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S. Dell'Agnello

A. Boni

C. Cantone

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NEXT-GENERATION LASER RETROREFLECTORS FOR GNSS, SOLAR SYSTEM EXPLORATION, GEODESY, GRAVITATIONAL PHYSICS AND EARTH OBSERVATION

S. Dell'Agnello[1], A. Boni[1], C. Cantone[1], E. Ciocci[1], M. Martini[1], G. Patrizi[1], M. Tibuzzi[1], G. Delle Monache[1], R. Vittori[1,2], G. Bianco[1,3], D. Currie[1,4], N. Intaglietta[1], L. Salvatori[1], C. Lops[1], S. Contessa[1], L. Porcelli[1], C. Mondaini[1], P. Tuscano[1], M. Maiello[1]
[1]National Institute for Nuclear Physics – Frascati National Labs, Frascati (Rome) Italy. [2]ASI and Italian Embassy of Italy, Washington DC, USA. [3]ASI-Space Geodesy Center, Matera (MT), Italy. [4]University of Maryland at College Park, MD, USA.

I. INTRODUCTION

The SCF_Lab (Satellite/lunar/gnss laser ranging and altimetry Characterization Facility Laboratory) of INFN-LNF is designed to cover virtually LRAs (Laser Retroreflector Arrays) of CCRs (Cube Corner Retroreflectors) for missions in the whole solar system, with a modular organization of its instrumentation, two redundant SCF (SCF_Lab Characterization Facilities), and an evolutionary measurement approach, including customization and potentially upgrade on-demand. See http://www.lnf.infn.it/esperimenti/etrusco/ for a general description.

The SCF_Lab is dedicated to the characterization and modeling of the space segment of SLR (Satellite Laser Ranging [1] to [4]), LLR (Lunar Laser Ranging, [5] to [12]) and PLRA (Planetary Laser Ranging and Altimetry) for industrial and scientific applications. A description of the different applications in SLR, LLR, PLRA can be found at http://www.lnf.infn.it/conference/laser2012/. The SCF_Lab consists of two OGSE called SCF (Satellite/lunar/gnss laser ranging and altimetry Characterization Facility, property of INFN) and SCF-G (which doubles our metrology capabilities for GNSS applications, property of INFN and of the Italian Space Agency, ASI). Views of the SCF are shown in Fig. 1 and 2. The SCF is very versatile for its large number of measurement ports (side and back), very long horizontal translations and capabilities for LLR and PLRA CCR payloads. The SCF-G is optimized for GNSS.

Together with the SCF and SCF-G we developed a new industry-standard thermal-optical-vacuum tests to characterize and model the detailed optical performance and thermal behavior in representative space conditions (SCF-Test, background intellectual property of INFN). The latter is described in detail elsewhere [1][2]. Here we only recall its key features:

- Laboratory-simulated space conditions. Concurrent/integrated:
  - Dark/cold/vacuum
  - Two Sun/Albedo AM0 simulators and Earth IR simulator
  - Non-invasive IR and contact thermometry
  - Laser interrogation and sun perturbation at varying angles
  - Payload thermal control, roto-translations
  - GCO, GNSS Critical Orbit (worst-case thermal and optical behavior).
- Deliverables / Retroreflector Key Performance Indicators (KPIs)
  - Thermal behavior (τ_{CCR}, thermal relaxation time) with probes and IR thermometry
  - Optical response 1: Far Field Diffraction Pattern (FFDP)
  - Optical response 2: (near-field) Wavefront Fizeau Interferogram (WFI).
- Integrated thermal-optical simulations both of the test data and of orbit configurations.

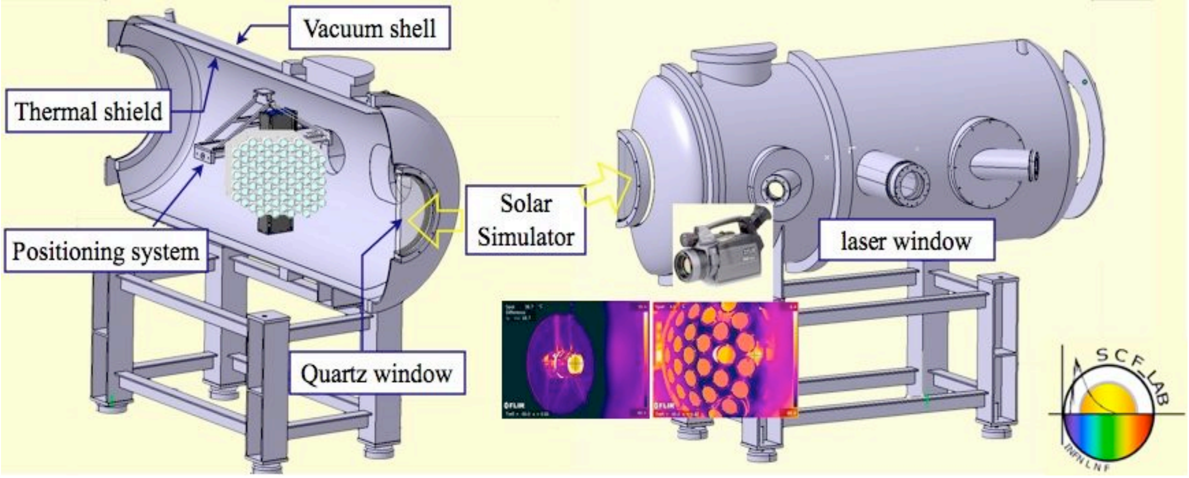


Fig 1. SCF cryostat, IR thermograms of LAGEOS/Galileo CCR under test, IR camera SCF_Lab logo.

