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Probing General Relativity and New Physics with Lunar Laser Ranging

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ABSTRACT

Over the past 40 years, Lunar Laser Ranging (LLR, developed by the Univ. of Maryland (PI) and INFN-LNF (Co-PI)) to the Apollo Cube Corner Retroreflector (CCR) arrays have supplied almost all the significant tests of General Relativity (Currie et al., 2009 [12]). LLR can evaluate the PPN (Post Newtonian Parameters), addressing this way both the possible changes in the gravitational constant and the self-energy properties of the gravitational field. In addition, the LLR has provided significant information on the composition and origin of the Moon. This is the only Apollo experiment that is still in operation. Initially the Apollo LLR arrays contributed a negligible fraction of the ranging error budget. Over the decades, the ranging capabilities of the ground stations have improved by more than two orders of magnitude. Now, because of the lunar librations, the existing Apollo retroreflector arrays contribute a significant fraction of the limiting errors in the range measurements. We built a new experimental apparatus (the 'Satellite/Lunar Laser Ranging Characterization Facility', SCF) and created a new test procedure (the SCF-Test) to characterize and model the detailed thermal behavior and the optical performance of cube corner laser retroreflectors in space for industrial and scientific applications (Dell'Agnello et al., 2011 [13]). Our key experimental innovation is the concurrent measurement and modeling of the optical Far Field Diffraction Pattern (FFDP) and the temperature distribution of the SLR retroreflector payload under thermal conditions produced with a close-match solar simulator. The apparatus includes infrared cameras for non-invasive thermometry, thermal control and real-time movement of the payload to experimentally simulate satellite orientation on orbit with respect to both solar illumination and laser interrogation beams. These unique capabilities provide experimental validation of the space segment for SLR and Lunar Laser Ranging (LLR). The primary goal of these innovative tools is to provide critical design and diagnostic capabilities for Satellite Laser Ranging (SLR) to Galileo and other GNSS (Global Navigation Satellite System) constellations. Implementation of new retroreflector designs being studied will help to improve GNSS orbits, which will then increase the accuracy, stability, and distribution of the International Terrestrial Reference Frame (ITRF) [4], to provide better definition of the geocenter (origin) and the scale (length unit). The SCF is also actively used to develop, validate and optimize the second generation LLR arrays for precision gravity and lunar science measurements to be performed with robotic missions of the International Lunar Network in which NASA and ASI participate (ILN). The capability will allow us to optimize the design of GNSS laser retroreflector payloads to maximize ranging efficiency, to improve signal-to-noise conditions in daylight and to provide pre-launch validation of retroreflector performance under laboratory-simulated space conditions. For the MAGIA lunar orbiter Phase A study funded by ASI (Dell'Agnello et al., 2010 [14]), we studied fundamental physics and absolute positioning metrology experiments, to improve test of the gravitational redshift in the Earth–Moon system predicted by General Relativity and a precursor test of our second generation LLR payload.

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1. INFN-LNF Satellite/Lunar Laser Ranging Characterization Facility (SCF)

The "Satellite/Lunar Laser Ranging Characterization Facility" (SCF) of INFN-LNF in Frascati, Italy, is devoted to the characterization of the detailed thermal properties and the optical performance of laser-ranged payloads (the 'SCF-Test') for GNSS (Global Navigation Satellite System) constellation, Space Geodesy and Fundamental Physics applications. The Optical Lab is a LNF facility dedicated to the Far Field Diffraction Pattern (FFDP) industrial acceptance test of laser cube corner retroreflectors (CCRs) for space applications. We tested about 200 flight CCRs to be deployed in space by imminent launches Figs. 1 and 2.

