

# Probing Gravity with Next Generation Lunar Laser Ranging

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**Abstract** Lunar and satellite laser ranging (LLR/SLR) are consolidated techniques which provide a precise, and at the same time, cost-effective method to determine the orbits of the Moon and of satellites equipped with laser retroreflectors with respect to the International Celestial Reference System. We describe the precision tests of general relativity and of new theories of gravity that can be performed with second-generation LLR payloads on the surface of the Moon (NASA/ASI MoonLIGHT project), and with SLR/LLR payloads deployed on spacecraft in the Earth–Moon system. A new wave of lunar exploration and lunar science started in 2007–2008 with the launch of three missions (Chang’e by China, Kaguya by Japan, Chandrayaan by India), missions in preparation (LCROSS, LRO, GRAIL/LADEE by NASA) and other proposed missions (like MAGIA in Italy). This research activity will be greatly enhanced by the future robotic deployment of a lunar geophysics network (LGN) on the surface of the Moon. A scientific concept of the latter is the International Lunar Network (ILN, see <http://iln.arc.nasa.gov/>). The LLR retroreflector payload developed by a US–Italy team described here and under space qualification at the National Laboratories of Frascati (LNF) is the optimum candidate for the LGN, which will be populated in the future by any lunar landing mission.

## 1 Lunar Laser Ranging

Lunar laser ranging (LLR) is mainly used to conduct high-precision measurements of ranges between laser stations on Earth and a corner cube retroreflector (CCR) array on the lunar surface. Over the years, LLR has benefited from a number of improvements both in observing technology and data modeling, which led to the current accuracy of postfit residuals of  $\sim 2$  cm.

Nowadays, LLR is a primary technique to study the Earth–Moon system and is very important for gravitational physics, geodesy, and studies of the lunar interior. LLR contributes to the realization of both the terrestrial and selenocentric reference frames. The realization of a dynamical inertial reference frame, in contrast to the

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kinematically realized frame of very long baseline interferometry (VLBI), offers new possibilities for mutual crosschecking and confirmation.

Since 1969, LLR has supplied many tests of general relativity (GR): LLR data have been used to evaluate geodetic precession [1, 2], probe the weak and strong equivalence principle, determine the parametrized post-Newtonian (PPN) parameters, and address the time change of the gravitational constant  $G$  and  $1/r^2$  deviations of gravitational interactions. LLR has also provided important information on the composition and origin of the Moon through measurement of its rotations and tides. Future lunar missions will expand this broad scientific program.

Initially, the Apollo arrays contributed a negligible portion of the LLR error budget. Today, the ranging accuracy of ground stations has improved by more than two orders of magnitude: the new Apache Point Observatory Lunar Laser-ranging Operation (APOLLO) station at Apache Point, USA, is capable of mm-level range measurements; The Matera Laser Ranging Observatory (MLRO), at the Agenzia Spaziale Italiana (ASI) “Centro di Geodesia Spaziale” in Matera, Italy, has restarted LLR operations. Now, owing to lunar librations, the Apollo arrays dominate the LLR error budget, which is a few cm.

## 2 The MoonLIGHT Program

LLR has for decades provided the best tests of a wide variety of gravitational phenomena, probing the validity of Einstein’s theory of GR [3, 4]. The lunar orbit is obviously influenced by the gravitational field of the Earth and the Sun, but is also sensitive to the presence of many other solar system bodies.

In 2006, Istituto Nazionale di Fisica Nucleare (INFN) proposed the Moon Laser Instrumentation for General Relativity High accuracy Tests (MoonLIGHT) technological experiment, which has the goal of reducing the error contribution of LLR measurements by more than two orders of magnitude. In Table 1, the possible improvements in the measurement of gravitational parameters achievable through reaching the ranging precision of 1 mm or even 0.1 mm are reported.

The MoonLIGHT program [5] is the result of a collaboration between two teams: the Lunar Laser Ranging Retroreflector Array for the twenty-first century (LLRRA21) team in the USA, led by Douglas Currie of the University of Maryland (UMD), and the Italian one led by National Institute of Nuclear Physics-National Laboratories of Frascati (INFN-LNF). We are exploring improvements in both the instrumentation and the modeling of the CCR.

To explain the MoonLIGHT experiment, we have to understand the limitations of a multi-CCR array.

The main problem that affects the Apollo arrays consists of the lunar librations in longitude, that result from the eccentricity of the Moon’s orbit around Earth [6–8]. Due to this phenomenon, the Apollo arrays are shifted so that one corner of the array is more distant than the opposite corner. Because of the librations tilt, the arrays

**Table 1** Narrowing of parameter bounds due to gains in the accuracy of ranging measurements by one or two orders of magnitude (reaching a precision of 1 mm or even 0.1 mm)

