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MOONLIGHT: A LUNAR LASER RANGING RETROREFLECTOR ARRAY FOR THE 21ST CENTURY

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Since the 1970s Lunar Laser Ranging (LLR) to the Apollo Cube Corner Retroreflector (CCR) Arrays (developed by the University of Maryland, UMD) supplied almost all significant tests of General Relativity: possible changes in the gravitational constant, gravitational self-energy, weak equivalence principle, geodetic precession, inverse-square force-law. LLR has also provided significant information on the composition and origin of the moon. This is the only Apollo experiment still in operation. In the 1970s Apollo LLR Arrays contributed a negligible fraction of the ranging error budget. Since the ranging capabilities of ground stations improved by more than two orders of magnitude, now, because of the lunar librations, Apollo CCR arrays dominate the error budget. With the MoonLIGHT project, in 2006 INFN-LNF joined UMD in the development and test of a new-generation LLR payload made by a single, large CCR (100 mm diameter) unaffected by the effect of librations. In particular, INFN-LNF built and is operating a new experimental apparatus (Satellite/lunar laser ranging Characterization Facility, SCF) and created a new industry-standard test procedure (SCF-Test) to characterize and model the detailed thermal behavior and the optical performance of CCRs in accurately laboratory-simulated space conditions, for industrial and scientific applications. Our key experimental innovation is the concurrent measurement and modeling of the optical Far Field Diffraction Pattern (FFDP) and the temperature distribution of retroreflector payloads under thermal conditions produced with a close-match solar simulator. The apparatus includes infrared cameras for non-invasive thermometry, thermal control and real-time payload movement to simulate satellite orientation on orbit with respect to solar illumination and laser interrogation beams. These capabilities provide: unique pre-launch performance validation of the space segment of LLR/SLR (Satellite Laser Ranging); retroreflector design optimization to maximize ranging efficiency and signal-to-noise conditions in daylight. Results of the SCF-Test of our CCR payload will be presented. Negotiations are underway to propose our payload and SCF-Test services for precision gravity and lunar science measurements with next robotic lunar landing missions. We will describe the addition of the CCR optical Wavefront Fizeau Interferogram (WFI) concurrently to FFDP/temperature measurements in the framework of an ASI-INFN project, ETRUSCO-2. The main goals of the latter are: development of a standard GNSS laser Retroreflector Array; a second SCF; SCF-Test of Galileo, GPS and other ‘as-built’ GNSS retroreflector payloads. Results on analysis of Apollo LLR data to test General Relativity will be presented.

THE MOONLIGHT/LLRRA-21[7] PROJECT

LLR has for decades provided the best tests, performed with a single experiment, of a wide variety of gravitational phenomena, probing the validity of Einstein’s theory of General Relativity (GR). The lunar orbit is obviously influenced by the gravity fields of the Earth and Sun, but is also sensitive to the presence of many other solar system bodies. In fig. 1 we report the improvement of the science measurement made possible thanks to the indicated improvement in the accuracy of LLR measurements of one or two orders of magnitude, reaching 1 mm or 0.1 mm of accuracy with the MoonLIGHT/LLRRA-21 CCR payload. The latter is the result of the collaboration of two teams: the LLRRA21 team in the USA, led by Douglas Currie of the University of Maryland, and the Italian one led by INFN-LNF. We are working on improvements of both

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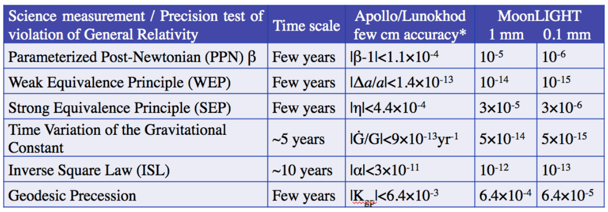
[7] Moon Laser Instrumentation for General relativity High accuracy Tests / Lunar Laser Ranging RetroReflector Array for the 21 Century.

the instrumentation and the thermal/optical/orbital modeling of the CCR. First of all, it is important to understand the limitation of arrays with a multi-CCR structure located on the lunar surface. The main problem that affects the Apollo arrays is the lunar librations; for example, in longitude, thse results from the eccentricity of the Moon's orbit around Earth. During the lunar phase, 27 days, the Moon's rotation alternatively leads and lags its orbital position, of about 8 degree. Due to this phenomenon the Apollo arrays are moved so that one corner of the array is more distant than the opposite corner by several centimeters. Because the libration tilt, the arrays increase the dimension of the LLR pulse coming back to the Earth. The broadening of the pulse will be greater proportionally to the array physical dimensions and to the Moon-Earth distance increase (in the position in which the libration phenomena are at the peak). Therefore for the biggest Apollo 15 the enlargement is about 30 cm, instead it is about 15 cm for Apollo 11 and Apollo 14 arrays. In agreement with this relationship, the pulse enlargement correspond to a time flight increase of ± 0.5 nanoseconds for Apollo 15 and ± 0.25 nanoseconds for Apollo 11 and Apollo 14.

