ETRUSCO-2 and SCF_LAB

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INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SCF_LAB
Satellite/Lunar/GNSS
laser ranging and altimetry
Characterization **F**acilities' **LAB**oratory

INTERNATIONAL TECHNICAL LASER WORKSHOP 2012 (ITLW-12)
ETRUSCO-2 WORKSHOP

NOVEMBER 7, 2012, INFN-LNF
Frascati (Rome), Italy

Outline

- ETRUSCO-2: ASI-INFN Project on Development and Test of SLR payloads for GNSS satellites
- SCF_LAB: Laboratory characterization of the space segment of laser ranging and altimetry to cube corner retroreflectors (CCRs)
  - **GNSS**
  - SLR
  - LLR
  - New: IR (1064 nm) laser altimetry
- Setting standards: SCF_LAB

ETRUSCO-2: ASI-INFN Program for GNSS

Optimized for Galileo and GPS-3

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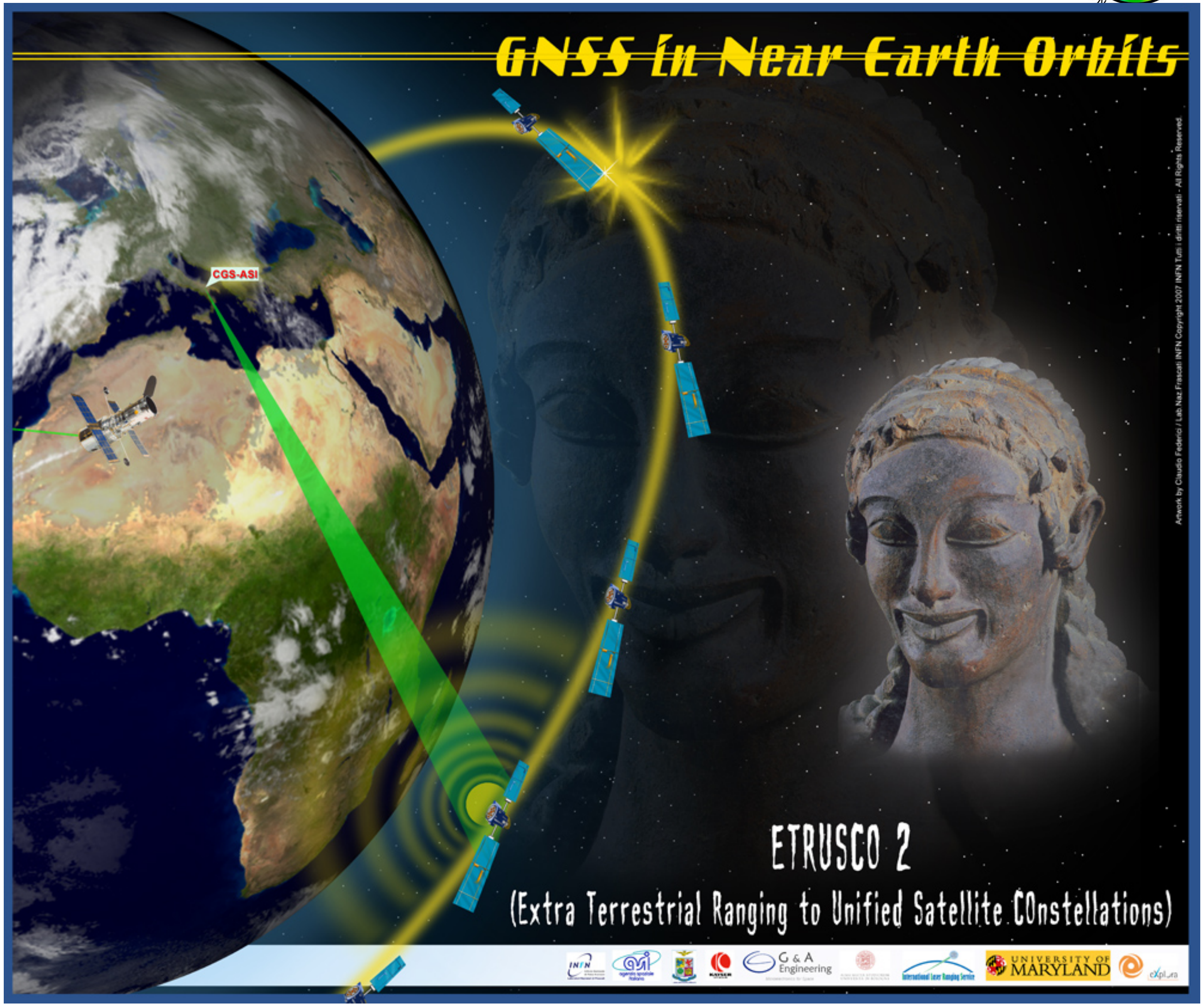
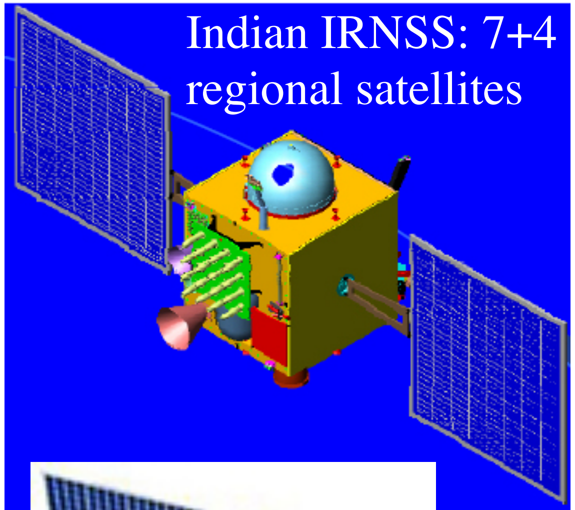
S. Dell'Agnello