2. MAGIA (Missione Altimetrica Gravimetrica GeochImica Lunare)

In 2008 ASI approved for Phase A study five proposals presented in response to the call for 'Small Missions' issued in 2007. One of these is MAGIA (Missione Altimetrica Gravimetrica GeochImica Lunare), whose Principal Investigator is A. Coradini (INAF-IFSI Rome) and Prime Contractor is Rheinmetall Italia S.p.A. MAGIA is an altimetry, gravimetric and geochemical mission consisting of a main orbiter in polar orbit, which will release a Subsatellite at the end of the mission. One of the LNF-INFN contributions in MAGIA will be the VESPUCCI (VEga or Soyuz Payload for Unified Clock vs. CCR Investigation) payload, with the aim to measure the gravitational redshift in the Earth–Moon system. The ILN (International Lunar Network) initiative comes at an opportune time when international space agencies are focusing unprecedented resources on lunar exploration. This will allow the network as a whole to monitor geophysical activity over the entire Moon. Each of the lander nodes will carry a core set of ILN defined instruments. One of the instrument categories that are being considered for the ILN, is a new generation of LRRs (Lunar Laser Ranging). We propose to test on MAGIA spacecraft a new LLR payload, MoonLIGHTP (Moon Laser Instrumentation for General Relativity Highaccuracy Test-Precursor), integrating with thermal and optical characterization at SCF (Space/Lunar Laser Ranging Characterization Facility) at LNF-INFN.

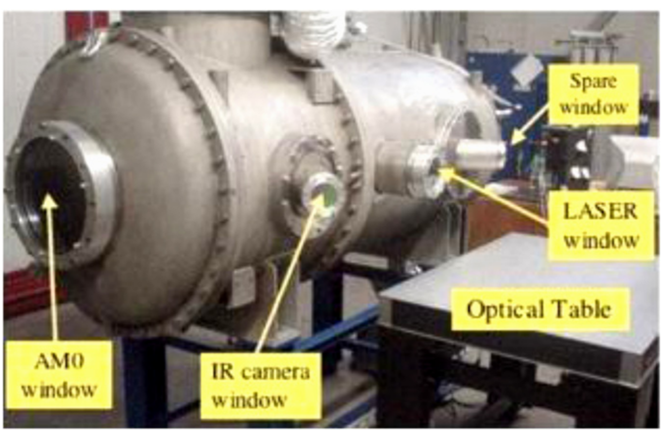

Fig. 1. SCF: Satellite/Lunar Laser Ranging Characterization Facility.

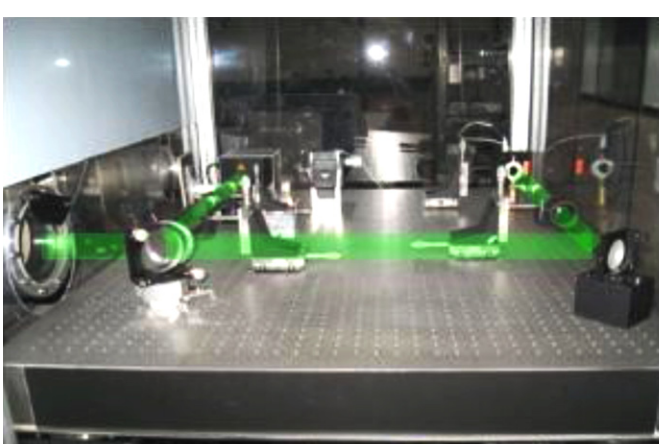

Fig. 2. Optical table.

The MAGIA's scientific goals have been identified in order to avoid overlaps with currently planned, ongoing, or just concluded orbiter or impactor missions: (1) study of the mineralogical composition of the Moon by means of a VIS/NIR imaging spectrometer; (2) characterization of the Moon polar regions by means of concurrent observations with different instruments, (imaging experiment, altimeter and thermal); (3) characterization of the lunar Gravity field with a two-satellite tracking similar to GRACE, with a main orbiter and a small Subsatellite; (4) characterization of the lunar radiation environment by means of a particle radiation monitor; (5) characterization of the lunar exosphere; (6) fundamental physics test of gravity; (7) absolute positioning metrology measurements; and (8) precursor technological test for the second generation LLR [2]. This work will exploit passive, maintenance-free laser retroreflectors and an atomic clock on the orbiter. With MAGIA we propose to perform the following experiments in the Earth–Moon system: (1) VESPUCCI: a significant improvement of the measurement of the gravitational redshift in the trans-lunar flight and in Moon orbits and (2) MoonLIGHT: a technological test of the payload for the second generation LLR. The importance of a precursor test will be explained in Section 2.1. The retroreflectors will be tracked by the ILRS [1]. If MAGIA will be approved, the performance of the two retroreflector payloads will be characterized at the dedicated 'Satellite/Lunar Laser Ranging Characterization Facility' (SCF) of INFN-LNF [3]. For the atomic clock analysis we consider a clock stability in the range between 10^{-13} and 2×10^{-14}.