The SCF/SCF-G AM0 sun simulators have 45/40cm diameters. They can be used together on the SCF (from the front solar window and from the back port), where they allow for the performance of the full space environmental test of CubeSats of MicroSats capable of modeling both the thermal inputs of Sun and albedo.
We also have a vibration- and air-turbulence insensitive WFI measuring instrument to characterize the WFI of CCR during SCF-Tests (in addition to separate, independent and redundant FFDP measurements of the CCRs). This can be done with different laser polarizations (linear and circular).

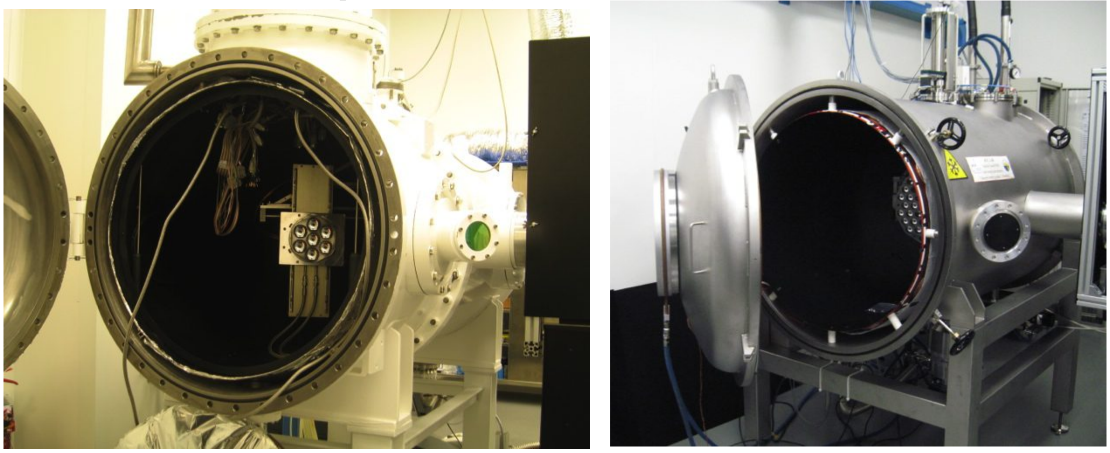


Fig. 2. SCF cryostat with GRA-H (GNSS Retroreflector Array of Hollow technology). IR port at right with Ge window. SCF-G cryostat with the "ILRS Standard GRA". IR port at right with black cover on.

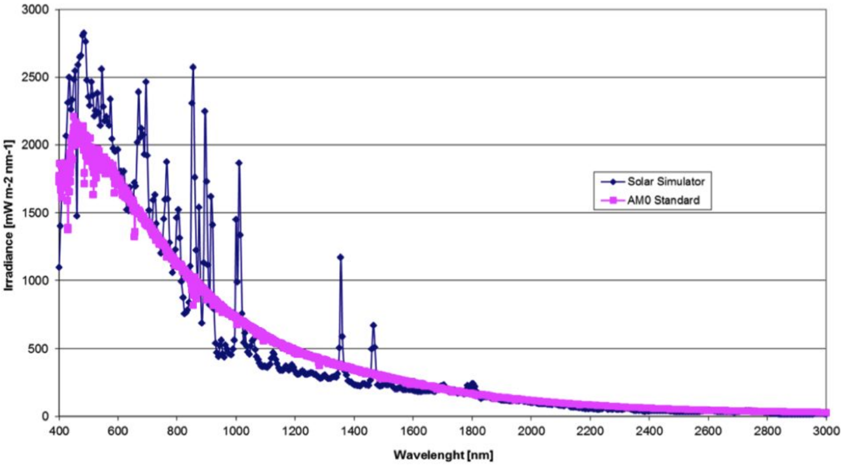


Fig 3. Spectrum of the SCF solar simulator (45 cm diameter) compared to the AM0 standard sun in space.

