Next Generation Lunar Laser Ranging and Its GNSS Applications

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Abstract—Over the past forty years, Lunar Laser Ranging (LLR) to the Apollo Corner Cube Reflector (CCR) arrays has supplied almost all of the significant tests of General Relativity, and provided significant information on the composition and origin of the Moon. These arrays are the only experiment of the Apollo program still in operation. Initially the Apollo Lunar arrays contributed a negligible portion of the error budget used to achieve these results. However over the decades, the performance of the ground stations has been greatly upgraded so that the ranging accuracy has improved by more than two orders of magnitude. Now, after forty years, because of the lunar librations, the existing Apollo retroreflector arrays contribute a significant fraction of the limiting errors in the range measurements. University of Maryland (UMD) and INFN/LNF are now proposing a new approach to the Lunar Laser Ranging Array technology, the experiment MoonLIGHT[12]. The new arrays will support ranging observations that are a factor 100 more accurate, reaching the micron level. The new fundamental physics and lunar physics that this new Lunar Laser Ranging Retroreflector Array for the 21st century (LLRRA-21) can provide, will be briefly described. The new lunar CCR housing has been built at the INFN/LNF[3]. In the design of the new array there are three major challenges: 1) validate that the specifications of the CCR required for the new array, which are significantly beyond the properties of current CCRs, can indeed be achieved, 2) address the thermal and optical effects of the absorption of solar radiation within the CCR, reduce the transfer of heat from the hot housing to the CCR and 3) define a method of emplacing the CCR package on the lunar surface such that the relation between the optical center of the array and the center of mass of the Moon remains stable over the lunar day/night cycle. Its evolutionary design may be suitable for future GNSS constellations guaranteeing ranging accuracy improvement (the concept of a single reflector introduces no laser pulse spreading at all angles), weight and area saving (being its absolute optical cross section equal to a large number of the CCRs that will be used for the upcoming GNSS constellations)[4].

TABLE OF CONTENTS

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1. INTRODUCTION

It is widely recognized that Laser Ranging is the most accurate and the most cost effective technique to measure the position of a payload (either on a satellite or on the Moon) equipped with CCR, prisms made of a radiation-resistant grade of fused silica, Suprasil 1, whose characteristic is to send the laser pulse entering the prism back in the same direction they came. Laser Retro-reflector Arrays (LRA) are passive, light-weight, maintenance free, and, if built with proper thermal design and choice of materials, can provide very good performance for several decades. This was historically demonstrated with the LRAs deployed on the surface of the Moon by NASA's Apollo 11, 14 and 15 missions, designed by a team led by C. O. Alley, D. Currie, P. Bender and Faller et al [1]. After four decades these arrays are still in operation, and are the only experiment on the Moon still producing scientific data. In the past 40 years, laser ranging to these arrays has provided most of the definitive tests of the many parameters describing General Relativity [2]. In addition, the analysis of the LLR data, in collaboration with some data from other modalities, has greatly enhanced our understanding of the interior structure of the Moon [3,4,5,6].
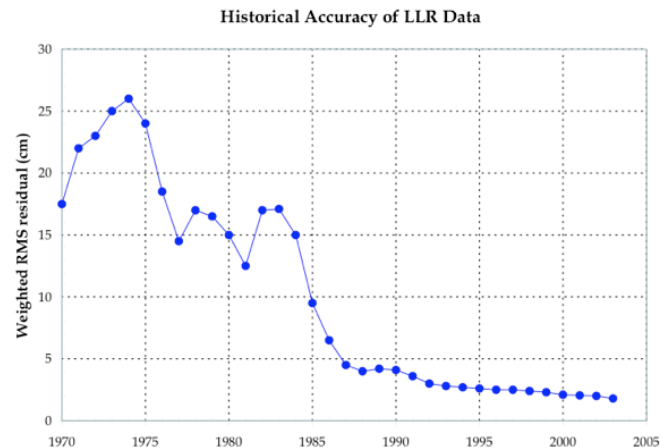

Figure 1-LLR accuracy improvements over the years

However over the past four decades the ground station technology has greatly improved, enhancing LLR accuracy (see Figure 1), such that the Apollo LRAs now contribute a significant portion of the ranging errors. This is due to the lunar librations, which move the Apollo arrays so that one corner of the array is more distant than the opposite corner by several centimeters. Thus even if a short pulse were sent to the Moon, the return pulse would be spread out in time, so that the accuracy achievable on the range estimate is no better than a few centimeters (for a single shot). At 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. The APOLLO LLR station at Apache point has done such an improvement successfully [7]. The ultimate goal of 2nd generation LLR is to install new LRAs whose performance is unaffected not only by lunar librations, but also by regolith motion due to

its very large thermal cycle, with a final LRA ranging accuracy below 10 μm.