2.1. MoonLIGHT: Moon Laser Instrumentation for General Relativity Highaccuracy Tests

MoonLIGHT-P is developed by the University of Maryland and INFN-LNF for NASA's Lunar Science Sortie Opportunities (LSSO) program [6,7], for two ASI studies and, currently, for the ILN. The Primary Investigator (PI) of LSSO was D.G. Currie and Co-PI was S. Dell'Agnello; Italian collaborators participated at no cost for NASA. This project is known to NASA as Lunar Laser Ranging Retroreflector Array for the twenty-first century (LLRRA21). The first generation LLR based on the retroreflector payloads deployed with Apollo and Lunokhod missions has provided numerous precision tests of gravity [8] and unique measurements of lunar planetary science [9].

Gravity Science Measurement	Timescale	LLR Measurement Accuracy		
		Current (cm)	1 mm	0.1 mm
Weak Equivalence Principle (WEP)	Few years	$\lvert\Delta a/a\rvert<1.3\times10^{-13}$	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 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}
Parameterized Post-Newtonian (PPN) β	Few years	$\lvert\beta-1\rvert<1.1\times10^{-4}$	10^{-5}	10^{-6}

Fig. 3. Expected physics reach of the first gen. LLR and with the second gen. LLR (with MoonLIGHT/LLRRA21).

MoonLIGHT will improve the accuracy of the space segment of LLR by a factor 100. This will extend very significantly the test of General Relativity (see Fig. 3) and allow for a test of new gravity theories. We probe General Relativity and New Physics with Lunar Laser Ranging. We report a search for new gravitational physics phenomena based on Riemann–Cartan theory of General Relativity including spacetime torsion [16]. These include the 'brane world' model by Dvali et al. [15]. This model weakens gravity at very large distances, therefore explaining the apparent acceleration of the universe without Dark Energy, and it predicts effects on the Moon orbit measurable with MoonLIGHT but not with Apollo arrays.

The deployment of our large, single retroreflector on MAGIA will allow for testing two critical instrumental effects: the thermal perturbation of the optical performance due to the Sun and the laser ranging return at lunar distances for an orbiting target, which is more difficult than for a payload on the surface. Finally, MoonLIGHT-P, a precursor test of CCR-M on MAGIA, will strengthen the Italian contribution to the International Lunar Network (ILN, see also http://iln.arc.nasa.gov/) in the areas of fundamental physics and lunar science. The ILN was formed by space agencies from nine countries (including ASI) to establish a network of standardized payloads composed by a set of common core instruments to be deployed with robotic missions. The ILN selected the following core instruments: (1) seismometer, (2) electromagnetic sounding, (3) heat flow probe, and (4) CCR [10]. The preliminary specs for the ILN CCR are fully compatible with our MoonLIGHT/LLRRA21 payload.

In 2007 a new station capable of mm-class range accuracy started operations: APOLLO, the Apache Point Apache Point Observatory Lunar Laser-ranging Operation, funded jointly by National Science Foundation (NSF) and NASA [11]. Following this, the largest source of error is now closely linked to the retroreflector arrays on the lunar surface, which are particularly affected by the lunar librations. The motivation for a sparse, distributed arrays of single, very large CCRs (10 cm diameter) on the lunar surface is to remove the perturbation of the geometric librations of the Moon from LLR. Currently the librations of the Apollo and Lunokhod retroreflectors are the dominant contribution to the LLR error. Our goal is to improve by a factor at least 100 this contribution, from cm level down to 0.1 mm. This new approach has been developed by UMD and INFN-LNF with thermal, optical and orbital simulations and is now being validated at INFN-LNF with the SCF-Test (Section 3) of a 100 mm diameter CCR funded by NASA for LSSO. The general concept of the second generation of LLR is to consider a number (notionally eight) large single cube corner retroreflectors spread over tens of meters, unaffected by the libration and, consequently, by increased spread of the return laser pulse. 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. 4. We currently envisage the use of 100 mm CCRs composed of T19 SupraSil I. 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 from the Moon surface, in order to maintain a relatively constant temperature through the lunar day and night. It is also isolated from the CCR, by two coassial 'gold cans', 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. Actual hardware prototype and the mounting of the CCR inside the housing are shown in Fig. 5. KEL-F rings could