We developed next-generation laser retroreflectors for: a flat, large LRA for satellite navigation, GRA (GNSS Retroreflector Array); a micro-reflector array for solar system exploration and geodesy, INRRI (Instrument for landing-Roving laser Retroreflectors Investigations); a midsize reflector array for Earth Observation (EO) and exploration, CORA (COsmo-skymed Retroreflector Array); a single, large retroreflector fro LLR, MoonLIGHT (Moon Laser Instrumentation for General relativity High accuracy Tests) for the precision test of General Relativity (GR) ([3], [5] to [12]) and new gravitational physics ([13] to [16]). These are being designed, built and fully characterized at the SCF_Lab.

We use LAGEOS (LAser GEOdynamics Satellite) and Apollo LRAs as ILRS reference payloads standards. The SCF-Test of an engineering model of a polar sector of LAGEOS on loan at the SCF_Lab by NASA is described in [1] and [2]. The thermal SCF-Test of a flat-shape 3x3 CCR matrix with LAGEOS/Apollo CCRs and mounting scheme, built by the SCF_Lab, is described in [3] and [4].

II. LLR AND GRAVITATIONAL PHYSICS

For the Moon we propose both MoonLIGHT (shown in Fig. 4) and INRRI. The latter will be described in detail in the section "SOLAR SYSTEM LRA". In the following we describe MoonLIGHT. Precision GR tests and search for new gravitational physics are carried out with Apollo, Lunokhod LRAs and with MoonLIGHT. Current GR test ([5] to [12]) with LLR include:

- Parametrized Post-Newtonian parameter beta

- Weak Equivalence Principle
- Strong Equivalence Principle
- Time Variation of the Gravitational Constant
- Inverse Square Law – Yukawa potential
- Geodetic Precession.

Development of new gravitational physics models and set experimental constraints using also laser ranging and laser reflectors in the solar system:

- Extension of General Relativity to include Spacetime Torsion [13][14]
- Non-Minimally Coupled (NMC) Gravity, non minimal coupling between matter and curvature (so-called “$f_1(R)+f_2(R)$”, [15][16]).

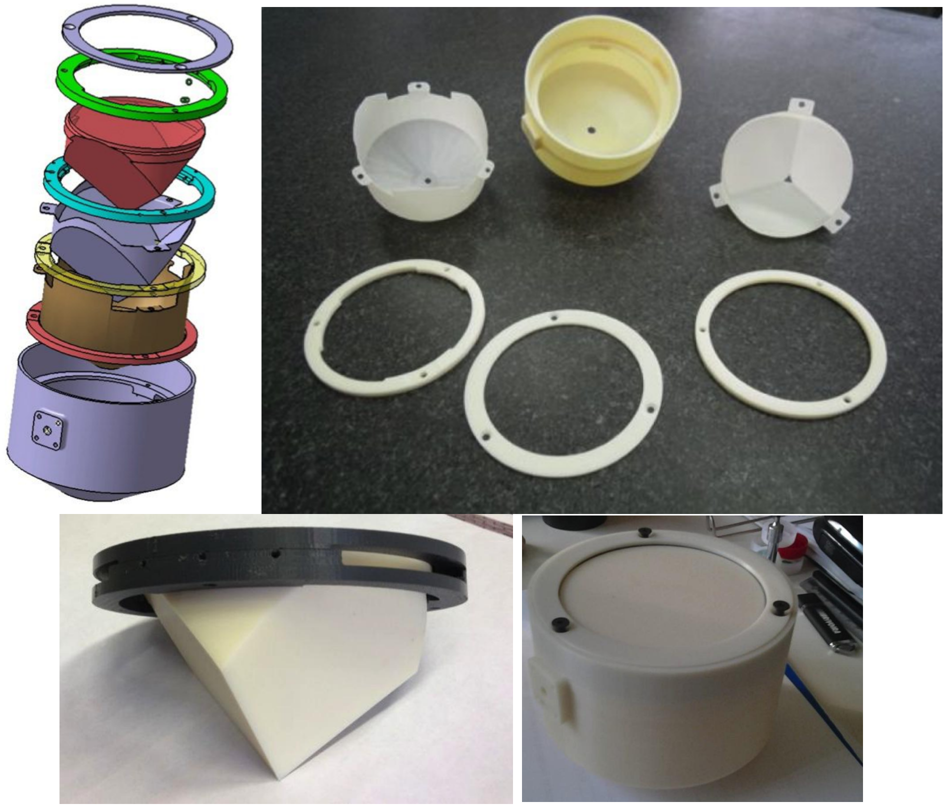


Fig. 4. Exploded view (top left) and photos of 3D-printed plastic components of MoonLIGHT.

III. LRA FOR SOLAR SYSTEM EXPLORATION AND GEODESY

We propose INRRI both for landers and rovers on Moon and Mars. The following description is for Mars.