2. SCIENCE OBJECTIVES OF LLRRA-21

The science objectives of the overall LLR program address a variety of goals, which primarily fall into three categories:

General relativity and beyond
Almost all of the most accurate tests of General Relativity (GR) are currently derived from LLR to the Apollo arrays [8,9,10]. Over the long term, we expect to improve the current accuracy of these tests by factors as large as 100. This will address many tests concerning the validity of GR at a new level of accuracy. This is especially important as we confront two of the major issues in fundamental physics, astrophysics and cosmology, that is, 1) the conflict between the current formulations of GR and Quantum Mechanics and 2) the role and reason for the acceleration of distant galaxies (i.e. Dark Energy). At LNF we are also studying new gravitational theories beyond GR and how to look for their signature or constrain them with LLR and SLR data.

Lunar science
Much of our knowledge of the interior of the Moon is the product of LLR [5,6,8,9], often in collaboration with other modalities of observation. These physical attributes of the lunar interior include Love number of the crust, the existence of a liquid core, the Q of the Moon, the physical and free librations of the Moon and other aspects of lunar science.

Cosmology
The improved accuracy of the LLRRA-21 would support the detection of the effects predicted by Dvali-Gabadadze-Porrati model [11] of Dark Energy and the acceleration of distant galaxies.

3. LLRRA-21 ARRAY

As mentioned earlier Laser Ranging stations have improved the accuracy of their measurements with the advances in technology. Currently the APOLLO station at Apache point has reached a level of accuracy whose only limit is given by the LRAs themselves. With MoonLIGHT we want to overcome this limitation by replacing the array of CCRs with a series of single bigger CCRs deployed separately on the surface on the Moon. Instead of having a single pulse, spread by the array and the libration effect, we will have single pulses coming back with the same dimensions as the incoming one (see Figure 2). This new concept for the LLRRA-21 is being considered also for the NASA anchor nodes of the International Lunar Network (ILN) and for the proposed Italian Space Agency's MAGIA [12] lunar orbiter
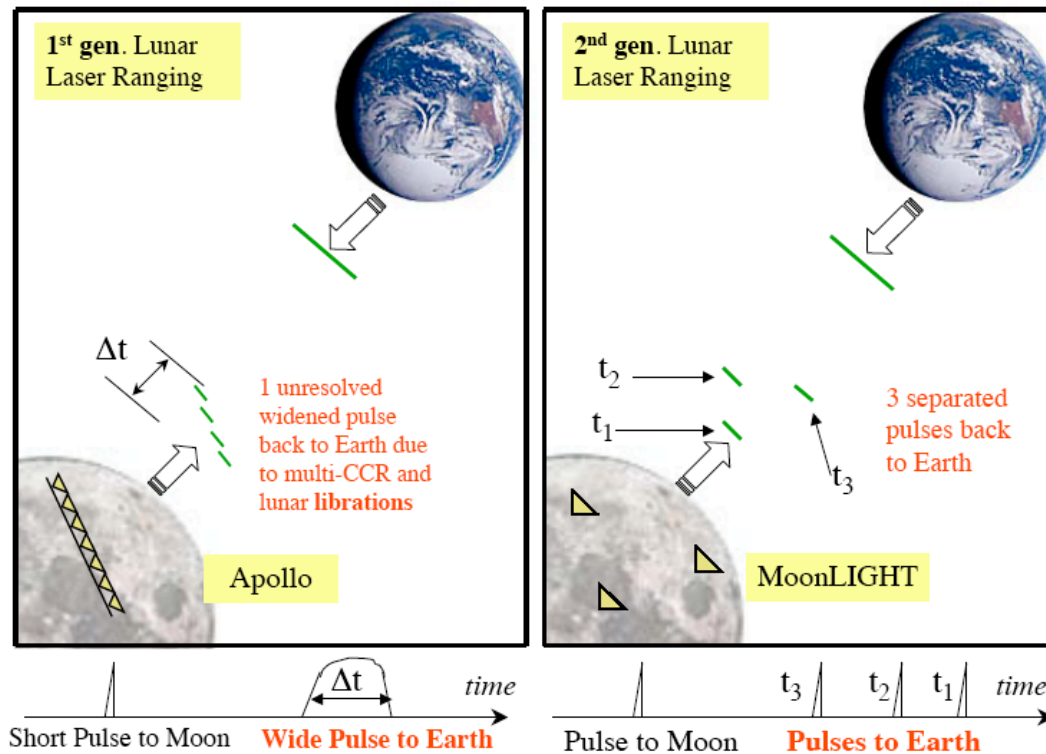

Figure 2- 2nd generation Lunar Laser Ranging concept

mission.

