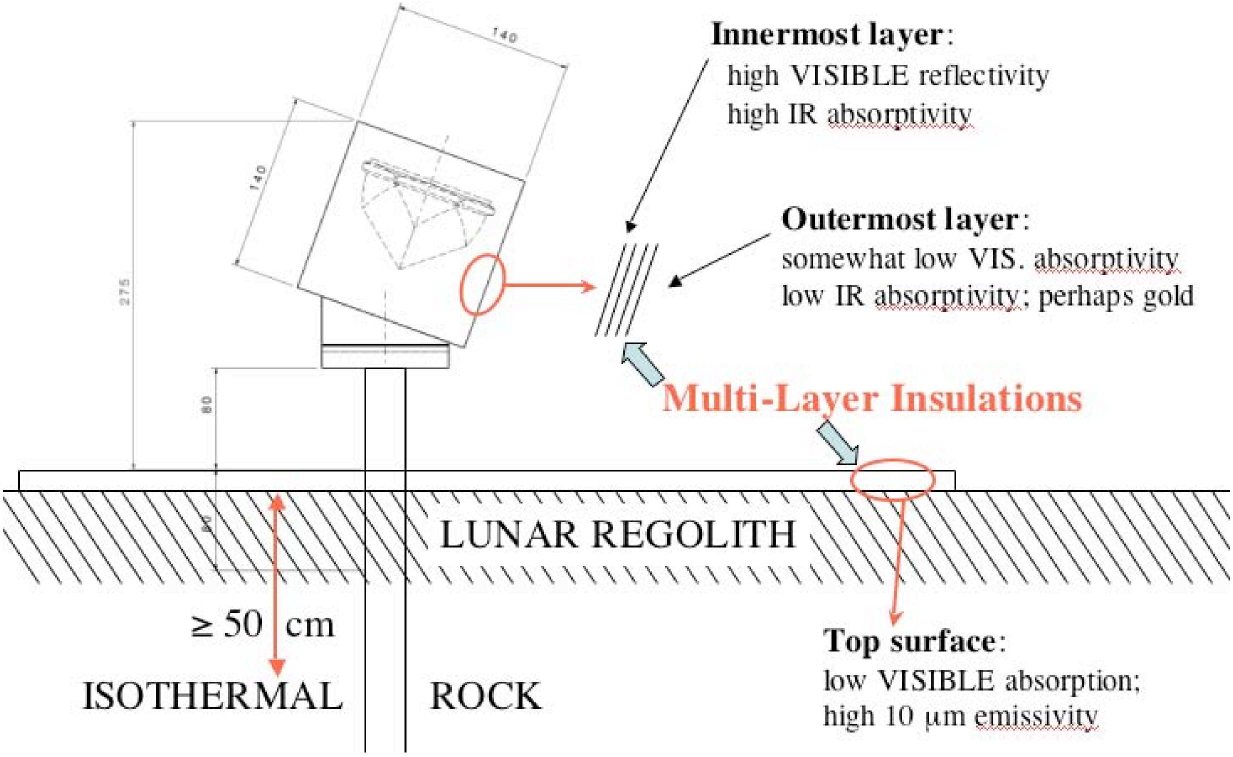

Figure 18. Scheme of a possible multi-layer insulation of the CCR installation components for the MoonLIGHT-R deployment.

N. Team Responsibilities

Professor Currie will organize and monitor the development of MoonLIGHT. He will coordinate the work at Frascati with the rest of the program in the US. He will work specifically on the optical measurements. He will also participate in the technical developments of the notional design.

Simone Dell'Agnello will supervise the work will take place at INFN in Frascati, Italy. The tasks to be accomplished at INFN will include the thermal simulations, thermal vacuum tests laser-optical tests and related analysis. He will also participate in concept design.

Colonel Roberto Vittori, a member of the Italian Astronaut Corp who has flown twice on the International Space Station will evaluate the differences, advantages and disadvantages of the robotic and manned approaches.

Giovanni Bellettini will work on the theoretical physics aspects of the study.

Giovanni Delle Monache will be responsible for oversight of the thermal analysis and for the conduct of the thermal vacuum tests and of mechanics and cryogenics operations.

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.