- INRRI (shown in Fig. 5) is a laser retroreflector micropayload of about 50 gr weight and about 55 mm x 20 mm size. It will be laser tracked by Mars orbiters capable of laser ranging and/or laser altimetry, like for example LOLA (Lunar Orbiter Laser Altimeter) on LRO (Lunar Reconnaissance Orbiter) and/or laser communication, like for example LLCD (Lunar Laser Comm demo) on LADEE (Lunar Atmosphere and Dust Environment Explorer), or OPALS (LADEE = Lunar Atmosphere and Dust Environment Explorer) on the ISS. INRRI is developed for US Mars landers and rovers and on European landers and rovers with Italian interest and/or involvement. INRRI has been sized to give the right signal for LRO
    - In addition: flashes of laser sent by orbiters and retroreflected back by INRRI can also be observed by optical cameras on the same orbiters. If INRRI would be now on the Moon at the poles LOLA receiver would see it (ordinary laser ranging/altimetry time-of-flight), and so probably also LROC (digital imaging camera of LRO).
- Deploying multiple INRRIs on landers and rover will lead over time to the establishment of the retroreflector components of a Mars Geophysics Network. The location of the Airy-0 prime meridian of Mars can be defined very effectively by an INRRI-equipped lander, or rover at EoL, laser-located by Mars orbiters (perhaps a future, Mars-adapted version of LOLA, whose more accurate mapping will

replace MOLA laser altimetry maps). Deployment of three or more LRA of the INRRIs on Mars will allow for triangulations by orbiters.

- INRRI for Mars Rovers is a new enabling technology for planetary exploration because: it will provide accurate Rover geo-referencing during its exploration activity, recording its positions where significant geological measurements have been made by Rover instruments as reference for future exploratory missions. Example of the latter: future sample return mission targeting an INRRI-georeferenced position explored/surveyed by the Rover of particularly high interest to NASA/ESA/ASI long-term goals for Mars exploration (outstanding astrobiologically relevant sites, potential biosignature locations).
- The rover/lander with INRRI will also be a passive, wavelength-independent, long-lived reference point enabling the performance of full-column measurement of trace species in the Mars atmosphere by future space-borne lidars. This will be complementary to highly localized measurements made by gas sampling techniques on the rover or by laser back-scattering lidar techniques on future orbiters and/or from the surface.
- INRRI for Mars Rovers is a new, wavelength-independent, enabling technology to test, validate, and locally diagnose, on Mars, certain aspects related to transmitter and receiver sub-subsystems for future laser-communication from Mars orbiters to Earth, an activity that is a long-term interest for future Mars missions. This will be also applied to future laser-comm between Mars orbiters and Mars surface (future Rovers and distributed installations).
- INRRI for Mars will also support future technology experiments of quantum laser communication exploiting the polarization states of laser photons, carried out among future Mars orbiters and the Mars Rovers.
- In summary, laser measurements by future orbiters with INRRI are:
  - Time-of-flight laser altimetry
  - Time-of-flight ranging from space to (Mars) ground: “inverse SLR network”, which will be an unprecedented activity. In fact, while to SLR/LLR has been done only by ILRS ground stations, no orbiting laser payload has ever ranged to a CCR outside Earth. The LOLA altimeter did not range to Apollo arrays because its receivers would have been damaged by too large a laser return. INRRIs on Moon and Mars surfaces need to be specially designed, with appropriately small optical cross section (and size), in order to be laser ranged by orbiters.
  - Rover geo-referencing during its exploration activity by laser altimetry and laser ranging
  - Lidar atmospheric trace species detection
  - Laser-communication test and diagnostics.

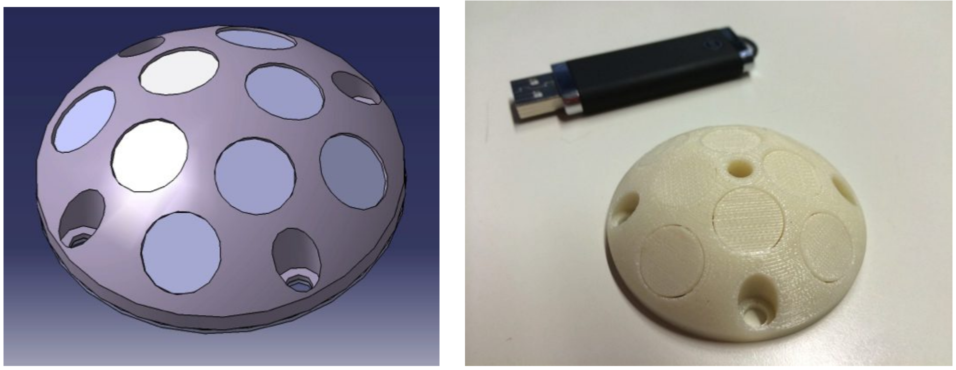


Fig. 5. INRRI

INRRI and/or appropriately adapted versions of INRRI are suited for deployment on the icy/rocky moons of Jupiter/Saturn: these payloads will be called ECCE-INRRI (Europa/Enceladus Cube Corners for Exploration and Exolife – Instruments for landing/Roving laser Retroreflector Investigations).

