SCF_Lab: Infrastructure and Satellite Laser Ranging

C. Cantone for the SCF_Lab Team

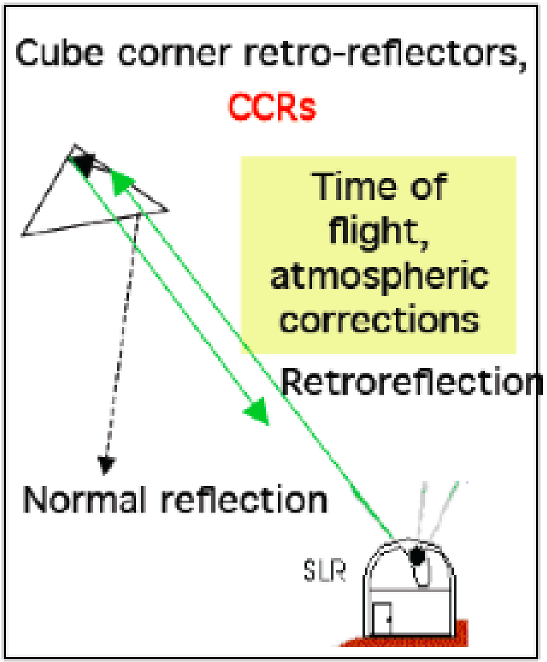
Laser, Synchrotron Radiation and Particle Beam Test Facilities at LNF

Outline

- Satellite Laser Ranging
- CCR and FFDP
- SLR applications
- SCF_Lab
- ETRUSCO-2 and Galileo IOV
- SCF-Test Revision ETRUSCO-2
- Conclusions

Satellite Laser Ranging

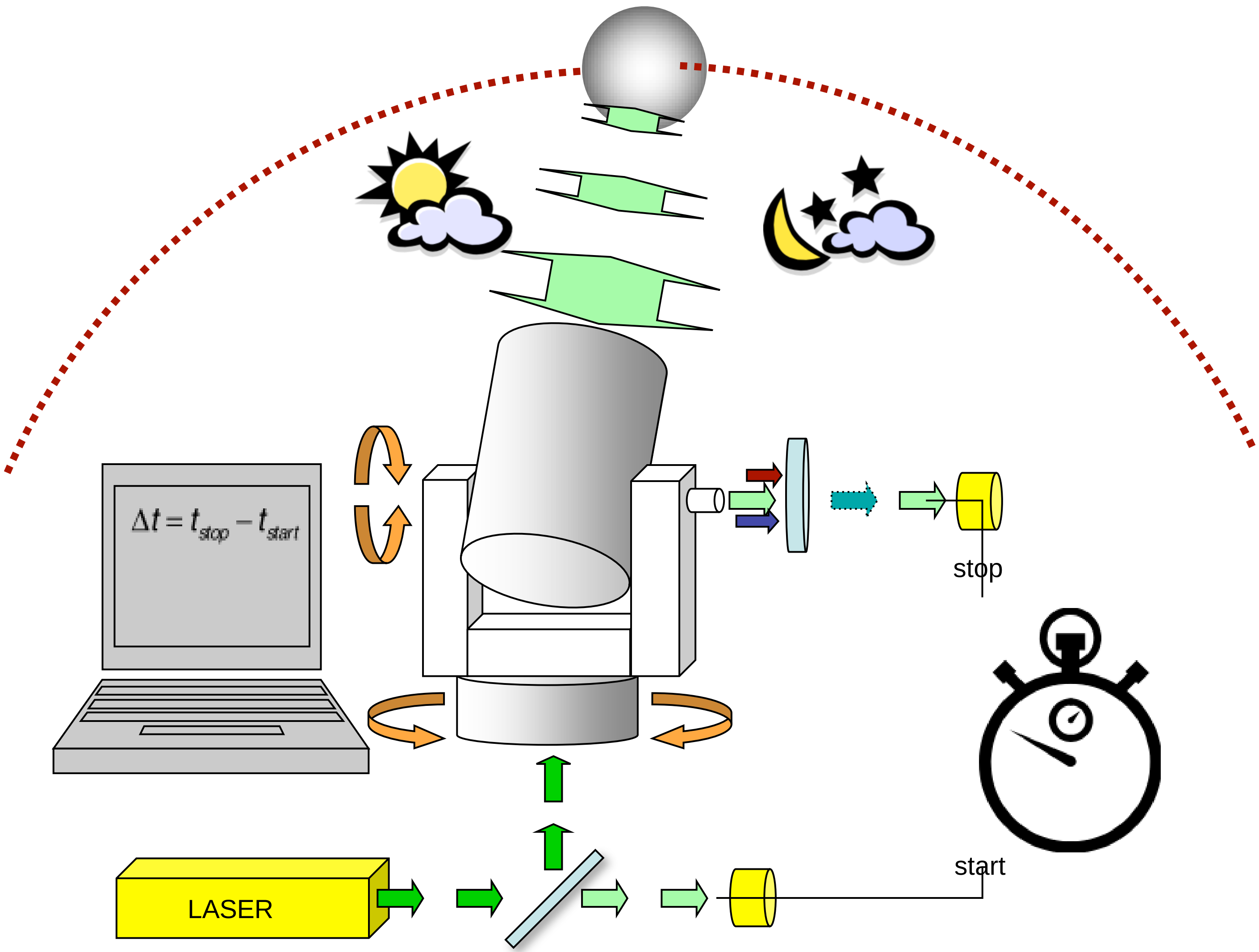
Satellite Laser Ranging (SLR)
Lunar Laser Ranging (LLR)
Time of flight measurements