Co-PIs:
R. Vittori, ESA
G. Bianco, ASI



Global Navigation Satellite System (GNSS)

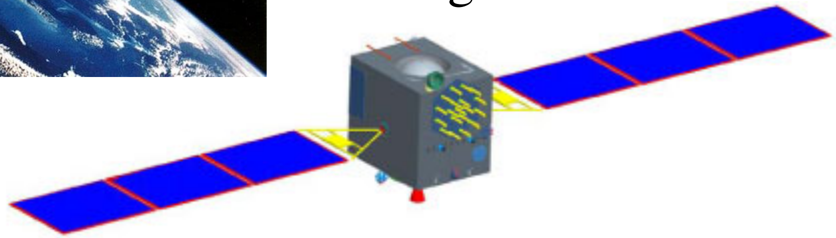
~100 satellites with laser retroreflectors (CCRs)



European Galileo:
30 satellites

Proposed SCF-Test of
IRNSS, Galileo IOV

Chinese COMPASS:
20 global and 5
regional satellites



Russian GLONASS:
24 global satellites

LRA characterization: Key Performance Indicators

- Accurately laboratory-simulated space conditions
  - Orbit/planetary surface environment
  - Orientation/attitude wrt laser interrogation and thermal (solar/albedo/IR) perturbation
  - Critical orbit configurations (worst-case thermal-optical behavior)
- Key Performance Indicators (KPIs) / Deliverables
  - **Thermal behavior (especially CCR thermal relaxation time)**
  - **Optical response**
    - **Far Field Diffraction Pattern (FFDP)**
    - **(Near Field) Wavefront Fizeau Interferogram (WFI), vibration insensitive, air-turbolence insensitive**
    - Also invariant Optical Cross Section in air/isothermal conditions
- Integrated thermal-optical simulations (upon request)

Note: reduced, partial, incomplete tests (compared to the realistic space environment) are randomly misleading (either optimistic or pessimistic)

ETRUSCO-2 @ SCF_LAB: an ASI-INFN Project of Technological Development and Test of SLR Payloads for GNSS Satellites

Contract ASI-INFN n. I/077/09/0

PI: S. Dell'Agnello (INFN-LNF)
Co-PIs: R. Vittori (ESA, AMI, INFN-LNF)
G. Bianco (ASI-CGS & ILRS)

SCF_LAB
Satellite/Lunar/GNSS laser ranging and altimetry Characterization Facilities' LABoratory

Prime Contractor:

INFN (Italian National Institute for Nuclear Physics)

Partners and National Collaborations:

ASI-CGS (G. Bianco et al)