The conceptual Fig. 6 summarizes the laser tracking of INRRI deployed on the Moon, Mars, Jupiter/Saturn moons or asteroid:

- Selenolocate Lander/Rover with laser retroreflector by:
  - Laser Altimetry at nadir (LRO-like) to rovers/landers at poles of moon(s)
  - Laser Ranging / Laser-Comm to reflectors anywhere, like LLCD, OPALS and iROC (integrated Radio and Optical Communications, under development by NASA-GRC).
- Deploy INRRI networks; also on far side of Earth’s Moon.

We are also considering of INRRI or its variations for applications to Near Earth Asteroids in particular (NEAs), that is of interest to NASA and the Europe (HORIZON2020 programme).

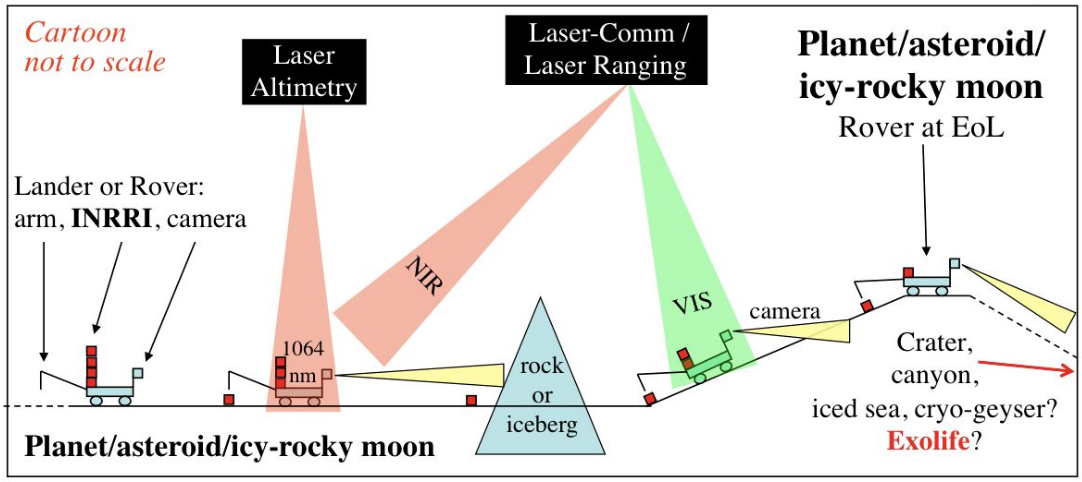
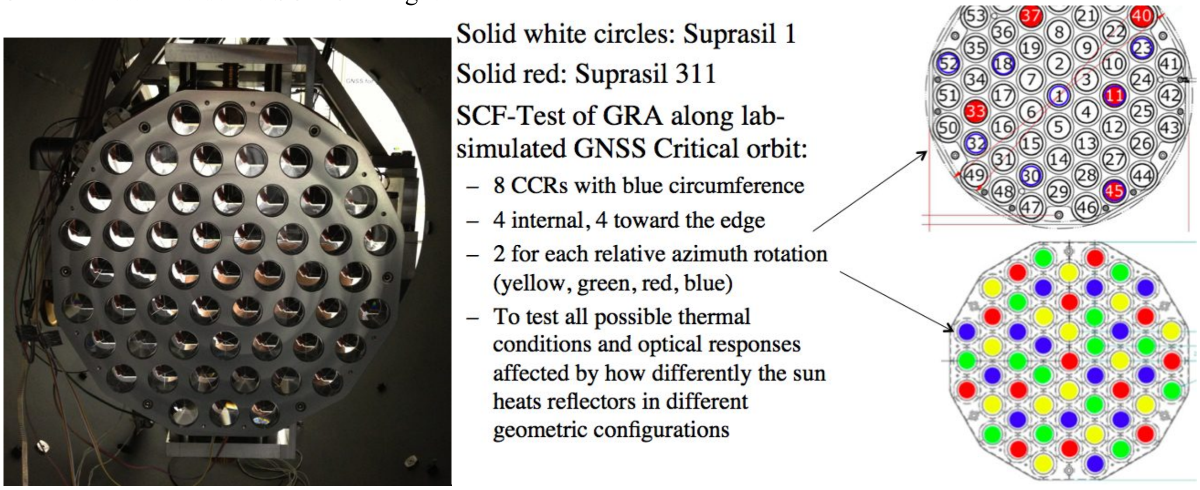


Fig. 6. Graphical sketch of describing conceptual deployment of INRRI in the Solar System.

IV. GNSS

Our work on GNSS with NASA, ASI, ESA and ISRO is consolidated and reported in [1] [2] [17].

Within the R&D ASI-INFN project dedicated to GNSS and to Galileo in particular, called ETRUSCO-2 (ETRUSCO = Extra Terrestrial laser Ranging to Unified gnss Satellite COnstellations, [2][17]) we designed, built and characterized a standard GRA using the consolidated fused silica retroreflector technology space-qualified first with Apollo LRAs and later with LAGEOS. Some of the criteria used in the GRA design are reported schematically in Fig. 7, right. Some of these are the ones endorsed by ILRS and reported in [1]. The GRA is shown inside the SCF-G in Fig. 7.