So the accuracy of the ranging measurements cannot go below few centimeters (for a single normal point made with thousahds of laser returns). At the present, without hardware improvement, one can only progress by timing an extremely large number of single photoelectron returns to reduce the errors by the root mean square of the single photoelectron measurement error. In order to solve this problem the University of Maryland proposed (with the collaboration of the SCF group) a new design of lunar CCR, named LLRRA-21/MoonLIGHT, whose performance is unaffected by lunar librations. The idea that we propose is: replace an array of multiple small CCRs (with 3.8 cm of front face diameter), with single large CCRs (with 10.0 cm of front face diameter), distributed on the lunar surface.

Instead of having a single pulse, spread by the array and the libration effect, we will have single short pulses coming back with the same dimensions as the incoming one, with a final Laser Retroreflector Array (LRA) ranging accuracy down to 0.1 mm. When the new CCRs will be placed on the lunar surface, will make sense to improve the stations capabilities. To summarize, in the beginning LLR was done with long laser pulses fired by Earth stations, bigger than array dimensions, that dominated the measurement uncertainty. Now laser are shorter amd the measurement uncertainty is dominated by the size of the (librating) array. In the future, with MoonLIGHT/LLRRA21, there will be a single CCR unaffected by librations. The measurement uncertainty will be dominated by laser pulses; however, modern technology can achieve shorter laser pulses.

To improve LLR measurements we have addressed the technical and fabrication challenges of Moon-LIGHT/ LLRRA21, through thermal-optical simulations and innovative and unique thermal-optical-vacuum chamber tests performed at the INFN-LNF SCF to validate the design the issues and their solutions (details in [1]).



Science measurement / Precision test of violation of General Relativity	Time scale	Apollo/Lunokhod few cm accuracy*	MoonLIGHT	
			1 mm	0.1 mm
Parameterized Post-Newtonian (PPN) β	Few years	$\lvert\beta-1\rvert<1.1\times10^{-4}$	10^{-5}	10^{-6}
Weak Equivalence Principle (WEP)	Few years	$\lvert\Delta a/a\rvert<1.4\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	Few years	$\lvert\eta\rvert<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of the Gravitational Constant	~5 years	$\lvert\dot{G}/G\rvert<9\times10^{-13}yr^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	~10 years	$\lvert\alpha\rvert<3\times10^{-11}$	10^{-12}	10^{-13}
Geodesic Precession	Few years	$\lvert K_{gp}\rvert<6.4\times10^{-3}$	6.4×10^{-4}	6.4×10^{-5}

Figure 1. Improvement of the science measurement thanks to improved LLR accuracy of one or two orders of magnitude (reaching 1 mm or 0.1 mm of accuracy) with the MoonLIGHT/LLRRA-21 CCR payload. Current Apollo/Lunokhod measurements are from [2].

MOONLIGHT/LLRRA-21 PAYLOAD DESCRIPTION

The payload consists of a single, large, 100 mm diameter, uncoated fused silica CCR inside a cylindrical housing (fig. 2) and with an external conical solar shade (fig. 3).

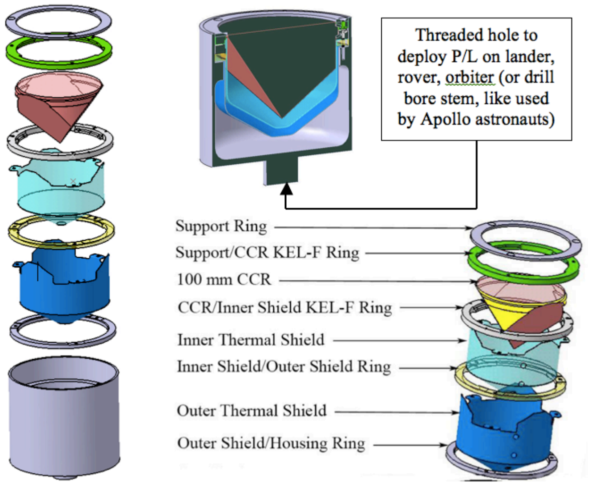


Figure 2. Drawings of the LLRRA-21/MoonLIGHT CCR with its internal mounting rings, thermal shields and aluminum housing. Current, upgraded shields have a shape conformal to the CCR, instead of the conical shape shown above.