University of Bologna (S. Zerbini)

G&A Engineering srl

Kayser Italia srl

Explora srl

Aeronautica Militare Italiana (AMI; R.Vittori)

International Collaborations:

Univ. of Maryland (UMD) (D. Currie at al)

International Laser Ranging Service (ILRS, M. Pearlman et al)

NASA-GSFC, (J. McGarry et al)

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International Technical Laser Workshop 2012 (ITLW-12) on

"Satellite, Lunar and Planetary Laser Ranging: Characterizing the Space Segment"

November 5-9, 2012

In conjunction with a one-day Workshop

"ASI-INFN ETRUSCO-2 Project of Technological Development and Test of SLR Payloads for GNSS Satellites"

November 7, 2012

Frascati National Laboratories of the INFN
Frascati (Rome), Italy

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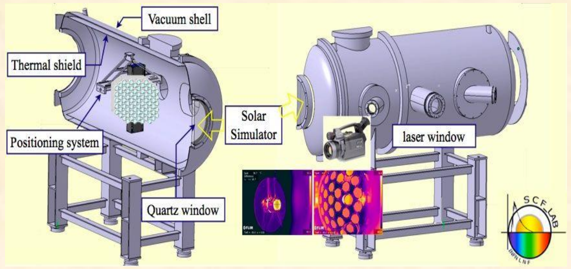
ETRUSCO-2

(Extra Terrestrial Ranging to Unified Satellite Constellations - 2)

- Background: continuation of ETRUSCO interdisciplinary R&D project of INFN (2006-09), dedicated to the characterization of Satellite Laser Ranging (SLR) of Cube Corner Retroreflectors (CCRs) for the Global Navigation Satellite System (GNSS).
- ETRUSCO2: Project of technological development (2010-13) in response to 2007 nation-wide call by ASI. Main goal: development and SCF-Test of GNSS Retroreflector Arrays, targeted to Galileo & GPS-3, open to other GNSS.

SCF: a Unique and Unprecedented OGSE (Optical Ground Support Equipment)

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 payloads under accurately laboratory-simulated space conditions produced with a close-match solar simulator. The SCF (Satellite/lunar/GNSS laser ranging and altimetry Characterization Facility) is a set of specialized instruments, which make possible the recreation of a realistic space environment around the tested CCRs and the concurrent monitoring of temperature variations of the tested payloads and of optical performance, in terms of FFDP and wavefront Interferogram. This new industry-standard space test is called SCF-Test, a background intellectual property of INFN [1].
The SCF is very versatile for its large number of measurement ports (side and back), very long horizontal translations and capabilities for lunar laser ranging (LLR) and laser altimetry CCR payloads.



Schematic view of SCF cryostat with: IR picture of the LAGEOS Sector, IR camera and SCF_LAB logo.

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Front and rear view of SCF cryostat. Optical instrumentation is in the black enclosure.

ETRUSCO-2 Work Program

- Definition of an improved and enhanced "**SCF-Test/Revision-ETRUSCO-2**"
  - Implementation of advanced and innovative operational procedures for the test of the "*GNSS Critical Orbit*" (**GCO**) developed for Galileo IOV [2]
  - Integration of the Wavefront Fizeau Interferometer (**WFI**)
- Design and construction of a 2nd OGSE optimized for GNSS constellations: **SCF-G**
  - Inherits from SCF, built in part by INFN and in part by SME (G&A Engineering) with INFN supervision and collaboration according to INFN Guidelines.
  - INFN part includes: state-of-art WFI insensitive to vibrations and air turbulence; 2nd, new Solar Simulator (SS).
- Integration of SCF-G with SCF_LAB infrastructure.
- Reduced-size prototype GNSS Retroreflector Array built with Hollow technology (**GRA-H**) according to INFN Guidelines
  - Inherits from R&D done with GSFC, built by SME (Kayser Italia) with INFN supervision and collaboration
  - 7 hollow CCRs, 6 on a ring and one in the center
  - Characterized with SCF and thermo-structural modeling
- Full-size prototype GNSS Retroreflector Array (**GRA**) for Galileo & GPS-3 built according to INFN Guidelines
  - Inherits from LAGEOS, built by SME (Kayser Italia) with INFN supervision and collaboration
  - 55 CCRs of solid retroreflector technology
  - To be characterized with the SCF-G according to the new SCF-Test/Revision-ETRUSCO-2
- Space geodesy study on the SLR of GNSS and gravitational redshift study with the SLR of Galileo with ASI-GCS and the University of Bologna.