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

Nicola Intaglietta will perform CAD drawing and mechanical installations.

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3. The Space Climatic Facility at INFN-LNF

A schematic view of the Space Climatic Facility (SCF) is shown in Fig. 19. 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.

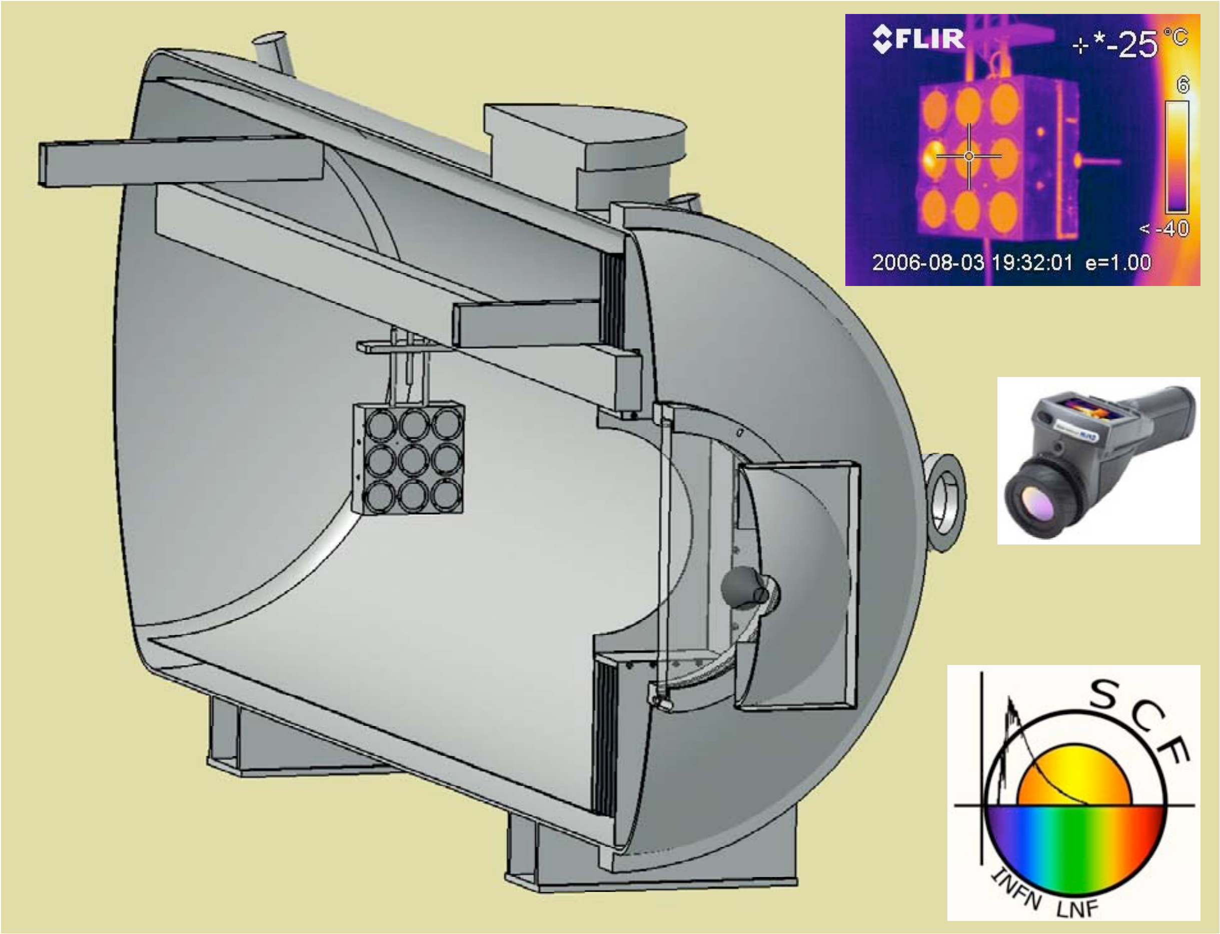

Figure 19. INFN/LNF Space Climatic Facility with the LAGEOS 3x3 CCR array built at LNF. The top right inset figure is a temperature photo taken with the IR camera (right middle inset), through the side tunnel of the cryostat. Bottom right is the SCF logo

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.