The CCR for LLRRA-21 has the same design style as the Apollo cubes (circular front face, with tabs on the non reflecting surfaces to help its emplacement inside the housing); however, it is much bigger than its predecessor, for the reasons explained above; the absolute intensity in return (optical cross section) would replace half of the Apollo 11 array intensity. Despite this loss in the intensity of the return, it should be noticed that with the APOLLO station, the efficiency of LLR is increased, and even with 50% reduction in the intensity of the return, a very good measurement is guaranteed.

Figure 3-Apollo and MoonLIGHT CCRs

The CCR has a diameter of the front face of 100 mm (Figure 3 is a comparison with an Apollo CCR). The angles between the three back surfaces have a specification on the offsets of 0 arcsec, as Apollo CCRs, though with a more challenging tolerance of ±0.2 arcsec. Fabrication, with certification of space qualification, has been commissioned to ITE Inc. of Beltsville, MD.

4. TECHNICAL CHALLENGES OF LLRRA-21

The primary technical objectives of the LLRRA-21 are to provide adequate laser return to Earth ground stations and to be stable over long term, decades, with respect to the center of mass of the Moon. The major technical/engineering challenges that follow from the technical objective are then:

- Fabricate a large CCR with adequate homogeneity and that meet the required tolerances, mentioned in the previous section.

- Thermal control to reduce thermal gradients inside the CCR to acceptable levels. Thermal gradients produce index of refraction gradients, which cause beam spread and low return.

- Emplacement goal of long-term stability of 10 μm with respect to the Center of Mass of the Moon.

Fabrication challenge

The large diameter of the CCR introduces a great challenge in its fabrication, the availability of such material of the required homogeneity, the fabrication and polishing procedures and the measurement methods. The angle between the three back reflecting faces, which govern the shape of the pattern, have a more challenging tolerance of ±0.2 arcsec; this is more restrictive by a factor of 2.5 than the current state of the art for SLR CCR fabrication. The material choice is primarily driven by three requirements:

- extremely uniform index of refraction (very good homogeneity)

- resistance to darkening by cosmic radiation

- low solar radiation absorption

To satisfy these requirements, this CCR has been fabricated with SupraSil 1. For the next generation of CCRs, LLRRA-21, we plan to use SupraSil 311 which has even better homogeneity.

Thermal/optical performance challenges

The optical performance of the CCR is determined by its Far Field Diffraction Pattern (FFDP), which represents the intensity of the laser beam reflected back to the ground by the CCR.
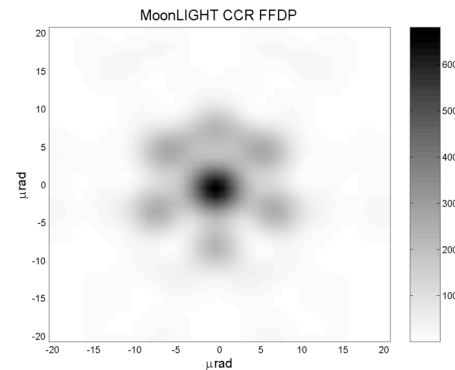

Figure 4-FFDP of LLRRA-21 under its design specification of offset angles (0.0'' 0.0'' 0.0''). Grid is in angular dimensions (μrad)

Figure 4 is a simulation of the FFDP of the LLRRA-21 (performed with the software CodeV) according to its dimensions and angle specifications; at the correct velocity aberration the intensity (calculated in optical cross section) should have a value which guarantees that enough photons come back to the ground station. Optical cross section is an intrinsic characteristic of CCRs or LRAs, and it's defined as follows:

$$\sigma_{CCR} = I_{CCR/MIRR}(\theta_x, \theta_y) \; 4\pi \left(\frac{A_{CCR}}{\lambda}\right)^2 \qquad (1)$$