SCF-G: 2nd OGSE Facility for GNSS

Based on the experience made with the SCF, we designed and built the "Satellite laser ranging Characterization Facility optimized for Galileo and the GPS-3", SCF-G, which is operative in the same Clean Room infrastructure of INFN, the SCF_LAB.

Front and rear view of the SCF-G cryostat.

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INFN-LNF logo, SCF_LAB acronym and logo in plaque-style.

In 2011 INFN-LNF, to provide a dedicated infrastructure, has completed the construction of a new Clean Room of class 10,000 (ISO 7) or better of about 85 m^2, kept at an isothermal temperature of about 21°C, which hosts both OGSEs.

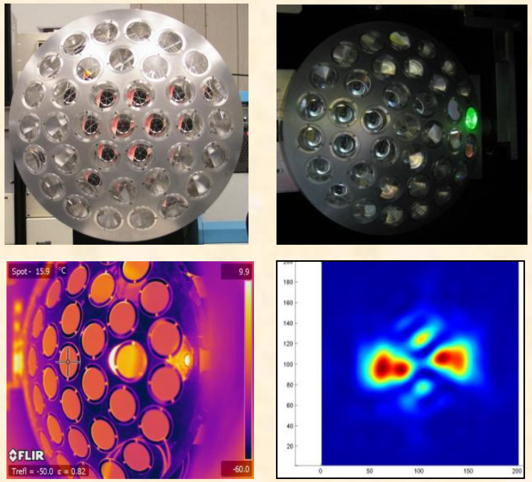
SCF_LAB ISO 7 Clean Room.

The primary goal of these unique OGSEs is to provide critical diagnostic, optimization and validation tools for SLR to all GNSS programs. The capability will allow us to optimize GRA (GNSS laser Retroreflector Arrays) designs to maximize ranging efficiency, to improve signal-to-noise conditions in daylight, to provide pre-launch validation of retroreflector performance under accurately laboratory simulated space conditions, as well as to characterize 'as-built' payloads.

Some young people of the SCF_LAB Team.

LAGEOS Sector

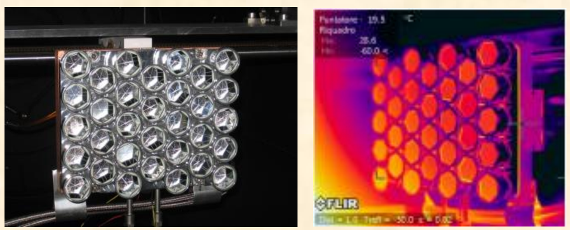
Uncoated retroreflectors are deployed on the SLR reference payload standard of the ILRS: LAGEOS (LAser GEOdynamics Satellite). Similarly, the uncoated Apollo CCRs are the reference standard for LLR. Uncoated retroreflectors with properly insulated mounting (like Apollo and LAGEOS) can minimize thermal degradation and significantly increase optical performance and, as such, are emerging as the recommended design for GNSS satellites. Therefore, in order to "calibrate" our SCF-Test, we tested in 2009 an engineering model of the LAGEOS satellite, lent by NASA-GSFC. LAGEOS is a satellite designed by NASA and launched in 1976. It is a passive sphere with a diameter of 60 cm, mainly made of Aluminum, covered by 426 uncoated CCRs. Since its launch the satellite provided important information on Earth's shape, gravitational field and tectonic plate movements, but, most important, due to its high mass-to-area ratio and orbit stability, it gives a reference for the Earth's center of mass (geocenter), along with other cannonball SLR targets.



LAGEOS Sector: at GSFC (top left); in the SCF, controlled in temperature by an interface Cu plate, with laser illuminating one CCR (top right); IR thermogram (bottom left); CCR FFDP in velocity aberration plane in microrad units (bottom right).