Greenbelt (MD) SLR station

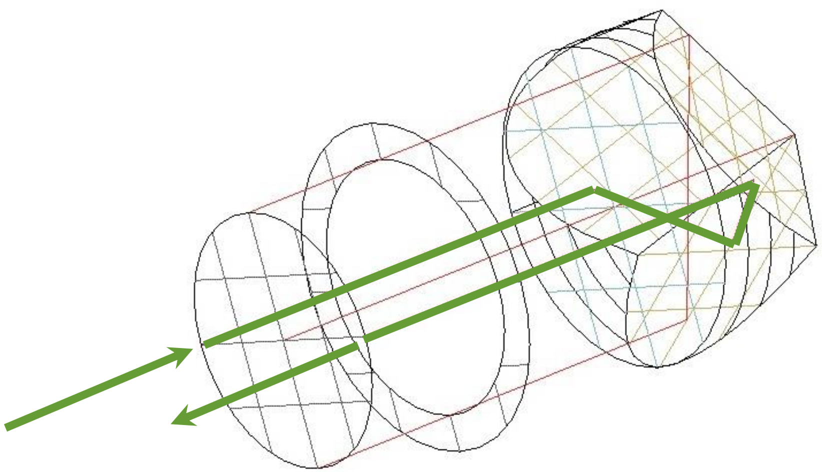
The most precise and cost effective distance measurement in space
(few millimeters to few centimeters) and (100K€ to M€)
Laser interferometry much more precise but much more expensive/difficult

Ranging technique



Corner Cube Reflector

- A CCR is a prism, usually made of Fused Silica, whose vertex is a corner of a cube. Each one of the back faces has an angle of 90° with another.
- A ray entering the CCR is retroreflected along the same direction.
- A ray entering the CCR, comes out in a point opposite to the origin.

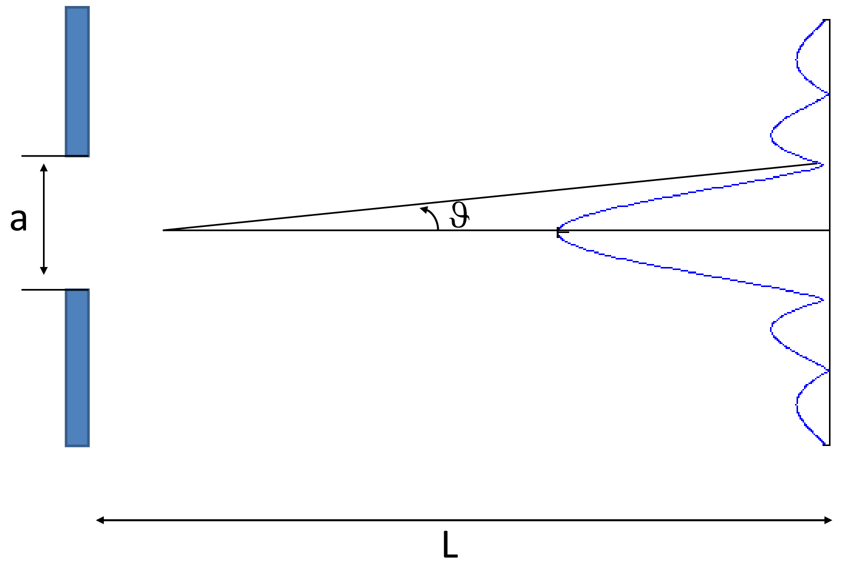


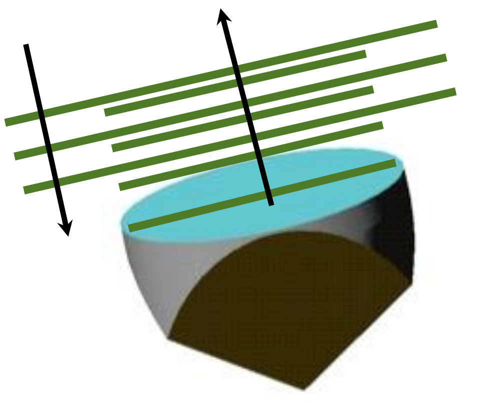
reflection on the three back surfaces through total internal reflection