Where $I_{CCR/MIRR}$ is the intensity of the FFDP of the CCR, at a certain point of the (θ_x, θ_y) plane, referred to a perfect mirror of the same aperture as the CCR, λ is the laser wavelength.
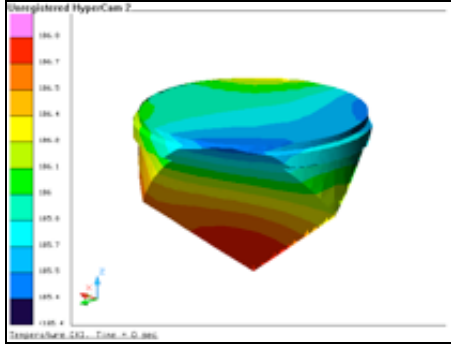
Figure 5-Typical distribution of temperature inside the CCR for a given set of conditions.

One of the most critical challenges of this new model is the issue of the thermal gradient. Since the index of refraction of the fused silica depends upon temperature, a thermal gradient inside the CCR will cause the index of refraction to vary within the CCR and thus modifying the FFDP. In Figure 6, is represented the average intensity over the velocity aberration for the LLRRA-21 at Standard Temperature and Pressure (STP). At the velocity aberration for the Moon, ~4μrad, we will test thermal perturbations and, if needed, develop an optimized design to control the drop of FFDP intensity to an acceptable level.
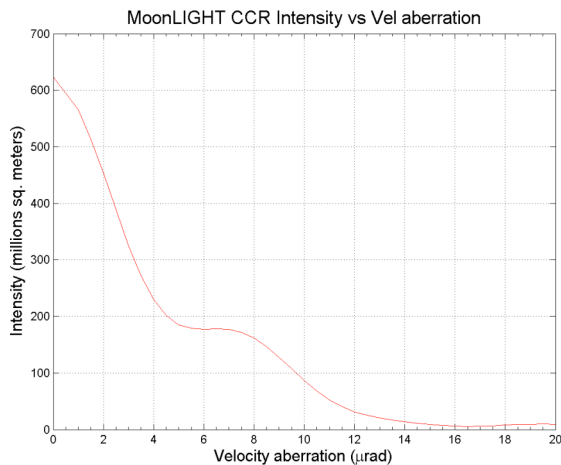
Figure 6-Average intensity over velocity aberration of an unperturbed MoonLIGHT CCR

For this reason we need to understand in detail how the external factors heat the CCR and in what magnitude, either

on the Moon or on a satellite. This is accomplished using dedicated programs developed in parallel at LNF and UMD. To perform these simulations we use Thermal Desktop, a software package of C&R Technologies of Boulder CO. Then using IDL and CodeV we translate these thermal gradients into the effects on the FFDP of the CCR. There are three primary sources of heat that causes thermal gradients; here we briefly describe their effect:

- *Absorption of solar radiation within the CCR*: during a lunar day, the solar radiation enters the CCR and portions of this energy are absorbed by the fused silica. Since the different wavelengths in the solar radiation are absorbed with different intensity, according to fused silica absorptivity characteristic, the heat is deposited in different parts of the CCR.

- *Heat flux flowing through the mechanical mounting tabs*: if the CCR is at a temperature that is different than the housing temperature there will be a flux of heat passing into (or out of) the CCR through the holding tabs. Conductivity of the mounting rings should be reduced.

- *Radiation exchange between the CCR and the surrounding pocket*: in the case of the Apollo LRAs, the back surfaces of the CCRs view the aluminum that makes up the housing, machined with a relative high emissivity/absorptivity. If the temperatures of the CCR and the aluminum are different there is a radiation exchange of thermal energy, which in turn causes a flux in the CCR as the heat exits out of the front face to cold space. In the Apollo array this is not been a serious issue, but the bigger dimensions of the LLRRA-21 complicate things, and we need to reduce this effect. Thus we enclose the CCR into two thermal shields, with a very low emissivity (2%), that should prevent this radiative heat flow.

Thermal simulations performed on the current configuration show that currently the variation of the ΔT between the front face and the tip of the CCR is within 1K. We are still proceeding to optimize this further, both with optical design procedures and with thermal stabilization of the overall housing.