GPS-2 Laser Retroreflector Array (LRA)

A flight model LRA of the GPS-2 constellation was lent by the University of Maryland to INFN-LNF for SCF-Testing and to measure its nominal optical ('lidar') cross section [1]. It is a rectangular array of 32 CCRs positioned on an aluminum tray of 239 mm length, 194 mm width and 1.27 kg weight.



Third GPS flight array inside the SCF (left) and an IR thermogram taken during Solar Simulator illumination (right).

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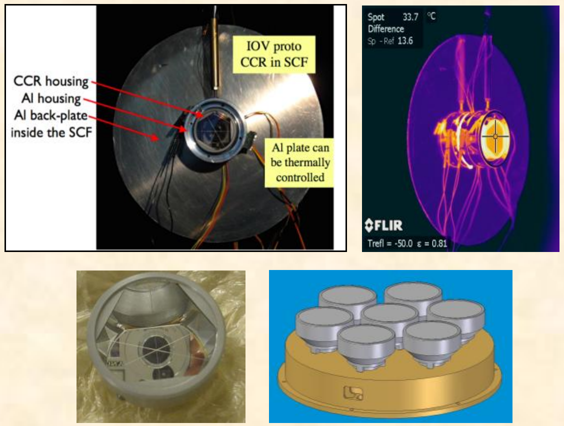
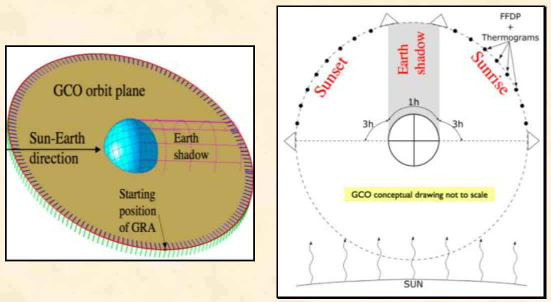
Galileo IOV Retroreflector

In 2010 INFN performed an extensive SCF-Test campaign requested by ESA on a prototype Galileo IOV retroreflector. This is a fused silica uncoated CCRs, deployed in planar arrays of 84 units.



Galileo IOV CCR: front view (bottom left); setup inside SCF for GCO test (top left); IR thermogram (top left). IOV engineering model LRA built by LNF for further SCF-Testing (bottom right).

We refined the SCF-Test introducing the GCO (GNSS Critical Orbit). Galileo satellites have a quasi-circular orbit with orbital period of about 14 hrs. We simulated half of the orbit, from the moment in which sunrays rise above the CCR front face till they fall on the other side for about 7 hrs. SCF-Test results are in [2].



GNSS Critical Orbit (GCO) in space (left); GCO SCF-Test concept with measurement sequence & Solar Simulator illumination (right).

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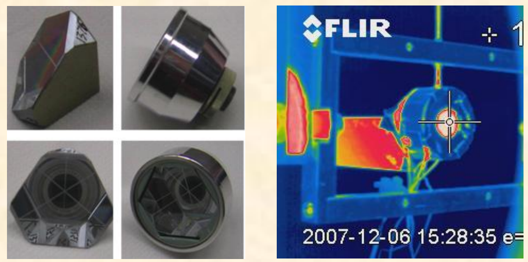
GLONASS Retroreflector

In 2007 and 2008 we SCF-Tested retroreflectors originally adopted by GLONASS. They are Al back-coated CCRs, with hexagonal front face of ~26mm of inscribed circle diameter. The CCR is inserted into a polished Aluminum housing screwed into the Aluminum baseplate of the LRA. LRAs of 32 GLONASS-type CCRs (identical to the flight LRA characterized at the SCF_LAB) were deployed on the GPS-35 and GPS-36 satellites. GLONASS LRAs were deployed also on GIOVE-A and GIOVE-B.

SCF-Test results reported in [1] have shown that the GLONASS suffers from sever degradation of the optical performance when operated in space conditions. From GLONASS-115 this Al back-coated CCR has been abandoned by modern GNSS (including Galileo IOV) in favour of uncoated CCRs.



Old generation GLONASS/GPS/GIOVE CCR: bare and mounted in its Al housing (left); IR thermogram during SS illumination (right).