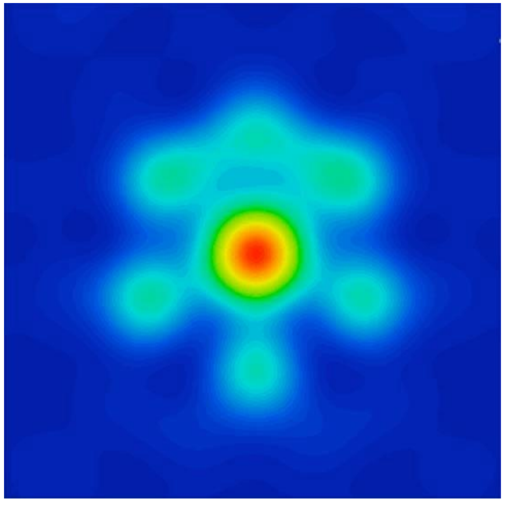
Far Field Diffraction Pattern

Diffraction is a phenomenon that occurs when a wave passes through an obstacle or a limited portion of space. On a distant screen a plane wave will result to have a known intensity variation.

$$L \gg \frac{a^2}{\lambda} \qquad \sin\theta_{min} = \pm\frac{\lambda}{a}$$





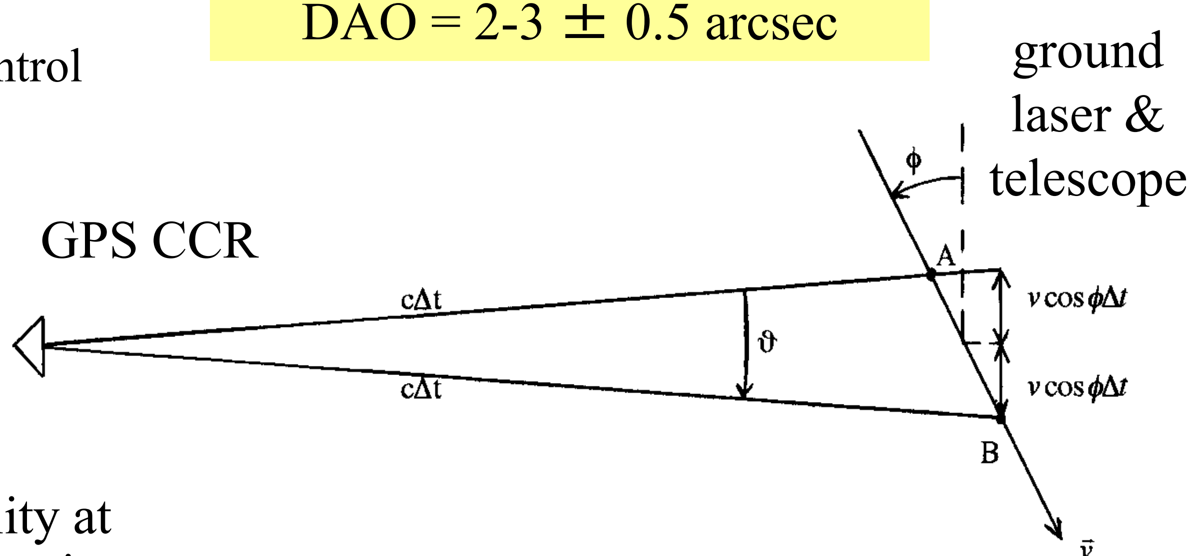


Why a thermal and optical test "in space"?

- **Thermal perturbations by SUN / EARTH.** T gradients across CCR ==> gradients of index of refraction, *dn/dT*, which cause some degradation of far field diffraction pattern
- **Velocity aberration**. Relative station-satellite velocity requires non-zero dihedral angle offsets (DAO) w/0.5 arcsec accuracy