Gravitational measurement	First generation LLR precision	Second generation LLR precision	2 <sup>nd</sup> generation LLR precision	Time scale
	( $\sim$ cm)	(1 mm)	(0.1 mm)	
WEP	$ \frac{\Delta a}{a}  < 1.4 \times 10^{-13}$	$10^{-14}$	$10^{-15}$	Few years
SEP	$ \eta  < 4.4 \times 10^{-4}$	$3 \times 10^{-5}$	$3 \times 10^{-6}$	Few years
$\beta$	$ \beta - 1  < 1.1 \times 10^{-4}$	$10^{-5}$	$10^{-6}$	Few years
$\frac{\dot{G}}{G}$	$ \frac{\dot{G}}{G}  < 9 \times 10^{-13} \text{ yr}^{-1}$	$5 \times 10^{-14}$	$5 \times 10^{-15}$	$\sim$ 5 years
Geodetic precession	$6.4 \times 10^{-3}$	$6.4 \times 10^{-4}$	$6.4 \times 10^{-5}$	Few years
$\frac{1}{r^2}$ deviation	$ \alpha  < 3 \times 10^{-11}$	$10^{-12}$	$10^{-13}$	$\sim$ 10 years

LLR Lunar laser ranging, WEP Weak equivalence principle, SEP Strong equivalence principle

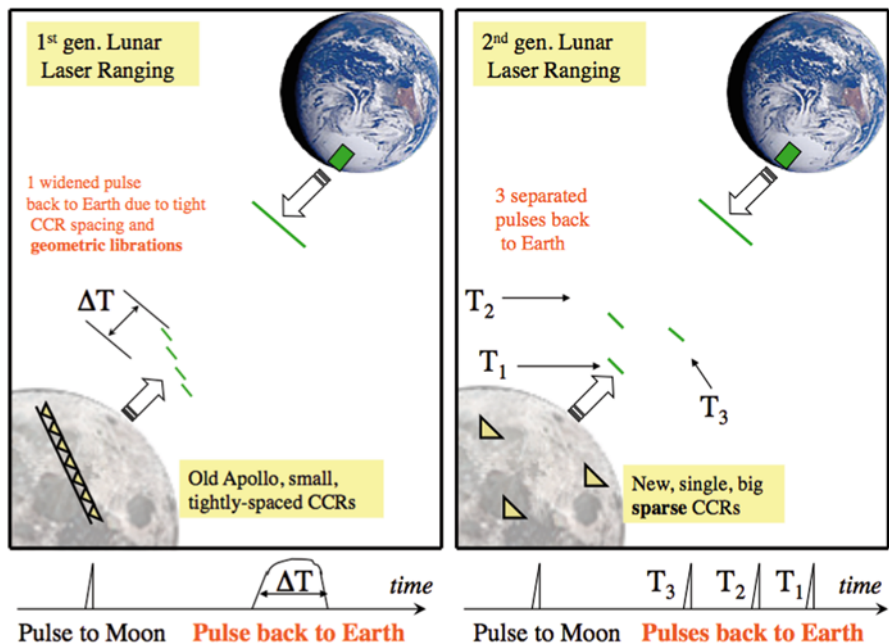
increase the dimension of the pulse coming back to the Earth (Fig. 1). The broadening of the pulse will be greater proportionally to the array physical dimensions and to the Moon–Earth distance increase. Therefore, for the largest array, from Apollo 15, the enlargement is about 30 cm, and for the Apollo 11 and Apollo 14 arrays, it is about 15 cm. In agreement with this relationship, the pulse enlargement corresponds to a flight time increase:

- $\pm 0.5$  ns for Apollo 15;
- $\pm 0.25$  ns for Apollo 11 and Apollo 14.

In order to solve this problem, LNF in collaboration with UMD, indicated a new design of lunar CCR, named the second generation LLR, whose performance is unaffected not only by lunar librations but also by the motion of the regolith due to its large thermal cycle. The idea that we propose is to move from a multi-CCR array to a series of single, larger CCRs, each with 10 cm of front face diameter (Fig. 2, 3, 4).

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 (Fig. 1), with a final laser retroreflector array (LRA) ranging accuracy below  $10 \mu\text{m}$ . When the new CCRs are placed on the lunar surface, it will make sense to improve the station capabilities [9–12].