Emplacement challenge

As mentioned earlier, to achieve the desired accuracy in the LLR, a long term stability is needed with respect the center of mass of the Moon; to attain this we must understand and simulate the temperature distribution in the regolith (and its motion), the effects of a thermal blanket that will be spread about the CCR and the effects of heat conduction in the INVAR supporting rod. A locking depth is chosen such that the thermal motion effects are small (~ 1m). The placement of the thermal blanket further reduces the thermal effects

and also reduces the effects of conduction in the supporting rod. This simulation cycles through the lunation and annual cycles.

Figure 7-SCF sketch (left side), SCF cryostat and optical table (right side)

5. LNF/SCF THERMAL-OPTICAL TESTING

Up to this point the discussions have addressed concepts for the LLRRA-21 and thermal-optical computer simulations developed to validate the design concepts. We now address the thermal vacuum testing to further validate design issues. Thermal-optical tests are being performed at the Satellite/lunar laser ranging Characterization Facility (SCF), facility of the INFN-LNF (see Figure 7). To validate design issues, we need to provide two classes of measurements. The first is the thermal behavior of the test configuration. A solar simulator that has a good representation of the AM0 solar spectrum (solar spectrum in space) is used to provide the solar input. To evaluate the thermal performance of the designs, we use both thermo-resistors and an infrared video camera. The former must be specially configured in order that the wires not conduct more heat than the test item, the latter yields temperatures over the entire test object at each instant. On the other hand, to address the relation between the thermal performance and the optical performance, we currently measure the far field diffraction pattern. This is the crucial test of a CCR package and is performed with the CCR inside the chamber. For the next run, we plan to implement a phase front measurement (which is optimal for diagnosing the details of the performance). Various configurations and designs of the CCR and the housing have been and are being tested in the SCF.

6. CURRENT HOUSING DESIGN

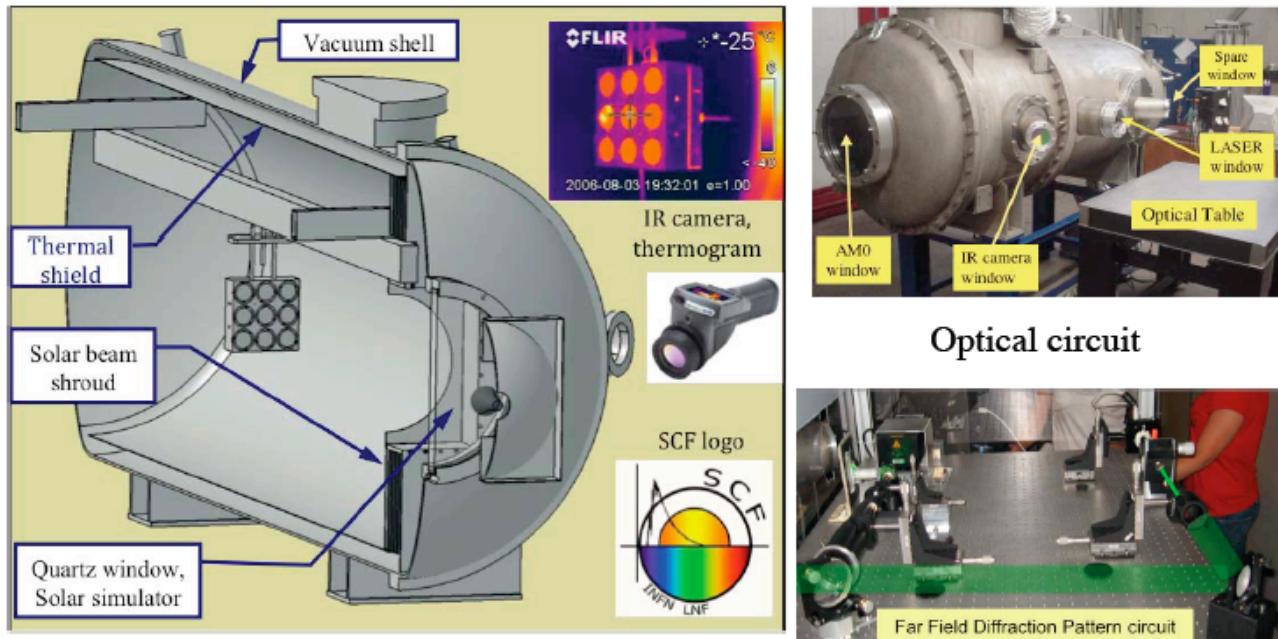We are successively refining our design upon maximizing the overall performance by jointly optimizing the effects of the various different phenomena that affect the overall performance. This has been addressed using the computer simulations described in section 4 and using the data obtained with the SCF measurements. This addressed both the design for the manned emplacement and the use of the 100mm solid CCR in the ILN anchor nodes. Thus we illustrate the current designs in Figure 8 and Figure 9.
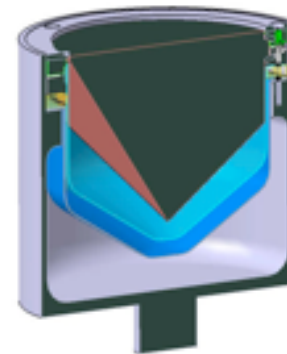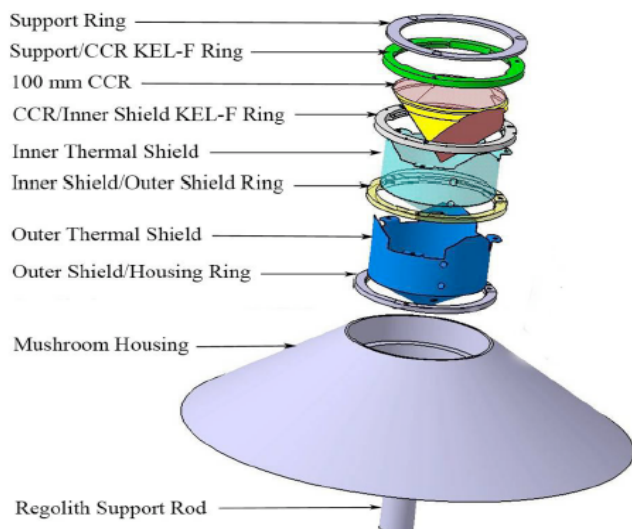