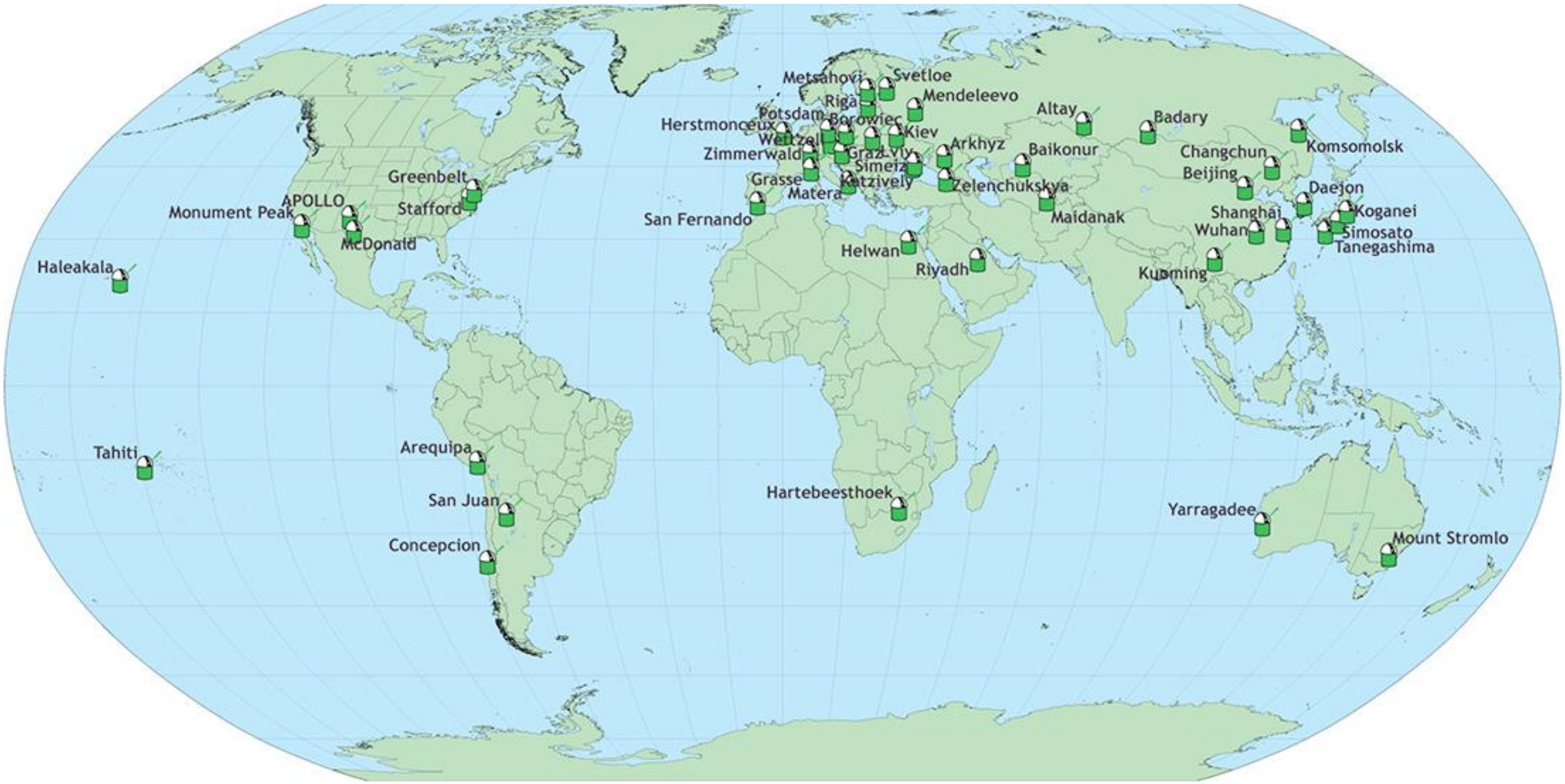
> GPS velocity aberration:
> $\theta \sim 2$ v/c $\cos\phi \sim 25$ microrad
> $\theta \times$ altitude ~ 500 m
> DAO = 2-3 $\pm$ 0.5 arcsec

- **Design** GRA payload to control dn/dT effect on FFDP



- **SCF-Test**
  - Check DAO at STP
  - SCF, new space facility at INFN-LNF to characterize space performance

International Laser Ranging Service



A network of about 40 ground stations routinely track satellites equipped with retroreflectors and give information about their orbit. 4 stations in the world track the Moon