Solid white circles: Suprasil 1

Solid red: Suprasil 311

SCF-Test of GRA along lab-simulated GNSS Critical orbit:

- 8 CCRs with blue circumference
- 4 internal, 4 toward the edge
- 2 for each relative azimuth rotation (yellow, green, red, blue)
- To test all possible thermal conditions and optical responses affected by how differently the sun heats reflectors in different geometric configurations

Fig. 7. GRA (55 uncoated CCR) on the roto-translation, positioning and thermal control system in SCF-G.

The GRA has been characterized with the SCF-G, according to the procedures foreseen by the SCF-Test/Revision-ETRUSCO-2, which include investigation of the GRA optical performance and thermal behavior along the GNSS Critical Orbit, under exposure to the solar simulator illumination (Fig. 8, left, and [2] for more details). The GRA optical performance has been assessed in terms of FFDPs (Fig. 9) and WFIs of its CCRs. The thermal behavior has been determined with IR thermometry and contact probes (Fig. 8, right).

Spare Galileo IOV flight CCRs are under SCF-Test in Frascati (Fig. 11, left), under a dedicated ESA-INFN contract to be completed by the end of 2014. The 5th Galileo IOV flight-quality LRA (Fig. 11, right is currently in Frascati to be characterized in the framework of a joint ASI-INFN "*Premiale*" project funded by the Italian Ministry of Research. This project, called "Laser Ranging to Galileo", is described synthetically in Fig. 12.

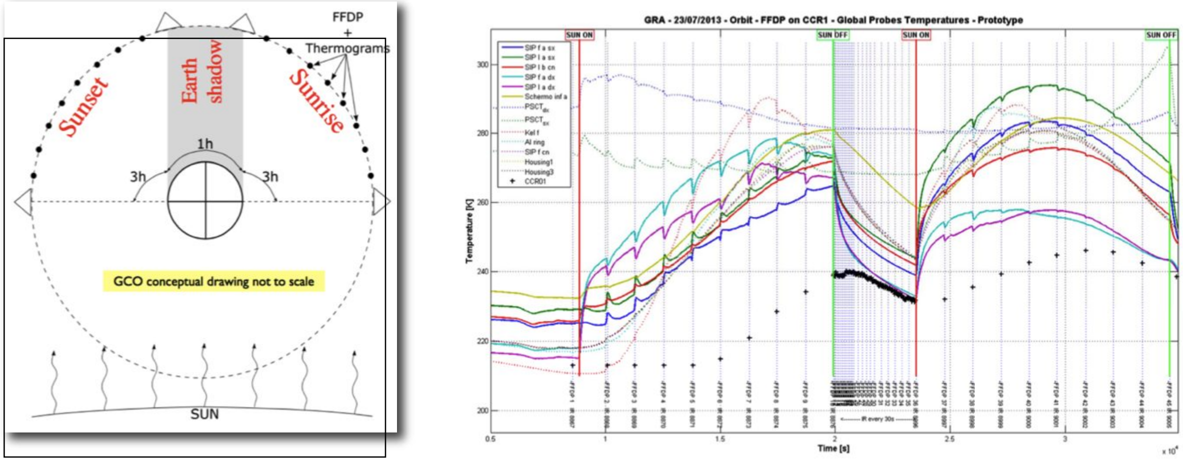


Fig. 8. Left: graphical sketch of GCO test. Right: thermal behavior of GRA during GCO SCF-Test.

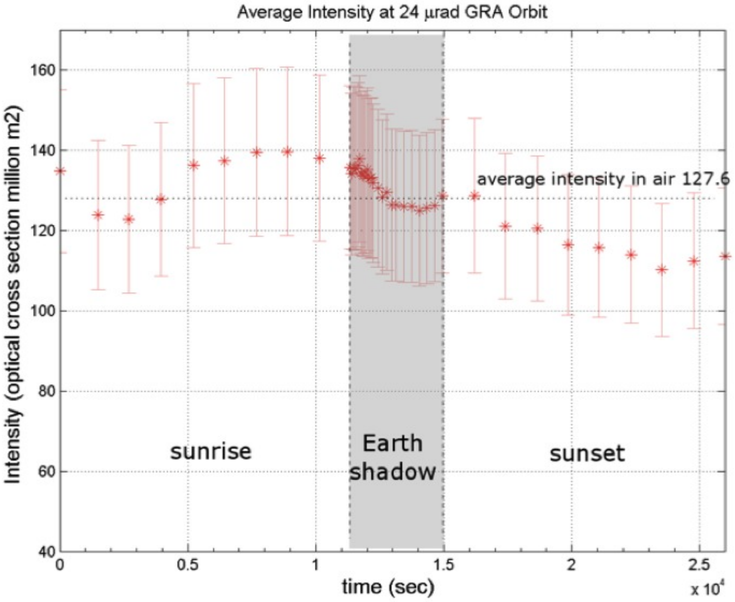


Fig. 9. FFDP intensity of GRA during GCO test compared to the nominal performance in air and isothermal conditions: the GRA developed by INFN shows on average no performance degradation under SCF-Test.