GRA-H

To verify the readiness of hollow retroreflectors for LRAs, we deigned and built the GRA-H as a prototype of reduced size, made of 7 hollow CCRs of 38.1 mm (1.5") optical clear aperture, purchased from PLX, Inc. Due to ITAR restrictions, only CCRs with zero values of the dihedral angle offsets were available for the ETRUSCO-2 project. All CCRs have reflecting faces made of a Pyrex substrate coated with a high reflectivity film. Two sets of retroreflectors were procured, with Aluminum and Silver coatings. An Invar foot mount holds one of the reflecting faces onto which the others are glued. The GRA-H has been extensively characterized with the SCF and the results reported at the ITLW-12 and ETRUSCO-2 workshops.

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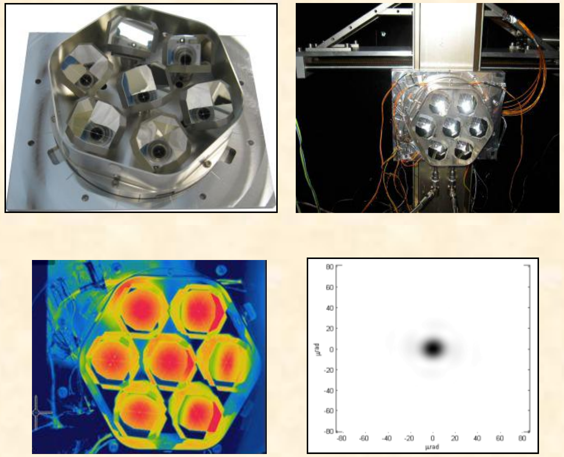
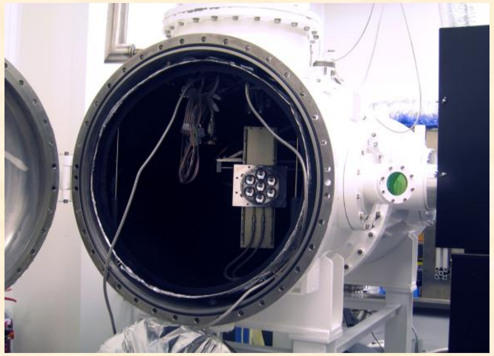


GRA-H fully assembled (top left), inside the SCF with PT100 temperature probe on each retroreflector (top right); IR picture during SS illumination (bottom left); FFDP of one of its CCRs.



GRA-H installed on the roto-translation positioning and thermal control system in the SCF (IR window in green color on the right).

GRA

Since the performance of the GRA-H hollow retroreflectors was not found satisfactory, as foreseen by the ETRUSCO-2 project guidelines, we designed and built the 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 the ones endorsed by ILRS and reported in [1].

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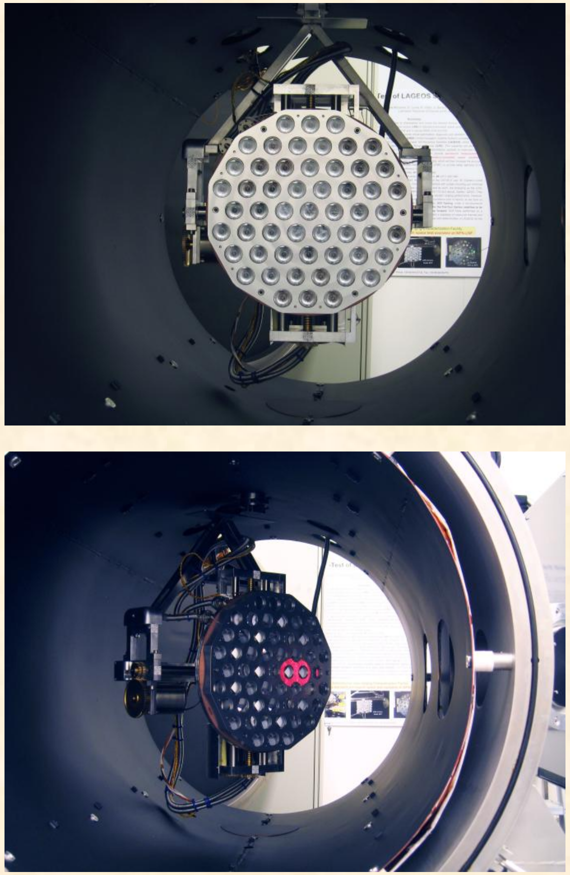

GRA (with the majority of its CCRs mounted) installed on the roto-translation positioning and thermal control system inside the SCF-G (top); GRA CCRs illuminated by external laser interrogation beam (bottom).