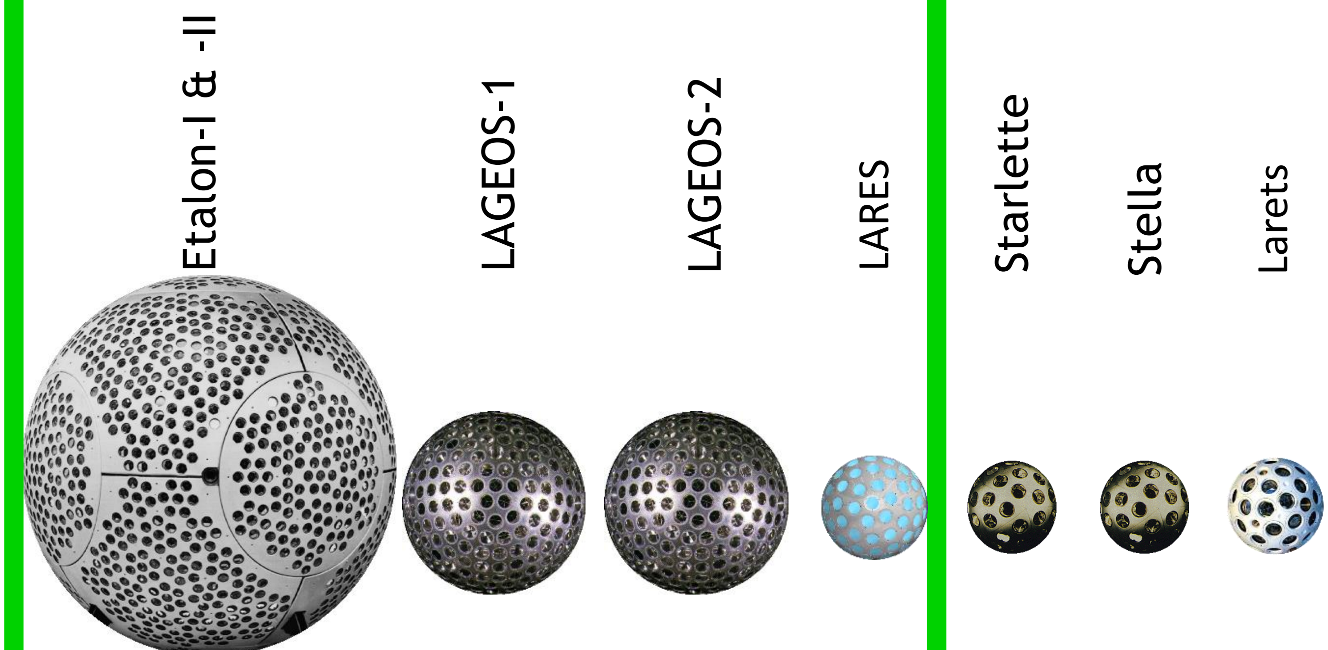
Matera Laser Ranging Station

MLRO

Geodetic satellites

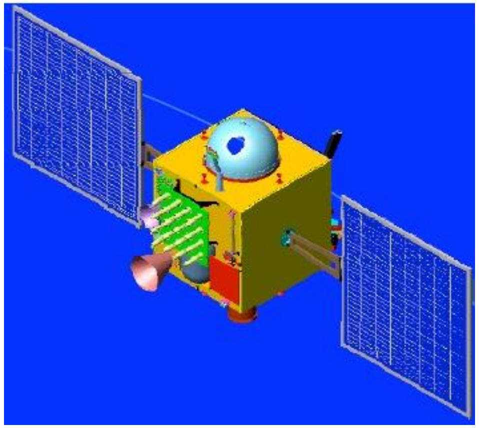
(Earth geocenter and Inertial frame)

ITRF Constellation



	Etalon-I & -II	LAGEOS-1	LAGEOS-2	LARES	Starlette	Stella	Larets
Inclination	64.8°	109.9°	52.6°	69.5°	50°	98.6°	98.2°
Perigee ht. (km)	19,120	5,860	5,620	1450	810	800	691
Diameter (cm)	129.4	60	60	36	24	24	24
Mass (kg)	1415	407	405.4	387	47.3	47.3	23.3