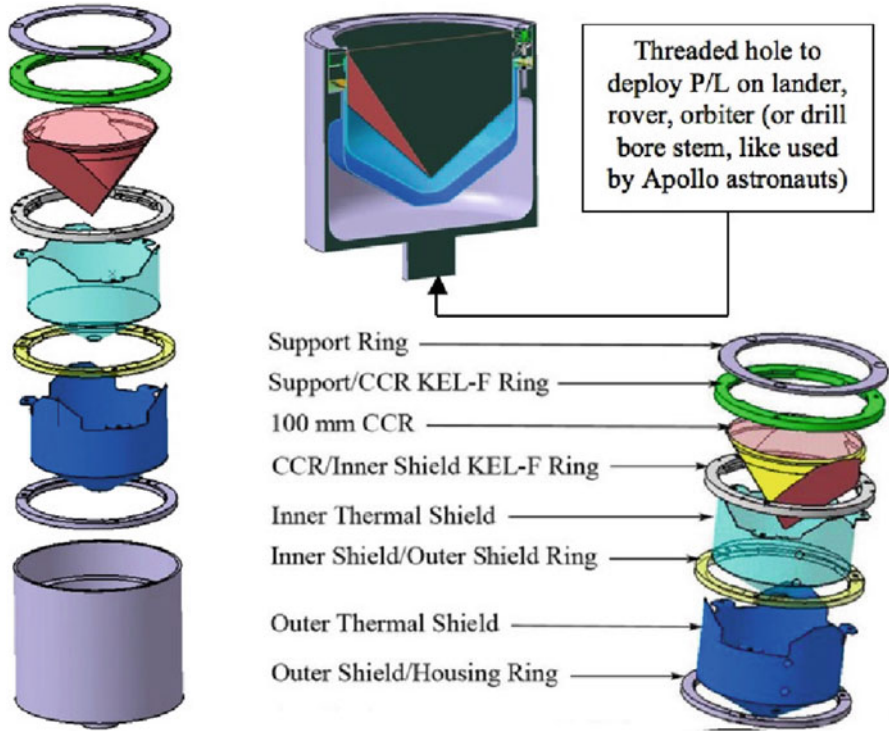
To summarize, in the past, LLR techniques have employed a large laser pulse fired from the Earth station, larger than array dimensions, which dominated the measurement uncertainty. Now there is a moderately-sized laser pulse, but still a large array, so that the measurement uncertainty is dominated by the array; in the future, with MoonLIGHT/LLRRA21, there will be a single CCR unaffected by librations. The measurement uncertainty will then be dominated by the laser pulse, which could be shortened through modern technology (Fig. 5).



**Fig. 1** Comparison between first and second generation laser retroreflector arrays (LRAs). The librations tilt the arrays (left), but the individual large corner cube retroreflectors (CCRs) are unaffected (right). So, by using the Moon Laser Instrumentation for General Relativity High accuracy Tests (MoonLIGHT) payloads, we receive single short pulses instead of one broadened pulse



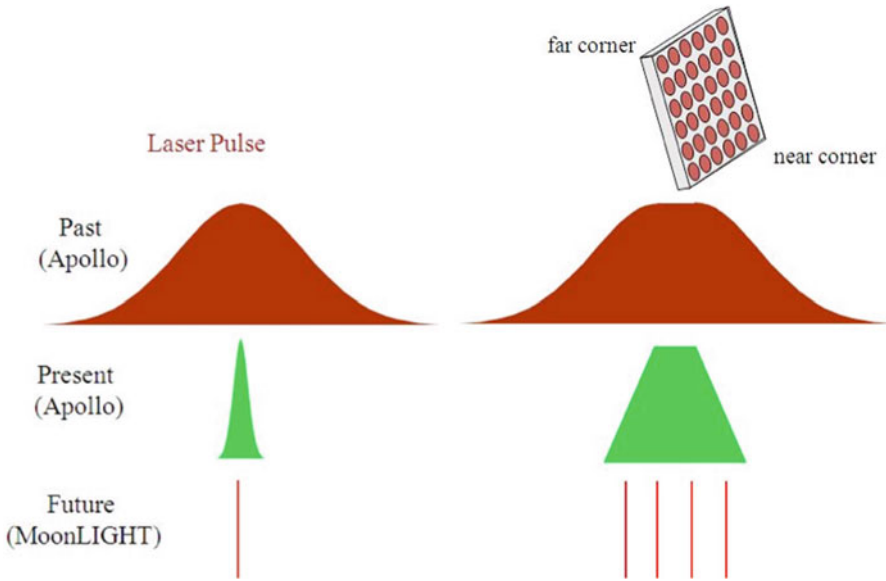
**Fig. 2** Picture of Apollo, first generation and MoonLIGHT/LLRRA21, second generation CCR



**Fig. 3** Drawings of the MoonLIGHT CCR with its internal mounting rings, thermal shields, and aluminum housing

**Fig. 4** Inner conformal shield of the MoonLIGHT CCR





**Fig. 5** The figure shows which contribution (between fired and retroreflected laser pulse size) dominates the measurement uncertainty; the *top horizontal stripe* shows the situation in the past; the *middle stripe* shows the current one and the *bottom one* the future possible situation with the MoonLIGHT/LLRRA21 CCR