The GRA will be 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. The GRA optical performance will be assessed in terms of FFDPs and of the WFIs of its retroreflectors. The thermal behavior will determined with IR thermometry and contact probes.

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Appendix

Milestones and Background Intellectual Properties, which paved the way for ETRUSCO-2

- 2005-06: Approval of the ETRUSCO interdisciplinary Project by INFN-LNF and by INFN-CSN5 (**Commissione Scientifica Nazionale 5**) and construction of SCF
- 2006-07: Development of SCF-Test
- 2007-08: SCF-Test of GPS-2 flight LRA and of GLONASS/GIOVE CCR prototypes
- 2008: Formal industrial optical acceptance test of 110 flight LARES CCRs for ASI (in isothermal conditions; no SCF-Test)
- 2009: SCF-Test of the NASA-GSFC LAGEOS Sector
- 2010: SCF-Test of the NASA-GSFC hollow CCR.

First-ever SCF-Tests of

- ***GPS-2*** retroreflector array flight model property of UMD
- ***GLONASS*** and Galileo's GIOVE-A and -B CCR prototypes
- ***LAGEOS Sector*** engineering model property of NASA-GSFC
- ***Hollow*** retroreflector prototype provided by GSFC
- ***Galileo IOV*** retroreflector prototype property of ESA
- ***MoonLIGHT*** New generation LLR retroreflector developed for NASA projects (led by UMD) and for INFN projects (led by LNF).

Main References

[1] Dell'Agnello, S., et al, *Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS*, J. Adv. Space Res. 47 (2011) 822–842. Galileo Special Issue on *Scientific Applications of Galileo and other Global Navigation Satellite Systems – II*, March 1, 2011, pub. Proc. of "2nd International Colloquium – Scientific and Fundamental Aspects of the Galileo Programme", Padua, September 2009. See also: http://ilrs.gsfc.nasa.gov/about/reports/other_publications.html.

[2] S. Dell'Agnello et al., *ETRUSCO-2, an ASI-INFN Project for the development and SCF-Test of GNSS laser retroreflector arrays*, ESA proceedings of ESA "3rd International Colloquium – Scientific and Fundamental Aspects of the Galileo Programme", Copenhagen, Aug. 31 - Sep. 2, 2011. See also: http://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/ga01_reflector.html.