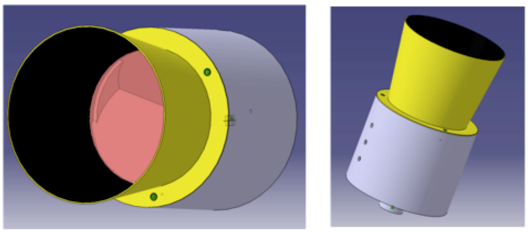


Figure 3. Drawing of assembled payload prototype: CCR (red), aluminum housing (grey), external conical solar shade (yellow).

SCF-TEST OF THE MOONLIGHT CCR

The “SCF-Test” is a new and unprecedented test procedure to characterize and model the detailed thermal behavior and optical performance of LRA in accurately laboratory-simulated space conditions, developed by INFN-LNF and in use by NASA, ESA and ASI [1][3][4][5][6][7][8]. Under ASI-INFN contract n. I/077/09/0 ETRUSCO-2 (Extra Terrestrial Ranging to Unified Satellite COnstellations-2) we have built a second “Satellite laser ranging Characterization Facility optimized for Galileo and the GPS-3” (SCF-G) and developed a significant evolution and refinement of the SCF-Test reported in [5]. We have also prototyped an innovative GNSS laser Retroreflector Array made of Hollow retroreflectors (GRA-H). Based on the outcome of the SCF-Test of this GRA-H, a full size GRA is under construction using the consolidated, uncoated fused silica technology space-qualified with NASA’s Apollo missions and with the two LAGEOS satellites built and launched by NASA and ASI in 1974 and 1992.

Two SCF pictures are shown in fig. 4 and fig. 5. Fig. 4 shows the solar simulator (SS) window (called “AM0” from the name of the standard solar spectrum in space), infrared (IR) camera, laser window, optical table (for measurements) and a spare window. A large size window for additional measurements is available in the back on the cryostat.

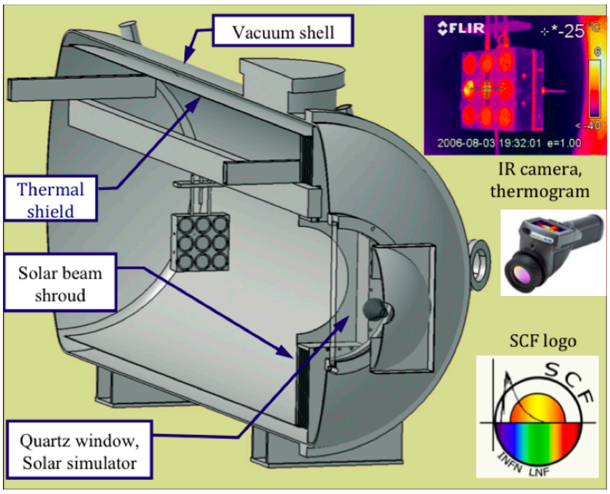


Figure 4. SCF cryostat with Apollo/LAGEOS array built at LNF, IR thermogram, IR camera and SCF logo.

For the SCF-test, the CCR with its housing was installed inside the SCF, attached to the rotation positioning system (see fig. 6). FFDP measurements reported here were performed with a green laser ($\lambda = 532$ nm), and the diameter of the beam hitting the CCR was 38 mm (Apollo/LAGEOS CCR diameter). It is now possible to widen the beam up to the 100 mm aperture of the CCR thanks to the upgraded instrumentation. The orientation of the CCR inside the housing was such that one physical edge was horizontal to the axis of the SCF’s rotation positioning system.

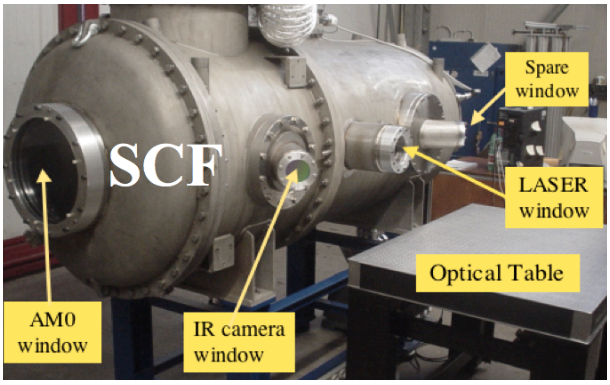


Figure 5. SCF cryostat and its windows.