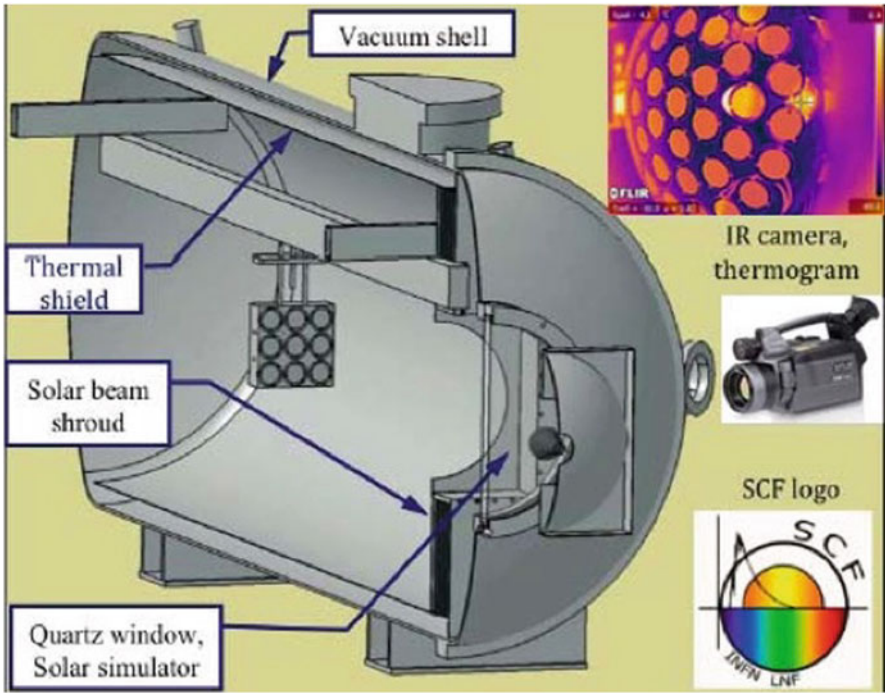
Opportunities for deployment of the MoonLIGHT/LLRRA21 payload will come from the participation of INFN-LNF and UMD, through their national agency programs, to international missions to develop a lunar geophysical network (LGN) [13].

In order to improve the ranging measurement, we have to investigate the technical and fabrication challenges of MoonLIGHT/LLRRA21, through thermal/optical simulations and vacuum chamber tests performed at the INFN-LNF Satellite/lunar/GNSS laser ranging and altimetry Characterization Facility (SCF). Beyond the simulations, we have performed thermal and optical vacuum chamber tests to further validate the design issues.

## 2.1 SCF\_Lab

In 2004, INFN started to build the SCF\_Lab in Frascati (Fig. 6). The main purpose of this apparatus is the thermal and optical characterization of CCR arrays in simulated space conditions.

In Fig. 6, the SCF apparatus is shown. It is a steel cryostat 2 m in length by 1 m in diameter. The inner copper shield is painted with Aeroglaze Z306 black paint (0.95 emissivity and low out-gassing properties) and is kept at  $T = 77$  K with liquid nitrogen. When the SCF is cold ( $\sim 80$  K), the vacuum is typically in the  $10^{-6}$  mbar



**Fig. 6** Drawing of the Satellite/lunar/GNSS laser ranging and altimetry Characterization Facility (SCF) cryostat

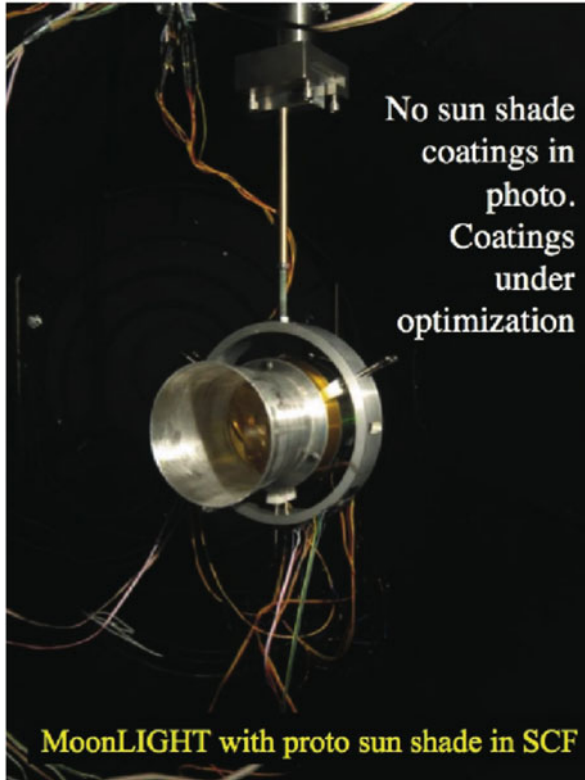
range. Two distinct positioning systems at the top of the cryostat hold and move the prototype in front of the Earth infrared simulator, the solar simulator (SS), the infrared camera, and the laser, all located outside the SCF.

The experimental apparatus is described in great detail in [14, 15].

## 2.2 SCF Test of the MoonLIGHT CCR

The SCF-Test [14] is a new test procedure to characterize thermal and optical behavior of laser retroreflectors in space for industrial and scientific applications. We perform an SCF-Test on the MoonLIGHT CCR to evaluate the thermal and optical performance in space environment, (Fig. 7).

The temperature of the housing has been controlled with resistive tape heaters. For thermal measurements, we use both an infrared (IR) camera and temperature probes, which give real time measurements. The IR camera, through a Germanium window, can give thermograms of all the components of the CCR and its housing.