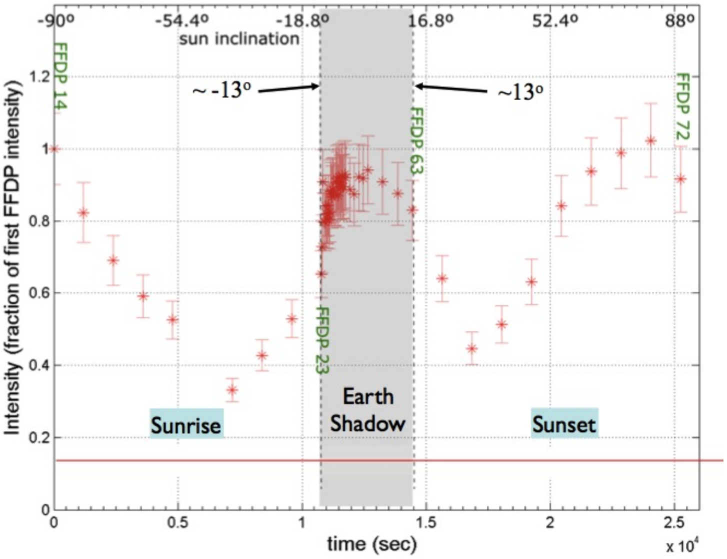


Fig. 10. FFDP intensity of a single Galileo IOV CCR during the GCO test of 2010 [2], showing on average a performance degradation by ~35%. The red line shows the GPS/GLONASS/GIOVE degradation by ~85% [1].

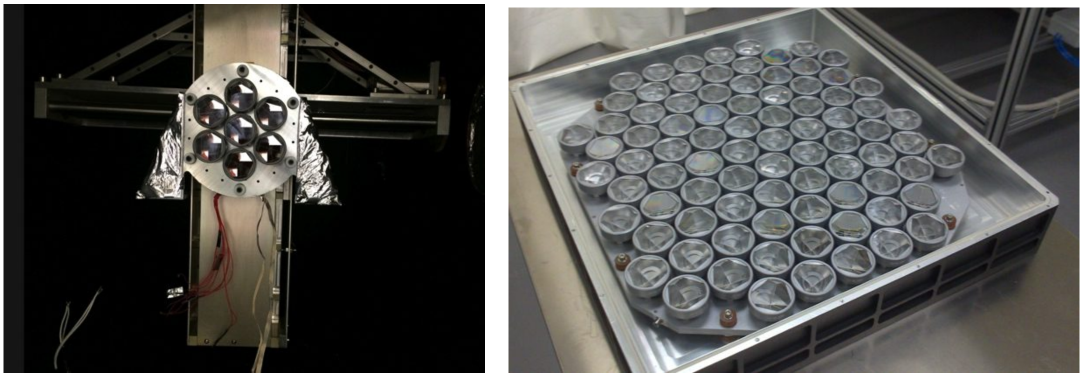
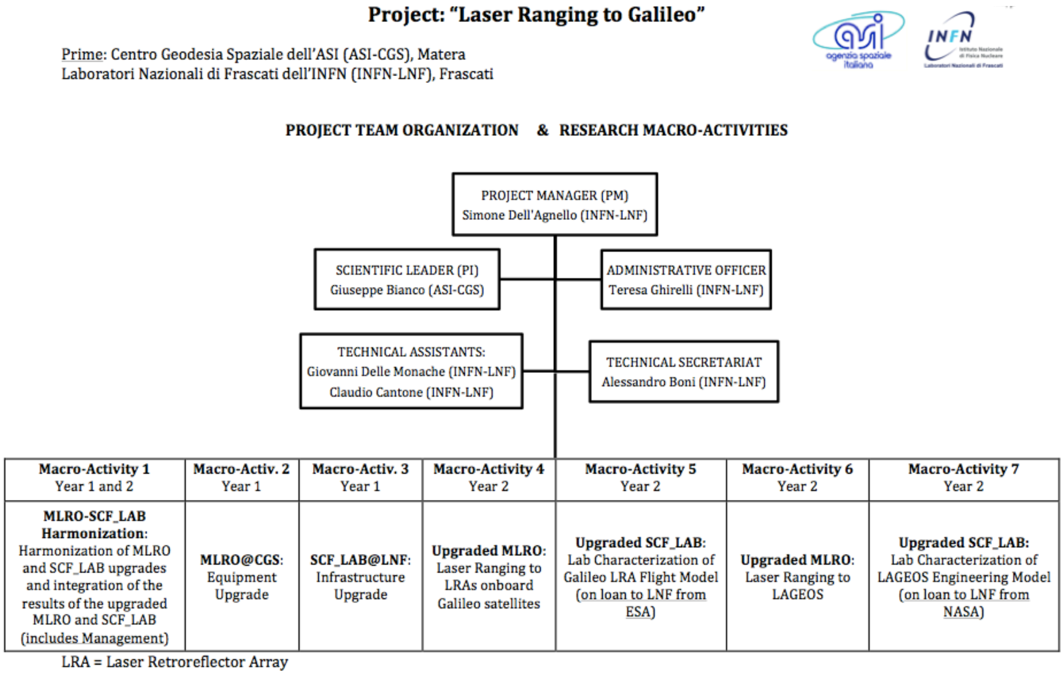