Once we established the simulated space environment (in terms of vacuum and cold) we heated the CCR with the SS, with the beam orthogonal to the CCR face. After this condition, which, thermally, is the best for the perfornace of an uncoated CCR, we simulated also an illumination of the Sun at lower elevations, so the CCR was rotated of 30° clockwise and 30° counterclockwise with respect to the SS. We had a Total Internal Reflection (TIR) breakthrough situation in one direction, in the other not. Temperature variation with time of various prototype’s parts is shown in fig. 7, while the respective FFDPs are shown as insets in fig. 7. Moving the CCR from an orthogonal SS beam to TIR non-breakthrough position to a TIR breakthrough position increased the temperature of the CCR and, most of all, the temperature of the gold thermal shields, as expected. In particular we noticed an increasing temperature gradient on the CCR face. Until the ”SUN ON break” phase the housing was controlled, while the housing was left floating during the last phase.

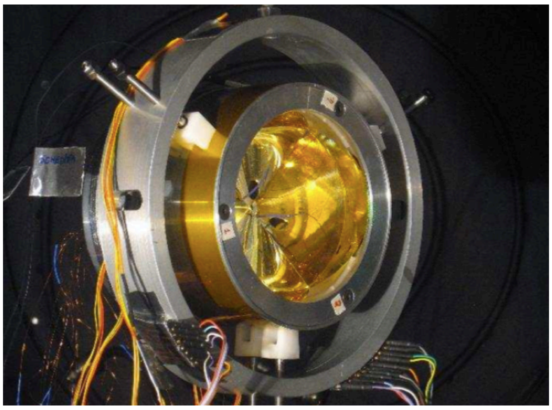


Figure 6. MoonLIGHT/LLRRA21 CCR inside the SCF.

As said before, the temperature difference between the two temperature sensors on a reflecting back face of the CCR (green and grey lines of fig. 7) increased, so the intensity of the FFDP at Moon velocity aberration decreased until the breakthrough phase lasted. On the contrary, as the temperature difference of temperature sensors on the CCR decreased during the last phase, the FFDP intensity increased.

The FFDP measurements vs time reflected this behavior: fig. 8 shows the MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at the Moon velocity aberrations (2V/c ~ 4.4microrad) during key points of the SCF-Test: in air, SS on orthogonal to the CCR's face with the housing temperature controlled at T=310 K, SS on at 30° of inclination (no breakthrough), SS on at −30° of inclination (breakthrough), SS on orthogonal with the housing temperature left floating, SS off. From this graph we can deduce that the intensity decreases during non-orthogonal lighting of the CCR, in particular when the Sun enters in the housing cavity during the break-thru phase. This effect is due to an increase of the "Tip-Face" thermal gradient during this two phases of the test. When the housing temperature is left floating, the intensity slightly increases because the "Tip-Face" gradient is decreasing.

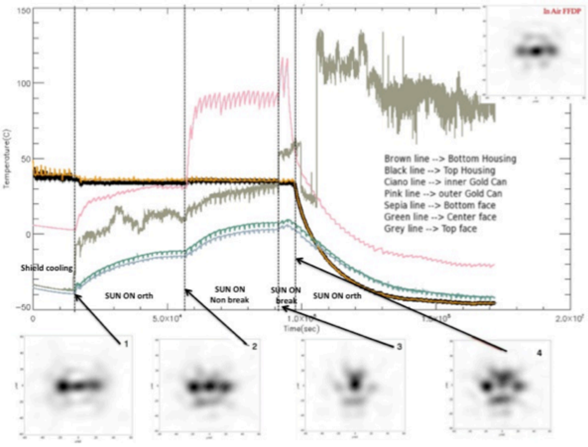


Figure 7. Temperature variations of the CCR payload elements.

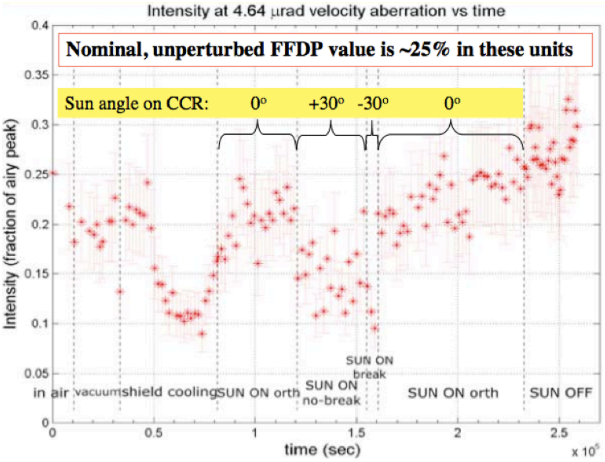


Figure 8. FFDP Intensity variation vs time during tests.