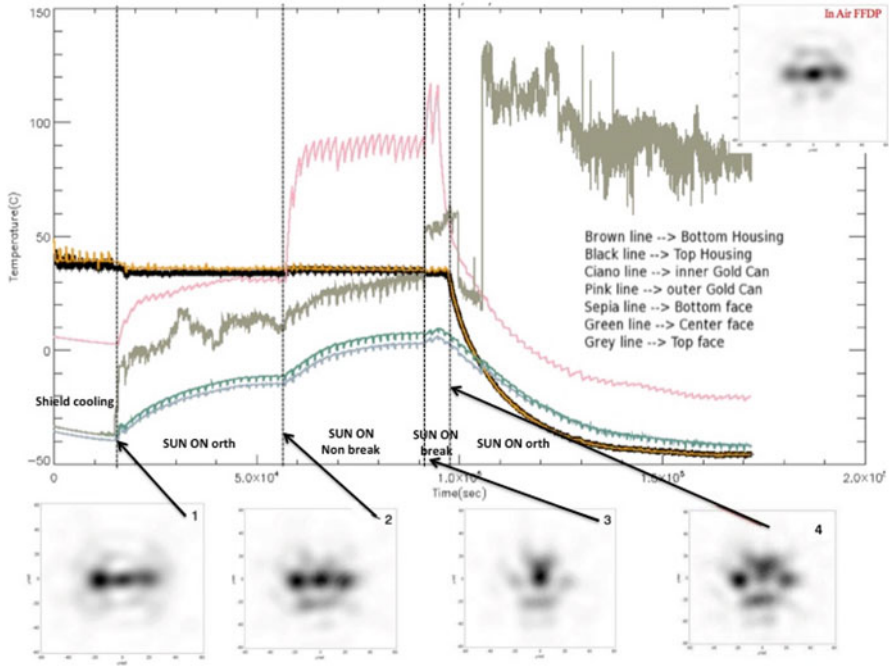
**Fig. 7** MoonLIGHT CCR inside the Satellite/lunar/GNSS laser ranging and altimetry Characterization Facility (SCF)

Instead, to measure the thermal gradient on the CCR surface, we glued three calibrated temperature sensors (silicon diode) along one of the back faces of the CCR, at a separation of 35 mm.

In particular, we look at the temperature from the front face to the tip, studying how the optical response (the far field diffraction pattern, FFDP) of the CCR changes during the different thermal phases. Various configurations and designs of the CCR and the housing have been tested in the SCF facility, with the solar simulator, the temperature data recording with the infrared camera, and the measurement of the FFDP. At the present time, we have a preliminary result indicating that the CCR has a satisfactory performance.

The orientation of the CCR inside the housing is such that one physical edge was parallel to the axis of the SCFs rotation positioning system. We simulated an illumination of the Sun at lower elevations, so the CCR was rotated  $30^\circ$  clockwise and  $30^\circ$  counterclockwise with respect to the SS. We report a total internal reflection breakthrough in one direction, but not in the other. Figures 8 and 9 show the temperature variation of the housing and the intensity variation of the FFDP.





**Fig. 8** Temperature variation of the housing and relative far field diffraction pattern (*FFDP*)

Looking at Fig. 9, we conclude that the intensity decreases during the phase when the CCR is not orthogonal to the SS, in particular when the Sun enters the housing cavity during the breakthrough phase. This effect is due to a strong increase of the “Tip-Face” thermal gradient during the test (Fig. 10). When the temperature of the housing is allowed to vary, the intensity increases because the “Tip-Face” gradient is reduced.

### 3 Analysis of LLR Data

#### 3.1 Planetary Ephemeris Program (*PEP*)

In order to analyze LLR data we used the PEP software, developed by the CfA (I. Shapiro et al.) starting from 1970s.

PEP was designed not only to generate ephemerides of the planets and the Moon, but also to compare the model with observations [16, 17]. One of the early uses of this software was the measurement of the geodetic precession of the Moon [1]. PEP can handle several observation types (LLR, radar ranging and doppler, optical positional measurements, transponder measurements, pulsar timing data, and so on).

### SCF: Optical response of MoonLIGHT (no sun shade)

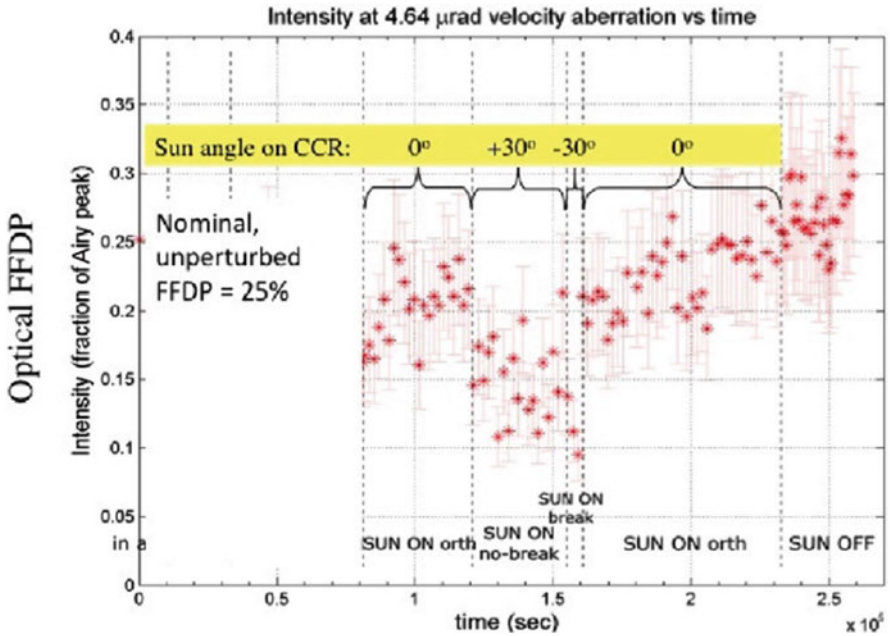


Fig. 9 Intensity variation of the FFDP during the tests

Since we care primarily about LLR observations, we describe the components of a range prediction, though most of the steps along the way are common to other observables as well.