Fig. 11. GRA (55 uncoated CCR) on the roto-translation, positioning and thermal control system in SCF-G.



Project: "Laser Ranging to Galileo"

Prime: Centro Geodesia Spaziale dell'ASI (ASI-CGS), Matera
Laboratori Nazionali di Frascati dell'INFN (INFN-LNF), Frascati

PROJECT TEAM ORGANIZATION & RESEARCH MACRO-ACTIVITIES

PROJECT MANAGER (PM)
Simone Dell'Agnello (INFN-LNF)

SCIENTIFIC LEADER (PI)
Giuseppe Bianco (ASI-CGS)

ADMINISTRATIVE OFFICER
Teresa Ghirelli (INFN-LNF)

TECHNICAL ASSISTANTS:
Giovanni Delle Monache (INFN-LNF)
Claudio Cantone (INFN-LNF)

TECHNICAL SECRETARIAT
Alessandro Boni (INFN-LNF)

Macro-Activity 1 Year 1 and 2	**Macro-Activ. 2** Year 1	**Macro-Activ. 3** Year 1	**Macro-Activity 4** Year 2	**Macro-Activity 5** Year 2	**Macro-Activity 6** Year 2	**Macro-Activity 7** Year 2
MLRO-SCF_LAB Harmonization: Harmonization of MLRO and SCF_LAB upgrades and integration of the results of the upgraded MLRO and SCF_LAB (includes Management)	**MLRO@CGS**: Equipment Upgrade	**SCF_LAB@LNF**: Infrastructure Upgrade	**Upgraded MLRO**: Laser Ranging to LRAs onboard Galileo satellites	**Upgraded SCF_LAB**: Lab Characterization of Galileo LRA Flight Model (on loan to LNF from ESA)	**Upgraded MLRO**: Laser Ranging to LAGEOS	**Upgraded SCF_LAB**: Lab Characterization of LAGEOS Engineering Model (on loan to LNF from NASA)

LRA = Laser Retroreflector Array

Fig. 11. Activities and team of project "Laser Ranging to Galileo".

III. EARTH OBSERVATION

We are developing a midsize LRA suited for LEO and EO constellations like Cosmo-SkyMed, ESA Sentinels and, in general, for the space segment of Copernicus (European Flagship space program, also part of HORIZON2020). One model is shown in Fig. 4, which is one co-developed and co-studied by INFN and the Italian Ministry of Defence for Cosmo-SkyMed 2nd Generation and the Italian Ministry of Foreign Affairs (high-relevance Italy-USA bilateral project AUGUSTUS-2014, Absolute crUst, Glacier and icebergG Georeferencing with Unified Sar, optical, gnss laser observations by ITaly and USa – 2014).

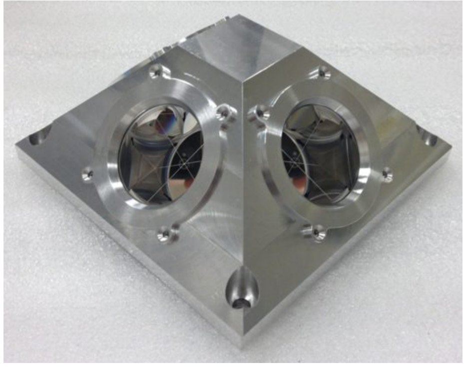


Fig. 4. Model of CORA.

CORA and/or appropriately adapted versions of CORA are suited for deployment as Phobos AND DeimOs laser Retroreflector Arrays (PANDORAs).

V. NATIONAL AND INTERNATIONAL FRAMEWORK

We work in strong synergism with the ground stations of ILRS, In particular with the Matera Laser Ranging Observatory in Italy, operated by ASI. We collaborate with NASA, ASI, ESA and ISRO. We are submitting proposals to Roscosmos and CNSA.

INFN has submitted a proposal for Affiliation to NASA-SSERVI (Solar System Exploration Research Virtual Institute) the research themes reported in this paper (with SDA as PI).

Some activities are carried out with co-funding (mentioned in the previous text) by the Italian Ministries of Research, Defence and Foreign Affairs.

Within INFN, this work is carried out in the INFN National Scientific Committees n. 2 (CSN2, including space science) and n .5 (including space technologies).

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