**Figure 8-MoonLIGHT CCR emplacement inside the housing**

Figure 8 is the current design of the housing as used for the early tests. Figure 9 is the current design for the complete emplacement configuration; a mushroom shield is added for thermal control reasons.

Figure 9-Current complete design for manned lunar mission

7. LAUNCH REQUIREMENTS

We are just beginning a study of the requirements of launch. This particularly addresses issues of the support of the CCR by the tabs in the vibration and acceleration environment of the launch phase. To this end, we have formulated a first example of a structural analysis with ANSYS [13,14].
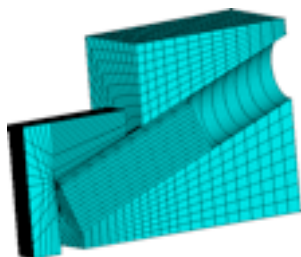
Figure 10-ANSYS model for tab support

In particular we are addressing the contact between the CCR edge (i.e. the three tabs on the side of the CCR) and support plastic rings made of KEL-F. The role of the rings is particularly important since we have presumed a configuration with extremely low mount conductance. This will check the stability and strength of the tab support and the KEL-F line support for 10 g launch accelerations (e.g. in excess to the 6 g characteristic of the ATLAS V launch specifications). We are also performing a modal structural analysis of the inner gold plated thermal shield for an ATLAS V launch.

8. MoonLIGHT AS A CONCEPT FOR FUTURE GNSS CONSTELLATIONS

The study which UMD and INFN/LNF are carrying on for the LLR modernization could have an high impact for future GNSS constellations. Modern GNSS constellations require better and better positioning stability and precision, both provided in absolute terms, that is, with respect the International Terrestrial Reference Frame (ITRF). This can be achieved by tight integration of GNSS microwave tracking with SLR, as stated by the ILRS[5][15] (the International organization responsible for data processing and publishing of SLR observations among a network of about 40 ground observatories all over the globe [16]). In recent years attention to SLR technique grew in the GNSS community to be used as an important improvement in the constellation performance. GPS constellation of the second generation has two satellites equipped with LRAs (GPS 35/GPS 36) and GLONASS has all of its satellites equipped with LRAs (both of them with coated retroreflectors). Measurements to both of them have demonstrated the great potential of SLR in increasing positioning accuracy of each satellite [17,18]. This has been done also by combining the separate SLR and MW orbit products. The long-term goal is to combine SLR and MW data at observational level, both in space and at the ground station level, with a latency of the order of an hour. All modern growing GNSS (GALILEO, COMPASS, GPS-3) and regional geosynchronous (QZSS, IRNSS) constellations have designed all of their satellites with co-located MW antennas and SLR payloads (with uncoated retroreflectors); GPS planned a third constellation to might also be equipped with LRAs. All SLR systems deployed or designed on GNSS satellites are planar arrays of CCRs; they use the same principle used for LLR Apollo missions, to install on a plate a certain number of small CCRs to achieve the sufficient level of intensity (established by the ILRS as a fundamental requirement to perform good ranging measurements [19]), at the correct velocity aberration (~24μrad for GALILEO). For example on GIOVE-A (the first test satellite for GALILEO) there is an array of 76 28mm CCRs (same design as GPS and GLONASS ones). It is important to develop a design to minimize thermal problems on the arrays and to enable daylight ranging; these refinements will greatly help the possibility of doing SLR based orbits in quasi real-time, having more data through the entire orbit.