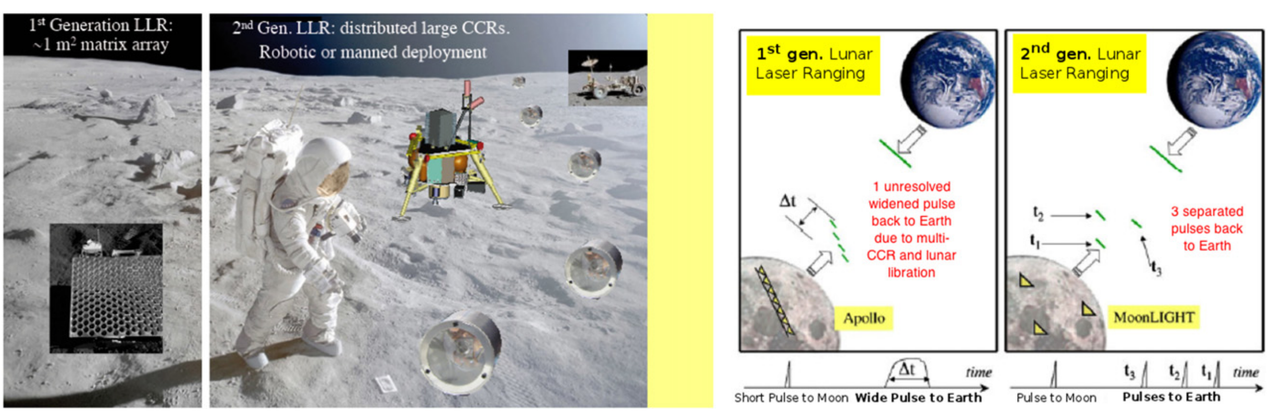

Fig. 4. Concept of the second generation of Lunar Laser Ranging.

Fig. 5. Views of current design of the MoonLIGHT/LLRRA21 CCR: (a) fully assembled and (b) exploded view with its internal mounting elements and outer aluminum housing.

be used for this mounting (its used in LAGEOS) due to its good insulating, low out-gassing and non-hygroscopic properties. The CCR and the thermal shield have been provided by LSSO funds. Mechanical design and construction of the housing, rings and SCF-testing has been provided by INFN-LNF.

3. Thermal and optical tests in Frascati

SCF (Satellite/Lunar Laser Ranging Characterization Facility) Section 2.1, at LNF/INFN in Frascati, Italy, is a cryostat where we are able to reproduce the space environment: cold (77 K with Liquid Nitrogen), vacuum, and the Sun spectra. The SCF includes a Sun simulator (www.ts-space.co.uk that 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 an uniformity better than ± 5 W/m^2 over an area of 35 cm diameter. Next to the cryostat we have an optical table, where we can reproduce the laser path from Earth to the Moon, and back, studying the Far Field Diffraction Pattern (FFDP) coming back from the CCR to the laser station, useful to understand how good is the optical behavior of the CCR. The SCF-Test [12] is a new test procedure to characterize and model the detailed thermal behavior (Figs. 6 and 7) and the optical performance of laser retroreflectors in space for industrial and scientific application, never before been performed. We perform an SCF-Test on the MoonLIGHT CCR to evaluate the thermal and optical performance in space environment. About thermal measurements we use both an infrared (IR) camera and temperature probes, which give a real time measurements of all the components of the CCR and its housing. In particular we look at the temperature difference from the front face to the tip, studying how the FFDP changes during the different thermal phases. This is the best representative of the thermal distortion of the return beam to the Earth. Various configurations and designs of the CCR and the housing have been and are being tested in the SCF Facility, with the solar simulator, the temperature data recording, the infrared camera and the measurement of the Far Field Diffraction Pattern (FFDP). In Figs. 8 and 9 is shown the MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at Moon velocity aberrations (2 V/c) during key points of the SCF-Test: (1) in air, (2) in vacuum, (3) during chamber's shields cooling, (4) Sun on orthogonal to the CCR's face with the housing temperature controlled at $T=310$ K, (5) Sun on at 30° of inclination (no break-through), (6) Sun on at $-30°$ of inclination (break-through), and (7) Sun on orthogonal with the housing temperature left floating. From this graph we can deduce that the intensity decreases during no orthogonal lighting of the CCR, in particular when the Sun enters