SLR on GNSS



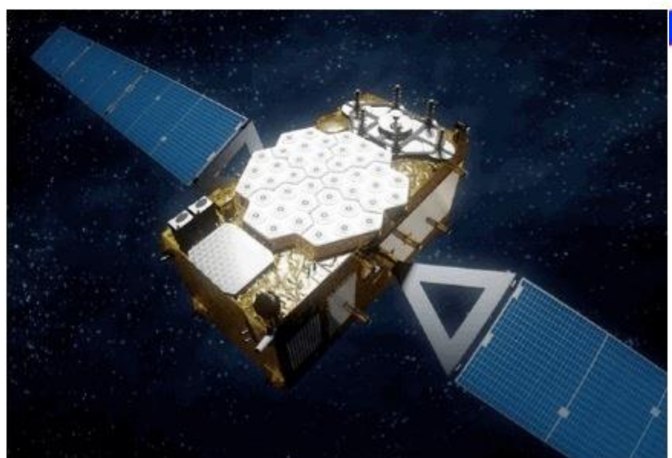
Indian IRNSS: 7 regional satellites

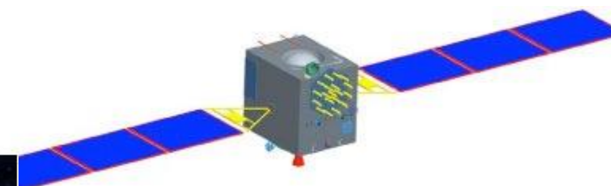
American GPS: 24 global satellites

Japanese QZSS: 3 regional satellites

Russian GLONASS: 24 global satellites

European Galileo: 30 global satellites





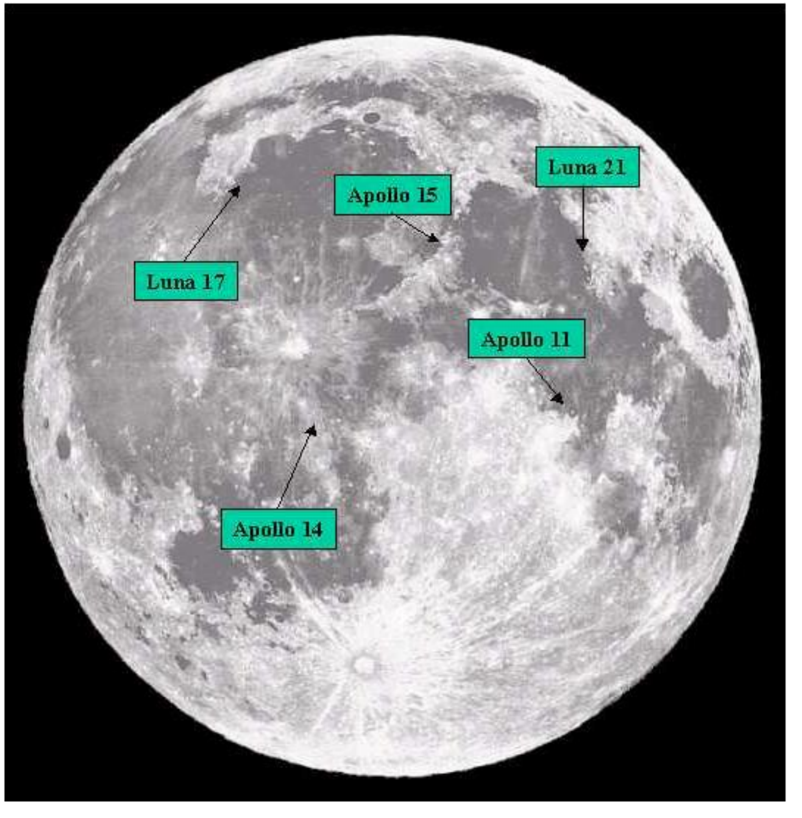
Chinese COMPASS: 30 global and 5 regional satellites

Ranging to the Moon

Lunar Laser Ranging: ToF/orbit at 2 cm ~ $5 \cdot 10^{-11}$ of Earth-Moon distance

Relative sizes and separation of the Earth–Moon. LLR tof ~ 2.6 sec (2-way)

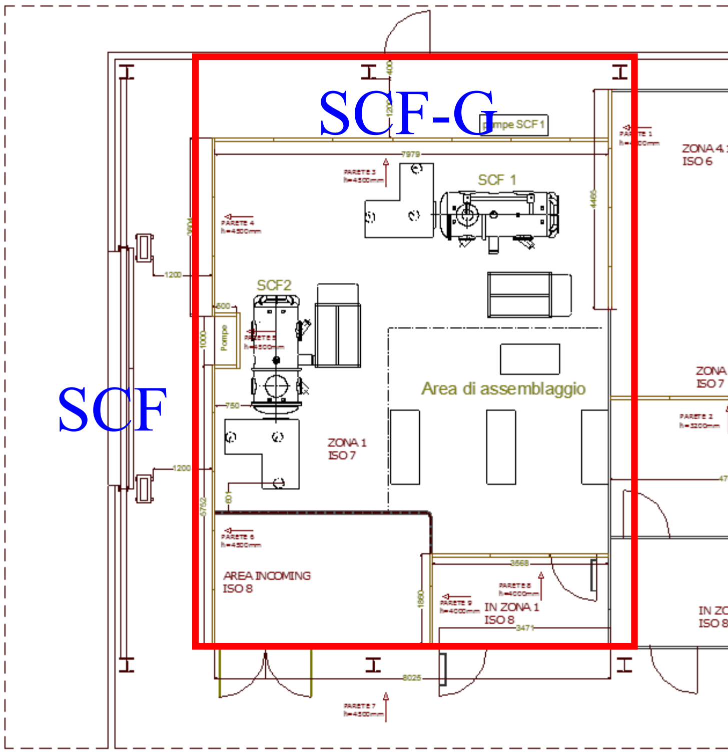
Locations
of 1st Generation
LLR Arrays



ILRS data applications

- Co-determination, with other space geodetic techniques, of the International Terrestrial Reference Frame (ITRF)
- Monitoring three dimensional deformations of the solid Earth
- Monitoring Earth rotation and polar motion
- Support the monitoring of variations in the topography and volume of the liquid Earth (ocean circulation, mean sea level, ice sheet thickness, wave heights, etc.)
- Tidally generated variations in atmospheric mass distribution
- Gravitational and general relativistic studies including Einstein's Equivalence Principle, and time rate of change of the gravitational constant, G
- Lunar physics including the dissipation of rotational energy, shape of the core-mantle boundary and free librations