CCR THERMAL MODELLING

Our SCF-Test measurements are complemented by detailed thermal-orbital-optical modelling performed with a suite of software programs (to be tuned and adapted to the SCF-Test data): Thermal Desktop for the thermal simulation and the orbital propagation and Code V for the optical simulation, integrated by in-house software developed ad-hoc and to interface the different packages (see [1][4][7] for details). Here we show in fig. 9 one typical thermal modelling of the MoonLIGHT CCR at noon, that is, under orthogonal sun illumination, with conformal thermal shields. The inner shield coated with Ag on the internal side (i.e. facing the CCR glass) and Au on the external side. The outer thermal shield is Au-coated on both sides. The Tip-Face temperature difference is < 1 K, confirming that in this (non-breakthrough) configuration the CCR has a good performance.

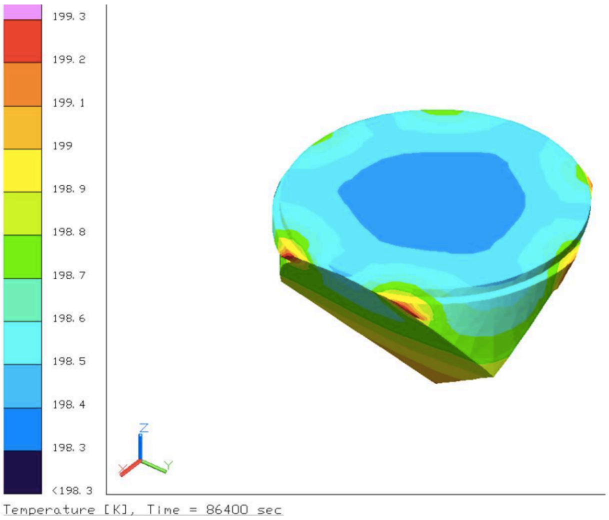


Figure 9. CCR temperature distribution at noon (orthogonal sunlight illumination) with conformal thermal shields.

DETERMINATION OF THE GEODETIC PRECESSION USING LLR DATA

In order to analyze LLR data we used the PEP (Planetary Ephemeris Program) software, developed by the CfA, by I. Shapiro et al. starting from 1970s. PEP has enabled constraints on deviations from standard GR physics. For example, it can be used to estimate PPN (Parametrized Post-Newtonian) parameters β and γ; geodetic precession, K_{GP} (percentile deviation from the GR prediction), and the time variation of the gravitational constant, dG/dt. Here we show a first determination of the K_{GP} parameter. We have used all the data available to us from the Apollo 11, 14 and 15 LRAs. Results are reported for data taken by the old ILRS[8] stations until 2003 (the McDonald station in Texas, USA, in the old location, TEXL, and in its new site equipped with the new laser, MLR2; the CERGA station in France) and data acquired by the new ILRS station, APOLLO[9], from 2007 to 2009:

APOLLO: $-9.6\text{x}10^{-3}$
CERGA: $-1.6\text{-x}10^{-2}$
MAUI: $6.0\text{x}10^{-3}$
MLR2: $9.5\text{x}10^{-3}$
TEXL: $-4.4\text{x}10^{-2}$

In this analysis $\beta=\gamma=1$, $dG/dt=0$. Nominal errors returned by the fit are significantly smaller than the above estimated values of K_{GP}.

This preliminary measurements are to be compared with the best result published by JPL ($K_{GP}=(-1.9\pm6.4)\times10^{-3}$ [1]), obtained using a completely different software package, developed over the last 40 years. On the contrary, after the original 2% K_{GP} measurement by CfA in 1988, the use of PEP for LLR has been resumed only since a few years, and it is still undergoing the necessary modernization and optimization.

CONCLUSIONS AND PROSPECTS

The payload development is well advanced and is currently at a Technology Readiness Level (TRL) of 6.5, thanks to inheritance from Apollo and to SCF-Testing. Negotiations and underway with several agencies (NASA, ESA, ASI, JAXA), either directly or through their respective national communities interested in the LLR science, SCF-Test services and technology applications. The analysis of existing LLR data with PEP is also making good progress, thanks to the important collaboration with CfA, as shown with the preliminary measurement of the geodetic precession (de Sitter effect) with an accuracy at 1% level.

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