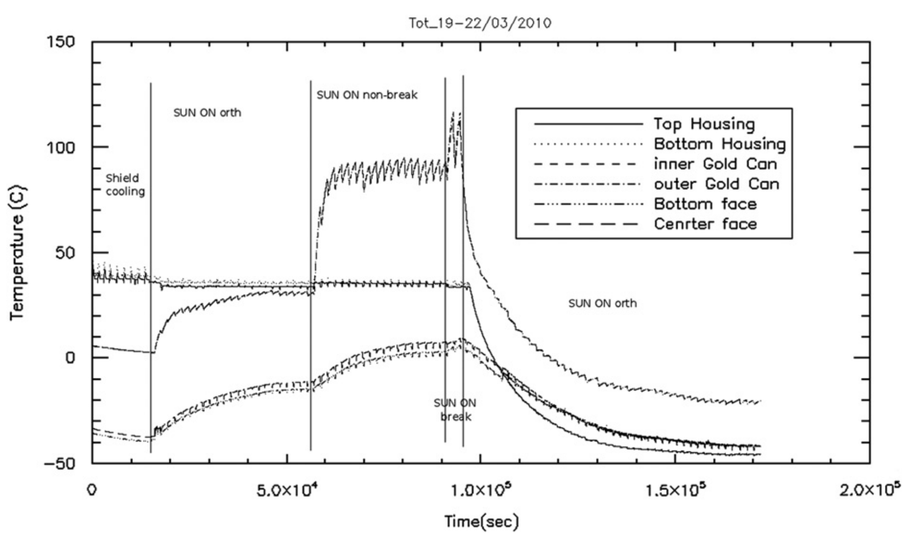

Fig. 6. MoonLIGHT/LLRRA-21 flight CCR temperature variations of various housing parts and of CCR (19–22/March/2010).

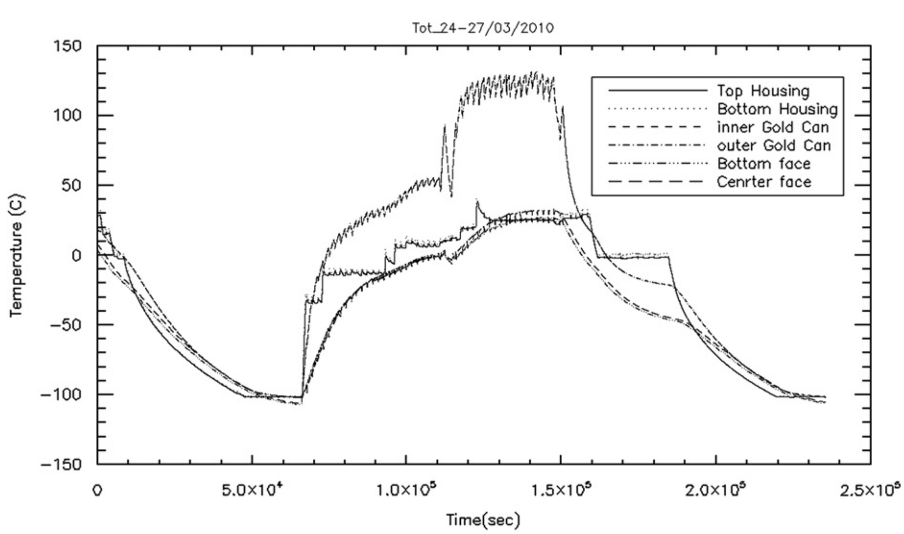

Fig. 7. MoonLIGHT/LLRRA-21 flight CCR temperature variations of various housing parts and of CCR (24–27/March/2010).