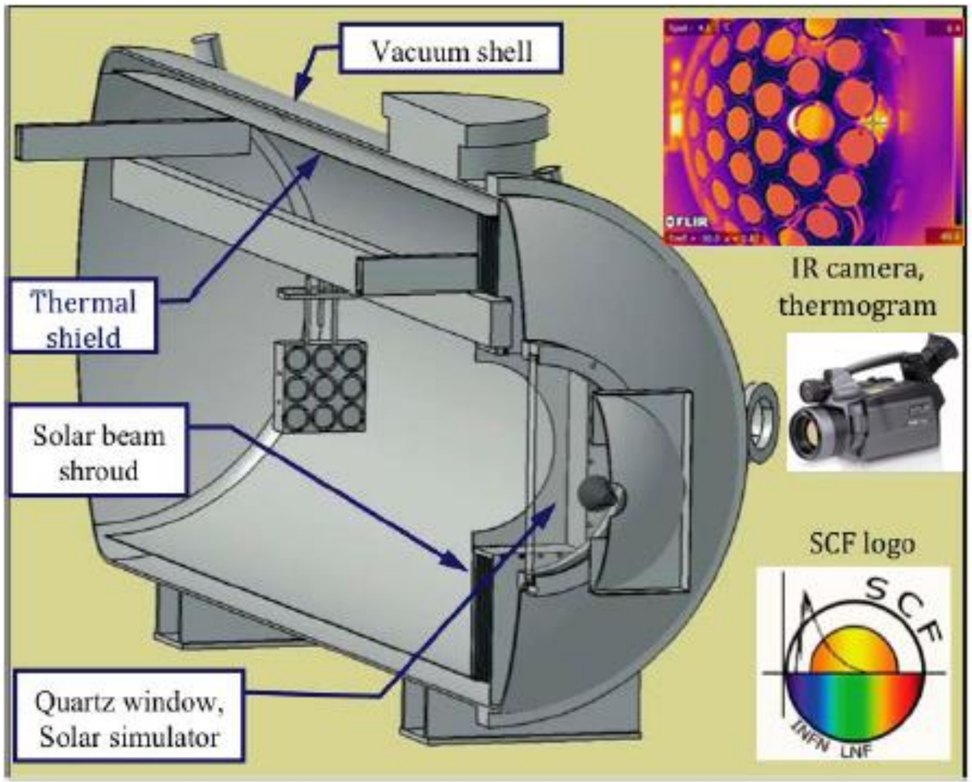
SCF_LAB Clean Room



SCF_Lab ~ 85 m^2
cleaning class 10000
or better

SCF_LAB @INFN-LNF

Two unique OGSEs (Optical Ground Support Equipment) facilities in a clean room to characterize the space segment of laser ranging altimetry



