Frascati Physics Series Vol. 66 (2018)
FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS
May 20-26, 2018

TESTING GRAVITY WITH THE MOON AND MARS

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Abstract

We present tests of fundamental relativistic gravity performed with solar systems experiments based on next-generation laser retroreflectors, lunar laser ranging and Mars surface missions.

1 Lunar Laser Ranging and Retroreflectors

There are laser retroreflectors on the Moon since 50 years ago (deployed in 1969 by Apollo 11 astronauts) and there were no laser retroreflectors on Mars, until the Italian *microreflectors* were recently deployed on Mars (next section). These instruments are positioned by time-of-flight measurements of short laser pulses (the so-called "laser ranging" technique) shot by ground stations of the International Laser Ranging Service (ILRS, see https://ilrs.gsfc.nasa.gov) or by orbiting spacecrafts equipped, for example, with laser altimeters (like NASA's

Lunar Reconnaissance Orbiter, LRO). Lunar laser ranging is performed by three currently acrive ILRS station: MLRO, the Matera Laser Ranging Observatory of the Italian Space Agency, the French station in Grasse and the US station, APOLLO (Apache Point Lunar Laser-ranging Operation). INFN-LNF and ASI-CGS work as a synergetic Joint Lab on laser retroreflectors, Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR) and their extension for Mars exploration and science. For 50 years LLR to Apollo/Lunokhod Cube Corner laser Retroreflector (CCR) arrays supplied accurate tests of General Relativity (GR) and new gravitational physics: possible changes of the gravitational constant $\dot{G}/G$, weak and strong equivalence principle, gravitational self-energy (Parametrized Post Newtonian parameter β), geodetic precession, inverse-square force-law [1] [2] [3], spacetime torsion [4] [5] and nonminimally couple gravity [6] [7]. LLR has also provided significant information on the composition of the deep interior of the Moon, complementary to that of NASA's mission GRAIL (Gravity Recovery And Lunar Interior Laboratory). In fact, already in the later 1990s LLR first provided evidence of the existence of a fluid component of the deep lunar interior [1], confirmed later by a re-analysis of Apollo lunar seismometry data in 2011 [8]. Therefore, Apollo/Lunokhod CCRs form the first realization of a passive Lunar Geophysical Network (LGN) for lunar science, exploration and precisions tests of GR [9]. For Moon missions we have developed two classes of next-generation CCR payloads: microreflectors of 25 gr mass for observation by orbiters and full-size payloads (order of kg mass) for direct LLR from Earth. In 1969 CCR arrays contributed a negligible fraction of the LLR error budget. Since laser station range accuracy improved by more than a factor 100, now, because of lunar librations, the Apollo/Lunokhod CCR payloads dominate the error due to their multi-CCR geometry and large geometric size. For direct LLR by ILRS, we developed a next-generation, single, large CCR, MoonLIGHT (Moon Laser Instrumentation for General relativity high-accuracy test) unaffected by librations that supports an improvement from a factor 10 up to a factor 100 of the space segment of the LLR accuracy (see [2] for details). Performance testing of next-gen payloads with two specialized OGSE (Optical Ground Support Equiment) space facilities [10] at INFN-LNF has been performed; for MoonLIGHT positive results are reported in [11]. Lunar landing mission opportunities for our next-generation laser retroreflectors in the international context are described in [12].

2 Laser Retroreflectors for the Mars Geophysical Network

There were no laser retroreflectors on Mars until the NASA InSight mission landed and started operating successfully on the surface of the red planet on Nov. 26, 2018 [13) 14)]. The ESA ExoMars Schiaparelli mission, which unfortunately failed Mars landing in 2016, was carrying a laser retroreflector like InSight [15)]. These instruments are positioned by laser ranging from Mars orbiters. The image of figure 1, taken in December 2018, shows LaRRI (Laser RetroReflector for InSight) on the lander deck in front of the camera calibration targets.