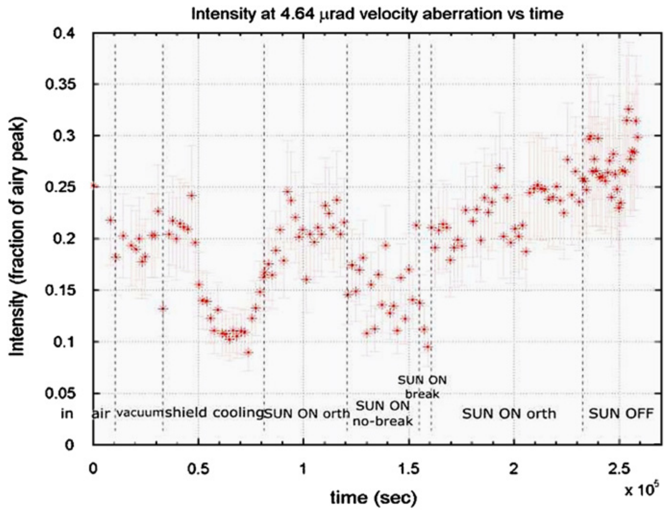

Fig. 8. MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at Moon velocity aberrations (2 V/c) during tests (time subdivision refers to Fig. 6).

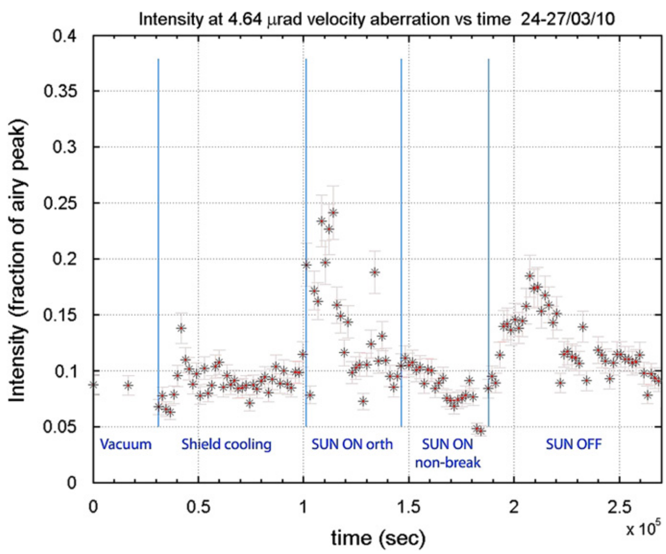

Fig. 9. MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at Moon velocity aberrations (2 V/c) during tests (time subdivision refers to Fig. 7).

in the housing cavity during the break-through phase. This effect is due to a strong increase of the 'Tip-Face' thermal gradient during these two phases of the test. When the housing temperature is left floating, the intensity slightly increases because the "Tip-Face" gradient is reducing.

4. Conclusion

The Phase A study was concluded in December 2008 with the final review and the full MAGIA proposal was submitted to ASI. The MAGIA collaboration is now awaiting the decision of the new ASI management and the new National Space Plan ASI supports ILN. In the meantime, the work of the INFN-LNF group on the development of the MoonLIGHT-P prototype continued in 2010–2011 in the framework of the ILN and with an R&D experiment approved by INFN for the period 2010–2012, called MoonLIGHT-ILN within the ILN. We wish to acknowledge the support of the University of Maryland via the NASA LSSO program (Contract NNX07AV62G) to investigate Lunar Science for the NASA Manned Lunar Surface Science and the LUNAR consortium (http://lunar.colorado.edu), headquartered at the University of Colorado, which is funded by the NASA Lunar Science Institute (via Cooperative Agreement NNA09DB30A) to investigate concepts for astrophysical observatories on the Moon.

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Further reading

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