In particular, we are primarily concerned with LLR observations. For this purpose, the software is able to calculate the residuals of the distances between observed LLR data and computed data, derived from the expectations of GR and of terrestrial and lunar geodesy. We have performed a very preliminary analysis of LLR data from three stations: McDonald Observatory in Texas (USA), Grasse in France, and APOLLO [18, 19] in New Mexico (USA). The latter station has been providing the best quality data since 2006. On March 25, 2010, the Matera Laser Ranging Observatory in Italy (MLRO, led by G. Bianco) recorded LLR echoes from the array of Apollo 15.

The histograms in Fig. 11 show photon-by-photon data and are used to form a single LLR “normal point” of the Apollo 15 array taken by the APOLLO station (led by T. W. Murphy) on November 19, 2007. A normal point contains a lot of information, for example, date of observation, atmospheric conditions, as well as time of flight, data quality, and CCR arrays. The APOLLO instrumental accuracy (in terms of laser, detector, timing electronics, and so on) shown by the fiducial returns in Fig. 11 is given by a root mean square contribution of 120 ps (18 mm).

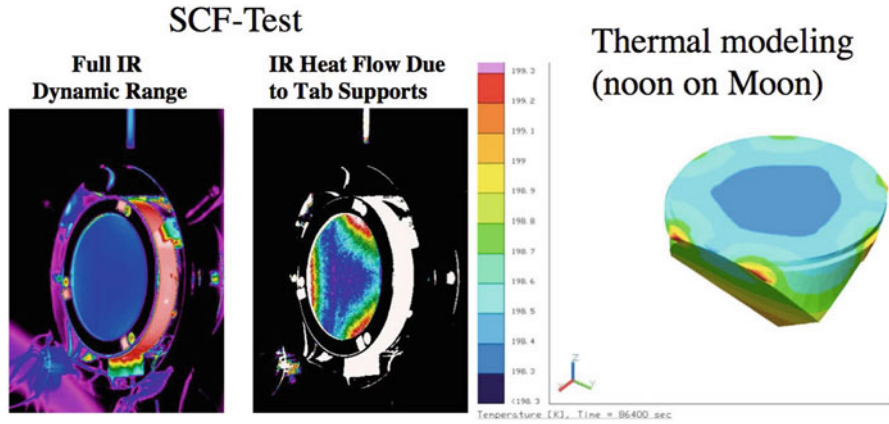


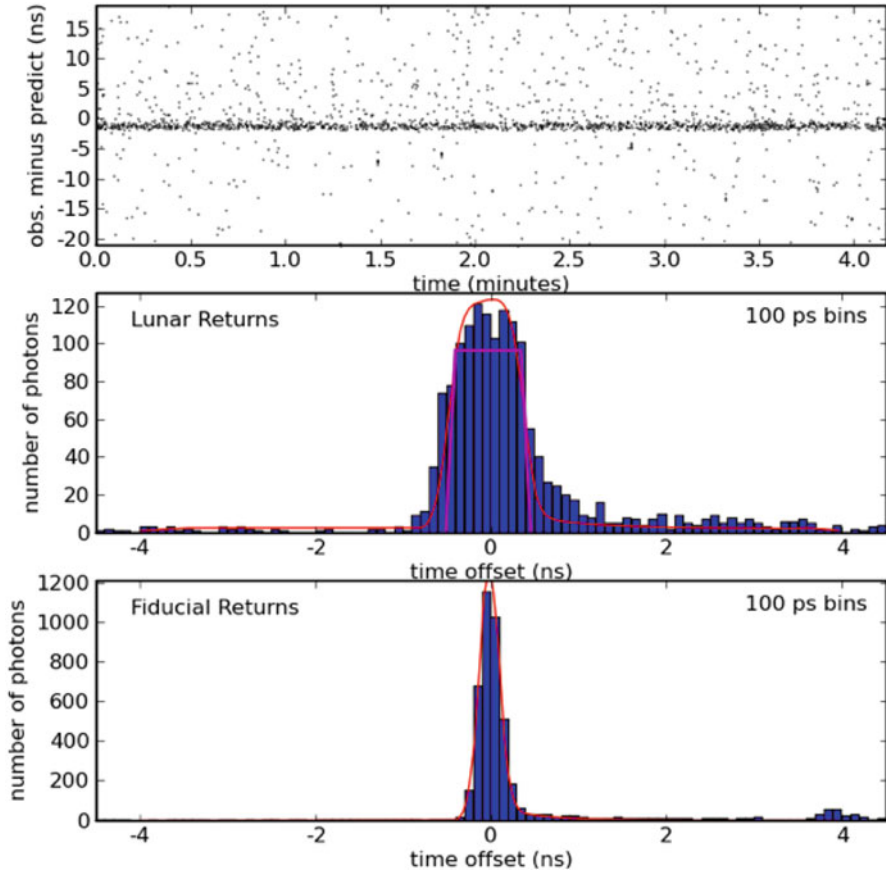
Fig. 10 CCR temperature distribution at noon (orthogonal illumination) with conformal thermal shield