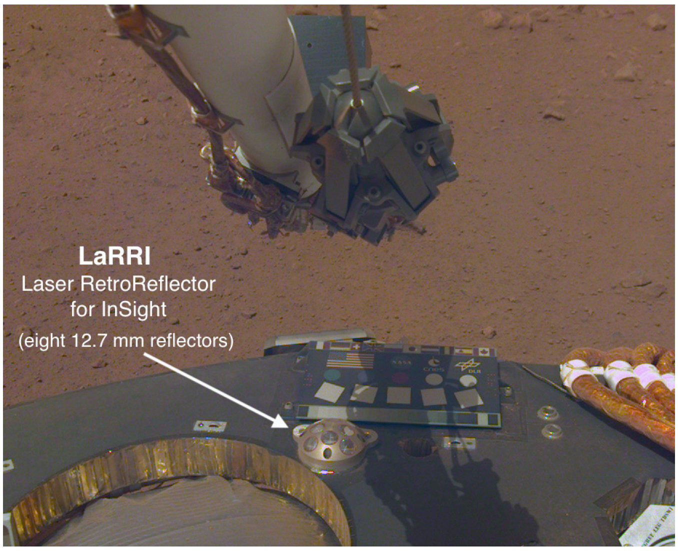

Figure 1: *LaRRI on InSight (December 2018).*

Starting from 2015 we initiated the delivery to ASI, ESA-ESTEC and NASA-JPL of several miniature laser retroreflector payloads (microreflectors) designed for Mars, Moon and other planetary missions. to be observed by orbiters capable of laser ranging measurements. Examples of the latter are the past Mars Global Surveyor (MGS), the currentLRO and similar future spacecrafts, like Hera (ESA's proposed mission to the Dydimos double asteroid, which is foreseen to carry a lidar/altimeter instrument onboard). The notional concept of microreflectors for solar system exploration research (a pillar of the INFN-ASI Affiliation-Association to NASA-SSERVI, http://sservi.nasa.gov) is shown in figure 2 below. The goals of the microreflectors and their role as the

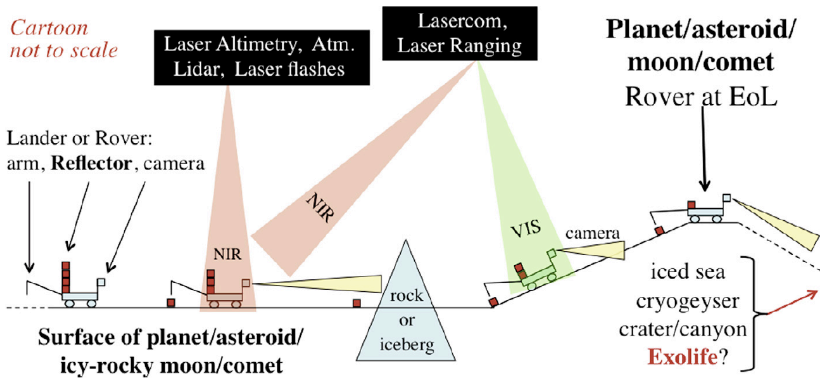

Figure 2: *Microreflectors for the solar system.*

passive, maintenance-free, long-lived instrument component of a future international Mars Geophysical Network (MGN) are described in [14) 15)]. InSight is the first, core node of such an MGN. Science and exploration applications of microreflectors include surface geodesy, geophysics (when combined with seismometers, heat flow probes, etc., like the instrument suites of InSight [13)] and Apollo[1] [16) 8)]) and the test of fundamental relativistic gravity.

To address the latter with Mars surface missions, we performed test physics simulations of the contribution of a 5-microreflector MGN to test General Relativity by means of the Planetary Ephemeris Program (PEP) developed by I. Shapiro et al (see for ex. [17)]). Under specific and conservative assumptions (described below) the contribution of this MGN is found to improve the measurements of $\dot{G}/G$ and of β (see table 1). γ is used as a control observable, by comparing its estimate with measurements by Cassini or the ESA missions GAIA (Global Astrometric Interferometer for Astrophysics) and BepiColombo (M. T. Crosta and L. Iess, these proceedings).

[1]EASEP, Early Apollo Scientific Experiment Package/Payload for Apollo 11 and ALSEP, Apollo Lunar Surface Experiments Package for Apollo 12-17.