In order to evaluate the performance of the CCRs, the optical table shown in Fig. 20 has been set up. 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.

Figure 20. The optical table to evaluate the optical performance of the CCRs.

On the optical bench (the circuit is described in Fig. 21), we measure the intensity distribution of the return from the retro-reflector. This is the far field diffraction pattern. This pattern is then recorded on a CCD camera (see Fig. 22) that then performs an analysis indicating the return as various offset angles to evaluate the effects at the velocity aberrated angle.

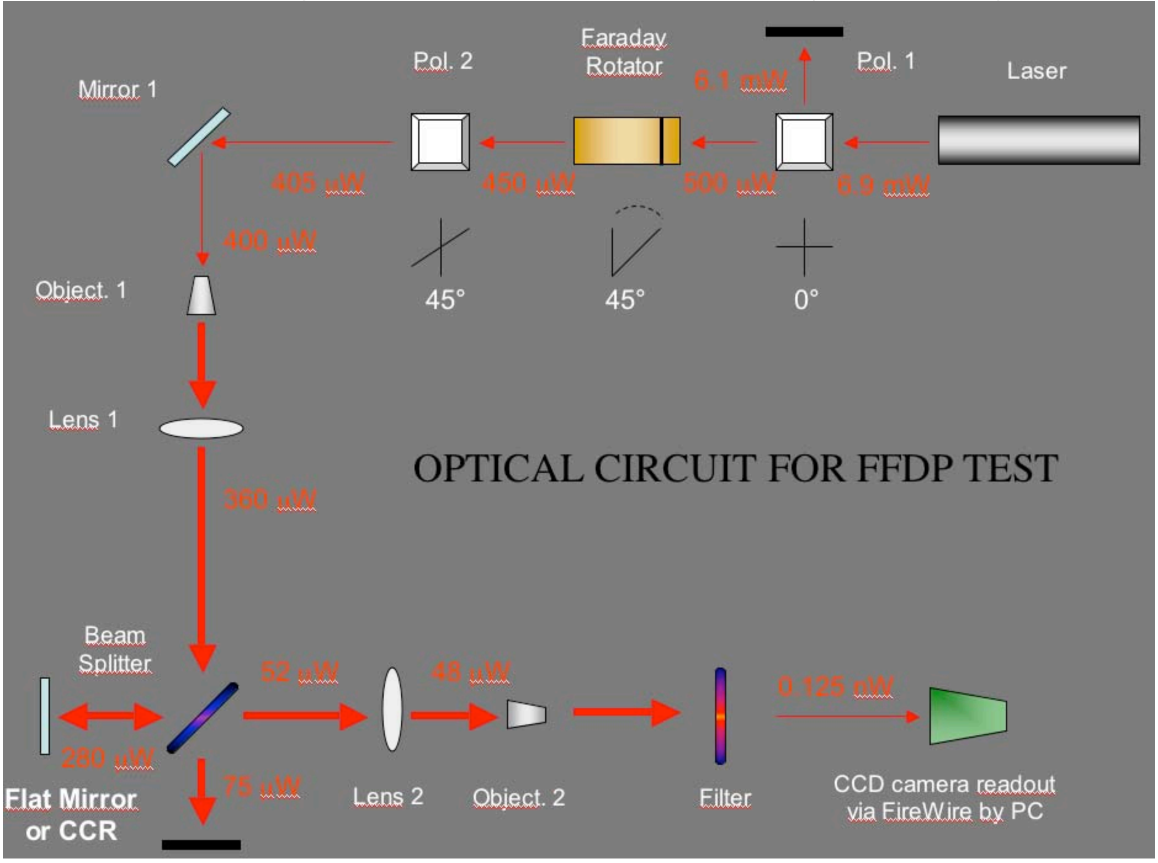

Figure 21. Scheme of the optical circuit to measure CCR far field diffraction patterns.