From a comparison between the middle and the last plot we can see how the tilt in the arrays affects the accuracy of the ranging measurements. The model parameter estimates are refined by minimizing the residual differences, in a weighted least-squares sense, between observations (O) and model predictions (C, stands for “Computed”), O-C. “Observed” is the round-trip time of flight. “Computed” is modeled by the PEP software. PEP software has allowed placing constraints on departures from standard physics. For example, it has been used to place limits on the PPN parameters  $\beta$  and  $\gamma$ , the geodetic precession, and the variation of the gravitational constant,  $\dot{G}$ . The equations of motion in a space-time with torsion [20, 21] can be included in PEP and constrained with all LLR data, including the newest APOLLO data (at the present time, the published constraints on space-time torsion are calculated using LLR data from other stations).

### 3.2 Determination of the Geodetic Precession

With PEP, we are able to measure the possible relative deviation of geodetic precession from the GR value (deviation from zero) that is expressed with  $K_{GP}$  parameter (Fig. 12).

Here we show our first determination of the  $K_{GP}$  parameter. We have used all the data available to us from Apollo CCR arrays (Apollo 11, Apollo 14, and Apollo 15). The results are reported in two tables, one until 2003, with data acquired by the old ILRS stations (Table 2) and one with data from 2007 to 2009 acquired by the new APOLLO station (Table 4). Results described in the tables are obtained by fixing  $\dot{G}/G = 0$  and  $\beta = \gamma = 1$ , that is, their value in GR.

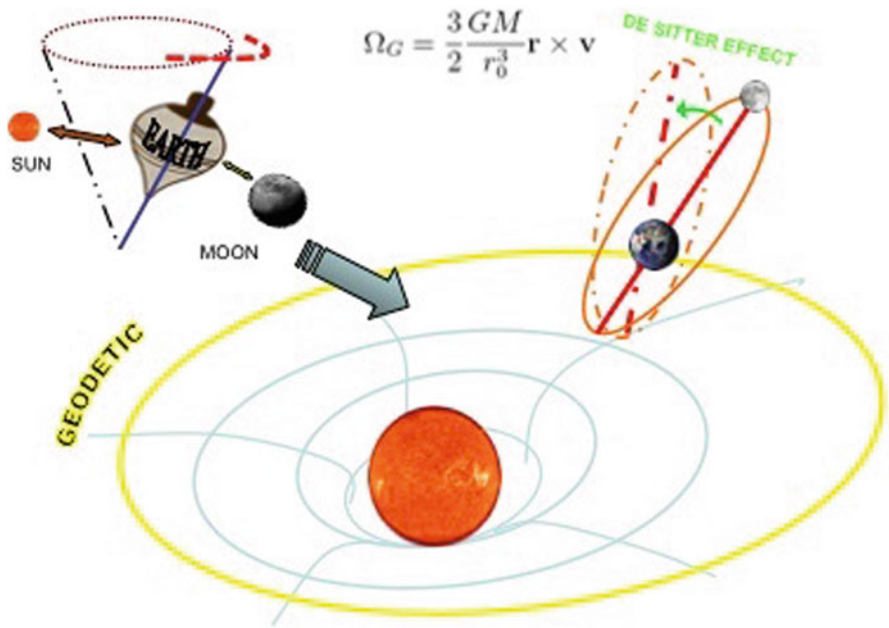


**Fig. 11** Example run of Apollo 15. In the plot, the *top panel* shows a 40 ns window of observed round trip time minus the predicted range. Background noise and detector dark current appear as scattered dots, while the lunar return is in the middle. The *middle panel* shows a histogram of the lunar returns, while the *bottom panel* shows the local “fiducial” CCR return, fitted by the red Gaussian. The lunar return is additionally spread by the tilted reflector array modeled by the superimposed magenta trapezoidal shape

Using APOLLO LLR data, the estimated value is consistent with the value obtained using old stations (see Table 3).

The nominal errors returned by the fit are significantly smaller than the value of  $K_{GP}$ , and smaller than the best published values. Therefore, we want to use the data to understand and estimate independently the size of the error budget.