Table 1: *Test of gravity with a laser retroreflector MGN (PEP simulations).*

Time/σ(CCR)	$\lvert\beta - 1\rvert$ accuracy	$\lvert\gamma - 1\rvert$ accuracy	$\dot{G}/G$ accuracy
10 years / 10 m	1.5 $\times 10^{-4}$	7.0 $\times 10^{-4}$	3.5 $\times 10^{-14}$
10 years / 1 m	3.4 $\times 10^{-5}$	1.4 $\times 10^{-5}$	1.1 $\times 10^{-14}$
10 years / 10 cm	7.1 $\times 10^{-7}$	3.0 $\times 10^{-6}$	2.6 $\times 10^{-15}$
Accuracy now	$< 1 \times 10^{-4}$	2.3 $\times 10^{-5}$	9 $\times 10^{-13}$
With data/mission	LLR/Messenger	Cassini	LLR

Table 1 is obtained under the following assumptions:

- Hypothetical MGN with coordinates: Phoenix (68N, 234E), Viking 1 (22N, 50W), Viking 2 (48N, 258W), Curiosity roving region (4S, 137E), Opportunity roving region (2S, 354E). This is a non-ideal MGN, since almost all nodes are in the northern hemisphere.
- One laser orbiter observation every 7 Sols. This takes into account weather conditions, although for example the visibility of Curiosity from MRO (Mars Reconnaissance Orbiter) is about once/Sol (source: NASA).
- $\sigma(CCR)$ is the positioning accuracy of the MGN node (the microreflector) on Mars. This is obtained by adding the Earth-Mars orbiter positioning by radio science, or with laser ranging/lasercom (*à la* LLCD, Lunar Laser Communications Demo, on NASA's LADEE, Lunar Atmosphere and Dust Environment Exploration) and the orbiter-reflector positioning by laser ranging/altimetry. The current accuracy of Mars ephemeris is 50-100 m (see [15]) for a discussion).

This GR test with Mars will be complementary to (and with experimental errors independent of) the one performed [18)] [2)] with current large-size lunar laser retroreflectors (Apollo 11, 14, 15; Lunokhod 1, 2) observed by LLR.

For Mars (and Moon) missions we designed, built, qualified for surface missions, and delivered six microreflector payloads of 25 gr mass, each equipped with eight 0.5 inch (12.7 mm) diameter laser retroreflectors of fused silica:

- INRRI [15)] (INstrument for landing-Roving laser Retroreflector Investigations) for ESA Schiaparelli 2016 [19)] (delivered to ESA on September 2015 for integration by Thales Alenia Space - Italy)

- LaRRI [14] [22] for NASA InSight 2018 (delivered to JPL on August 2017 for integration by Lockheed Martin Co.)
- INRRI for ESA ExoMars Rover 2020 [20] (delivered to ESA-ESTEC on October 2018; the second identical spare is available at INFN for other international mission opportunities in the whole solar system; for example in partnership with ESA and NASA-SSERVI or with/for others)
- LaRA (Laser Retroreflector Array) for NASA Mars 2020 Rover [21] (see figure 3; two flight models delivered to JPL in 2019; after Mars 2020 launch one will be returned to INFN for other mission opportunities).

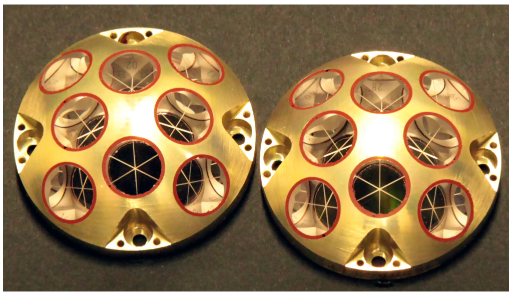

Figure 3: *The two LaRA flight models for Mars 2020.*

Prior to delivery the optical performance and thermal behavior of laser retroreflectors is characterized at the SCF_Lab [23] of INFN-LNF in environmental conditions accurately representative of their deployment at their respective destinations. For LaRRI on InSight see [22]. See [10] for a detailed description of the general approach, OGSE equipment and test procedures and applications to LAGEOS (Laser GEOdynamics Satellite by NASA in 1976, LAGEOS-2 by ASI in 1993) and for CCR payloads for the GNSS (Global Navigations Satellite System constellations), like GPS, Galileo, IRNSS, the Indian Regional Navigation Satellite System). For Galileo see also [24] [25]; for IRNSS see also [26].

3 Acknowledgements

The INFN authors wish to thank the support of the INFN National Scientific Committee n. 2 on astroparticle physics research, through funding of the

MoonLIGHT-2 experiment. We also wish to thank ASI-NASA for the agreements signed on InSight and Mars 2020, and ASI-ESA for similar agreements on the ExoMars Schiaparelli and Rover missions.

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