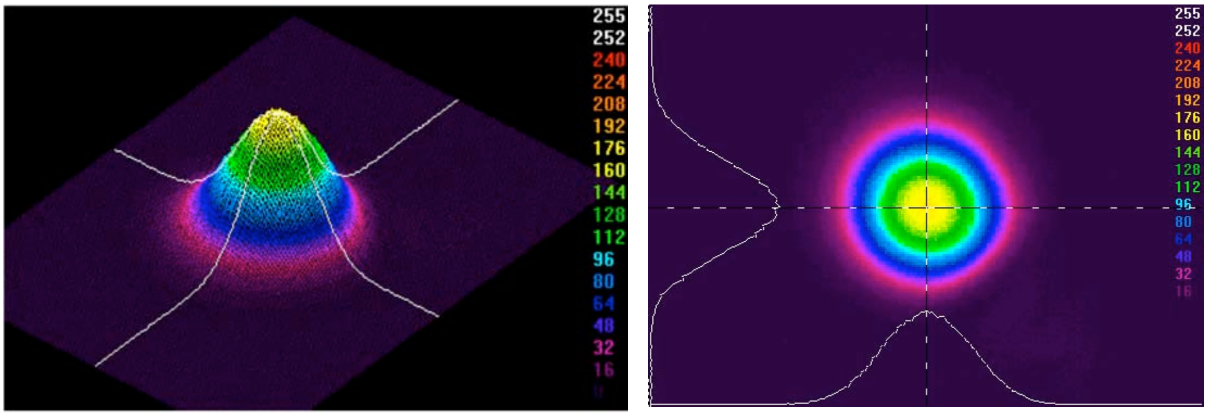

Figure 22. Laser beam profile taken by the CCD camera.

A similar configuration to evaluate the “space-climatic” far field diffraction pattern is currently being developed in conjunction with the thermal/vacuum chamber, as shown in Fig. 22. To our knowledge, these space-climatic test have never been performed in an extensive and accurate way before. Funding for this integration of thermal and optical tests has been provided by INFN for the ETRUSCO experiment.

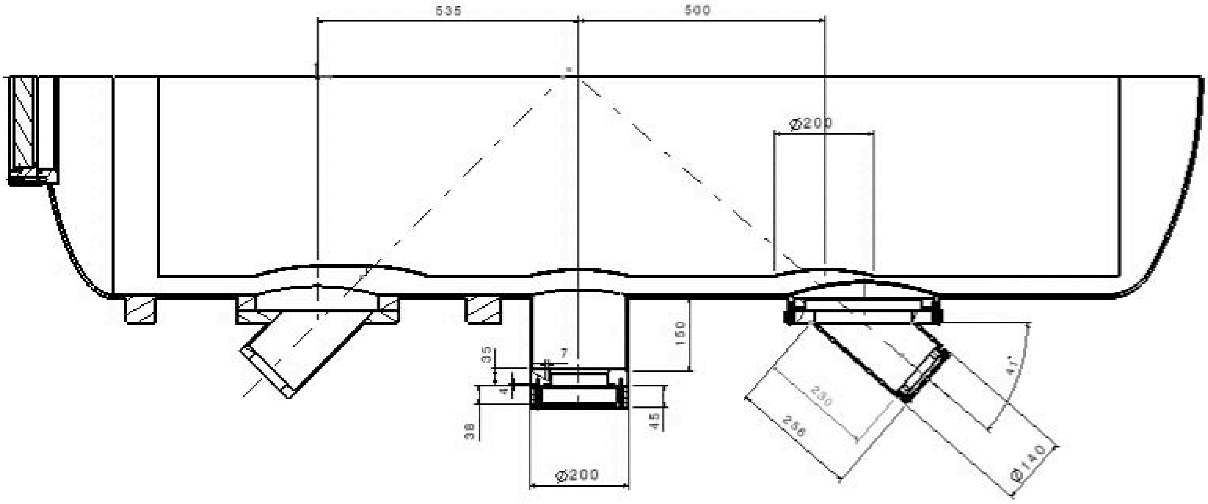

Figure 23. Top view of the SCF, with the solar simulator window located at the far left and the optical table to be located next to the three side windows, in between the right and left tunnels.

The three tunnels at the bottom of the Fig. 23 are (left, center and right): (i) the main window for thermography measurements with the IR camera (with a Ge window), (ii) the entrance window (fused silica) of the laser beam for optical tests of the CCRs when they are inside the SCF, (iii) a spare window for thermography or laser-optical tests.