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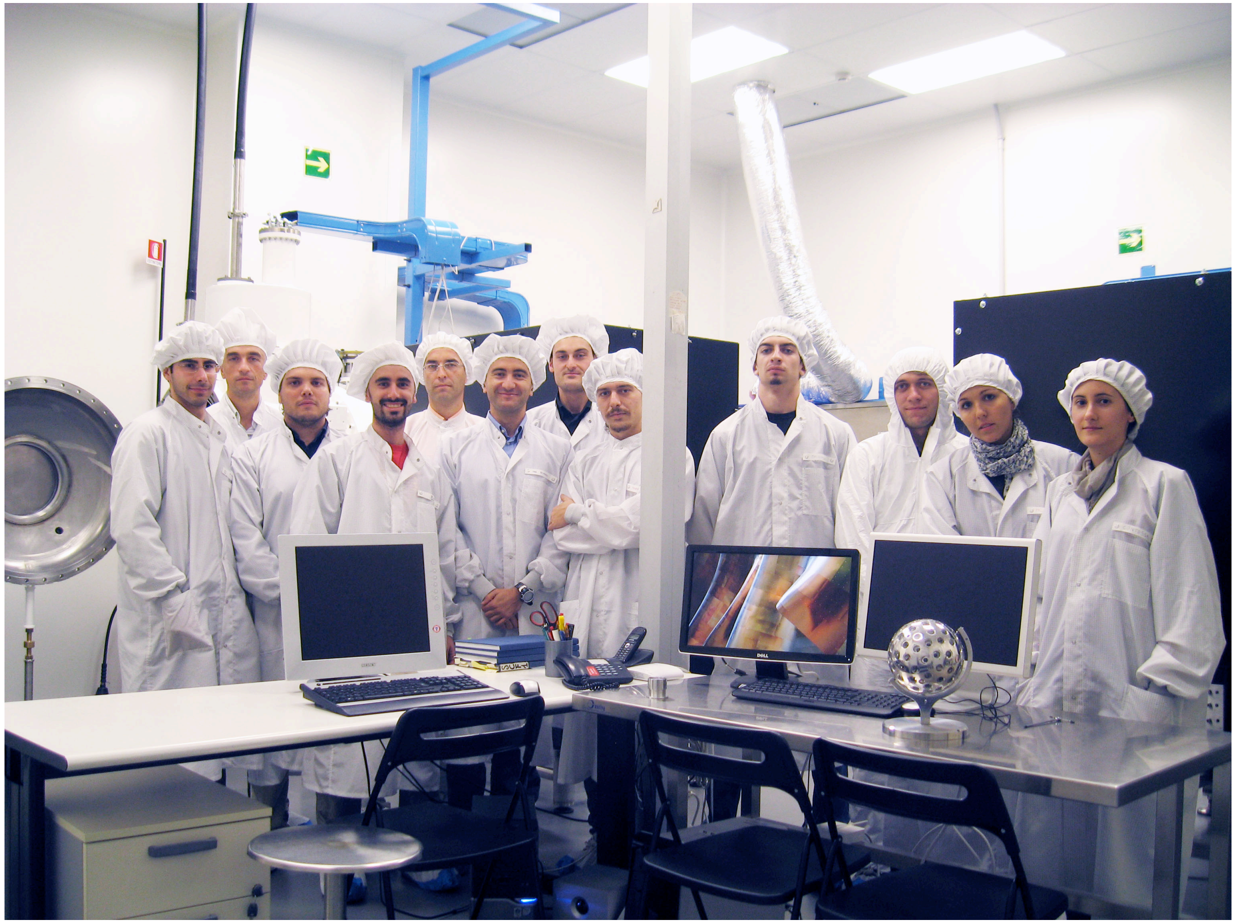
Setting standards: SCF_LAB

SCF_LAB

Satellite/Lunar/GNSS laser ranging and altimetry Characterization Facilities' LABoratory



Main Reference Documents

- [RD-1] Dell'Agnello, S., et al, **Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS**, J. Adv. Space Res. **47** (2011) 822–842.
- [RD-2] P. Willis, Preface, Scientific applications of Galileo and other Global Navigation Satellite Systems (II), J. Adv. Space Res., **47** (2011) 769.
- [RD-3] D. Currie, S. Dell'Agnello, G. Delle Monache, **A Lunar Laser Ranging Array for the 21st Century**, Acta Astron. **68** (2011) 667-680.
- [RD-4] Dell'Agnello, S., et al, Fundamental physics and absolute positioning metrology with the MAGIA lunar orbiter, Exp Astron, October 2011, Volume 32, Issue 1, pp 19-35 ASI Phase A study.
- [RD-5] Dell'Agnello, S. et al, **A Lunar Laser Ranging Retro-Reflector Array for NASA's Manned Landings, the International Lunar Network and the Proposed ASI Lunar Mission MAGIA**, Proceedings of the 16th International Workshop on Laser Ranging, Space Research Centre, Polish Academy of Sciences Warsaw, Poland, 2008.
- [RD-6] International Lunar Network (http://iln.arc.nasa.gov/), Core Instrument and Communications Working Group Final Reports.
- [RD-7] Yi Mao, Max Tegmark, Alan H. Guth, and Serkan Cabi, Constraining torsion with Gravity Probe B, Physical Review D **76,** 104029 (2007).
- [RD-8] March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., **Constraining spacetime torsion with the Moon and Mercury**, Physical Review D **83**, 104008 (2011).
- [RD-9] March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., **Constraining spacetime torsion with LAGEOS**, Gen Relativ Gravit (2011) 43:3099–3126.
- [RD-10] **ETRUSCO-2: An ASI-INFN project of technological development and "SCF-Test" of GNSS Laser Retroreflector Arrays**, S, Dell'Agnello, 3rd International Colloquium on on Scientific and Fundamental Aspects of the Galileo Programme, Copenhagen, Denmark, August 2011.

Laser Retroreflector Arrays (LRAs)