The array setup suffers though the same problems of the Apollo arrays: relative angular movement of the array with respect laser-CCR direction (of the same order of magnitude of the effect due to lunar librations on Apollo arrays). For GNSS satellites this effect has two different causes:

1. During a passage over the ground station, the array, always pointing to the nadir, will be hit by the laser beam at different inclinations (for example varying from 0º to ~12º for GALILEO orbit), thus resulting in a significant pulse spread, especially for low elevations on the horizon (high laser inclination on the array).

2. Satellite attitude control.

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[5] International Laser Ranging Service

To further increase the positioning precision, this uncertainty must be overcome. MoonLIGHT design could be feasible for such an improvement. Looking at the optical cross section formula (eq. (1)), the intensity is proportional to A_{CCR}^2, hence R^4, so an increase, for example, of two times in the radius would produce a 16 times increase in the intensity; thus the passage from an array of small CCRs to a single one. Comparing new LRAs equipped with uncoated CCRs with LLRRA-21, we can see that the solo CCR optical cross section, at the central peak, would be equal to the one of ~80 CCRs (with no angle offsets, at the central peak). No pulse spread will result during the passage of the satellite and the location of a reference point for the distance calculation won't be uncertain. Moreover the reduction on the number of CCRs will reduce the area of the SLR system on the satellite and its weight. There are currently other configurations under design [20], always involving one big CCR, but the hollow CCR technology rather than solid fused-silica CCR is considered.

As described in the previous section, LLRRA-21 application for MoonLIGHT experiment needs a specific design which takes into account the environment around the CCR, to limit thermal gradients on the CCR and guarantee long-term stability with respect to the center of mass of the Moon; in the same way the proper design for GNSS applications would need simulations and tests of the characteristic heat and mechanical loads in the GNSS orbits. The single big CCR solution however has some disadvantages with respect to the array one. The passage to a single CCR will introduce a possible single-point failure; if the CCR didn't work (low intensity, strong thermal gradients or damage at launch) that satellite wouldn't have a functioning SLR payload (possible to be overcome using a second CCR as a backup). As mentioned in the previous sections, if the CCR were bigger, thermal gradients inside it would have greater effects than CCRs now under use; a design to reduce them will be necessary. Proper dimensions and dihedral angle offsets of the CCR will have to be studied to reach the proper absolute optical cross section required by ILRS, at the right velocity aberration (~24μrad for GALILEO). A specific design and lab testing such as the one described in this work would help to overcome the difficulties of this new approach to GNSS SLR and reach the desired capabilities.
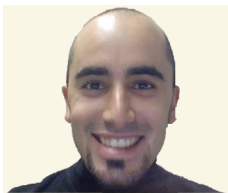
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BIOGRAPHY

Alessandro Boni is a PhD student at the University of Rome "Tor Vergata", his research activity, carried on in collaboration with the INFN/LNF, is based on the analysis and tests of the optical performance of modern LRAs for GNSS constellations, with the purpose to enhance SLR accuracy, and make possible SLR based orbits, and finally enhance GNSS ephemeredes accuracy. From 2006 to 2008 he worked at INFN/LNF at the development of the Data Acquisistion System of the SCF, on the thermal-optical tests of a flight model of a GPS2 array and of prototypes of GPS2/GLONASS/GIOVE-A CCRs, and on thermal effects simulations of CCRs with CodeV software. In 2006 he worked at the Particle Beam Physics Laboratory of University of California Los Angeles (UCLA) at the mechanical design of an RF Hybrid Gun and the design of its solenoids. He has a Master of Science degree on Astronautic Engineer at the "Scuola di Ingegneria Aerospaziale" of Rome.