We have also performed a fit using every single old station (CERGA: Centre d’Etudes et de Recherches Godynamiques et Astronomiques, MLR2: McDonald Laser Ranging Station, TEXL: Texas Laser Ranging, MAUI: Hawaii Laser Ranging Station). The results are shown in Table 4:



**Fig. 12**  $K_{GP}$  is the relative deviation of geodetic precession from the general relativity ( $GR$ ) value

**Table 2** Estimates of geodetic precession,  $K_{GP}$ , with the data set from MLRS, MLR2, and CERGA stations

Parameter	GR initial value	Final value
$K_{GP}$	0	0.009

$GR$  General relativity,  $CERGA$  Centre d'Etudes et de Recherches Godynamiques et Astronomiques,  $MLR2$  McDonald Laser Ranging Station,  $MLRS$  McDonald Laser Ranging Station

**Table 3** Estimates of geodetic precession,  $K_{GP}$ , with the new data set from APOLLO station

Parameter	GR initial value	Final value
$K_{GP}$	0	-0.0096

$APOLLO$  Apache Point Observatory Lunar Laser-ranging Operation

These preliminary measurements are to be compared with the best result published by the Jet Propulsion Laboratory (JPL) ( $K_{GP} = (-1.9 \pm 6.4) \times 10^{-3}$ ), obtained using a completely different software package, developed over the past 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.

**Table 4** Estimates of geodetic precession,  $K_{GP}$  using every single old station

Station	$K_{GP}$
CERGA	-0.016
MAUI	0.0060
MLR2	0.0095
TEXL	-0.044

*CERGA* Centre d'Etudes et de Recherches Godynamiques et Astronomiques, *MLR2* McDonald Laser Ranging Station, *TEXL* Texas Laser Ranging, *MAUI* Hawaii Laser Ranging Station

## 4 Determination of $\beta$

Using LLR data is also possible to measure PPN parameter  $\beta$  that is of great interest. In order to do this, we start from the equivalence principle (EP).

There are two different kinds of EP: weak equivalence principle (WEP that concerns nongravitational contribution to mass) and strong equivalence principle (SEP that extends the WEP to include gravitational self-energy of a body).

In GR, SEP is exact and a possible violation can be expressed by:

$$\left[ \frac{M_G}{M_I} \right]_{SEP} = 1 + \eta \frac{U}{Mc^2}, \quad (1)$$

where  $\frac{M_G}{M_I}$  is the ratio between gravitational and inertial mass,  $U$  is the gravitational energy, and  $\eta$  is a constant expressed by:

$$\eta = 4\beta - \gamma - 3. \quad (2)$$

Considering the Earth–Moon–Sun system, we have:

$$\left[ \left( \frac{M_G}{M_I} \right)_e - \left( \frac{M_G}{M_I} \right)_m \right]_{SEP} = \left[ \frac{U_e}{M_e c^2} - \frac{U_m}{M_m c^2} \right] \eta = -4.45 \times 10^{-10} \eta, \quad (3)$$

where  $e$  is relative to the Earth and  $m$  is relative to the Moon.

Fitting the data using LLR measurements:

$$\left[ \left( \frac{M_G}{M_I} \right)_e - \left( \frac{M_G}{M_I} \right)_m \right]_{EP} = (-1.0 \pm 1.4) \times 10^{-13}. \quad (4)$$

The combination of laboratory experiments of EP [22] with LLR data gives:

$$\left[ \left( \frac{M_G}{M_I} \right)_e - \left( \frac{M_G}{M_I} \right)_m \right]_{SEP} = (-2.0 \pm 2.0) \times 10^{-13}. \quad (5)$$

Considering the previous equation and the most accurate result of  $\gamma$  [23], the value of the  $\beta$ -parameter is:

$$\beta - 1 = (1.2 \pm 1.1) \times 10^{-4}. \quad (6)$$

Our value of the  $\beta$ -parameter calculated using the PEP software is:

$$\beta = (6.4 \pm 6.4) \times 10^{-4}, \quad (7)$$

which is consistent with the value obtained by [4].

## 5 Conclusions and Future Prospects

The analysis of the existing LLR data with PEP is 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 level of 1 %.

In the future, we are going to enhance our knowledge of data and software in order to better estimate the  $K_{GP}$  uncertainty and other GR parameters. A possible way to improve the precision of LLR measurements is to improve the intercalibration among the stations, that is, to range not only to the Moon but also to satellites around the Earth and primarily to laser geodynamics satellites (LAGEOS).

Before the end of the decade, a robotic mission on the lunar surface will deploy new scientific payloads, which include MoonLIGHT-type laser retroreflectors, and thus extend the LLR reach for new physics in three ways: (i) using a significantly improved second-generation retroreflector design; (ii) increasing by a factor of about 2 the geometric lever arm of LLR with missions to the lunar poles or limbs; (iii) combining LLR payloads with radio/microwave transponders (at least two) for same-beam microwave interferometry (SBI) capable of additional accurate measurements of lunar rotations and librations.

In particular, the single, large, fused-silica retroreflector design developed by UMD and INFN-LNF will improve by a factor of 100 or more the performance of current Apollo arrays, removing in this way the dominant contribution to the LLR error budget. Such a contribution is of the order of 2 cm. It is due to the multi-retroreflector structure of the arrays together with the librations and rotations of the Moon with respect to the Earth. The functionality of this specific new design, which inherits and is evolved from the successful Apollo 11, 14, and 15 experience, is being validated by thermal–vacuum–optical testing in space conditions accurately simulated in the laboratory at the INFN-LNF SCF\_Lab.”

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