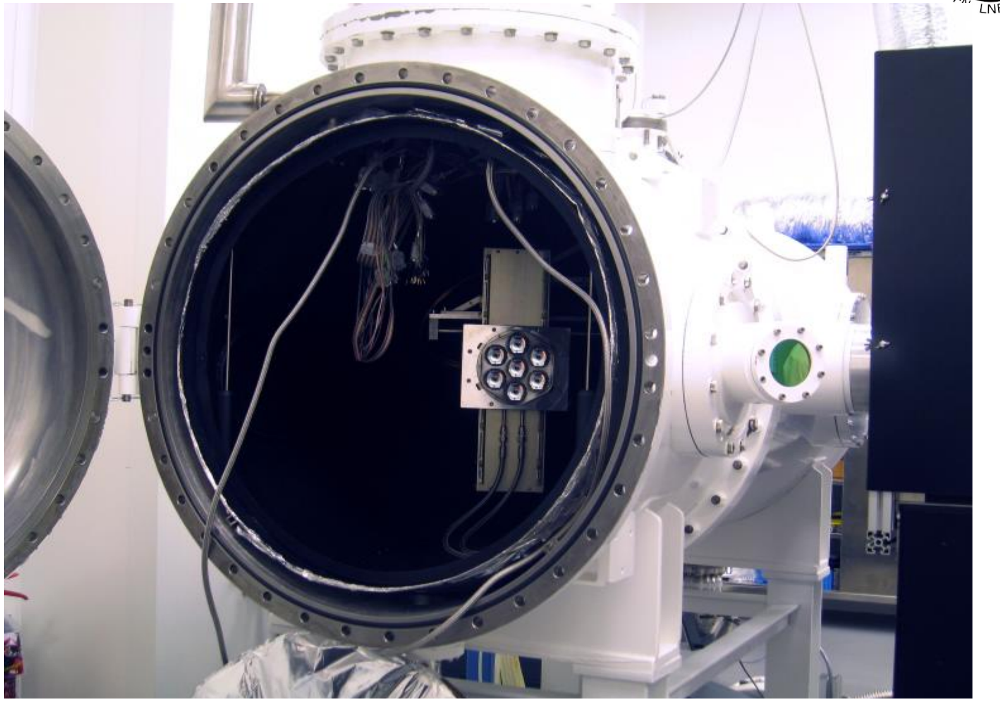
SCF for SLR/LLR/ Altimetry

SCF-G for GNSS

SCF-G

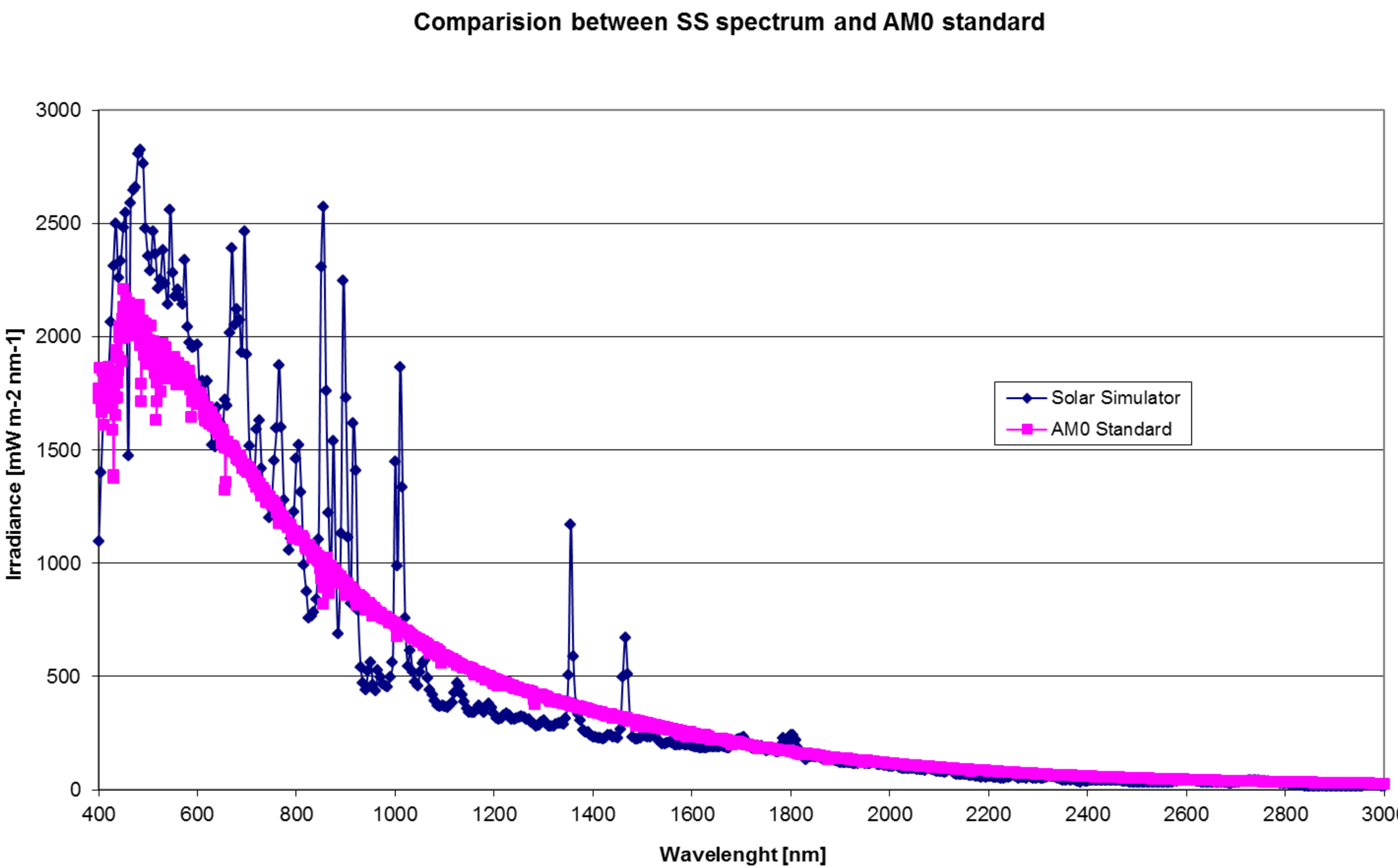
- Solar quartz window
- IR Germanium window
- Laser quartz window

SCF



- Solar quartz window
- 2 IR Germanium windows
- Laser quartz window
- Back port

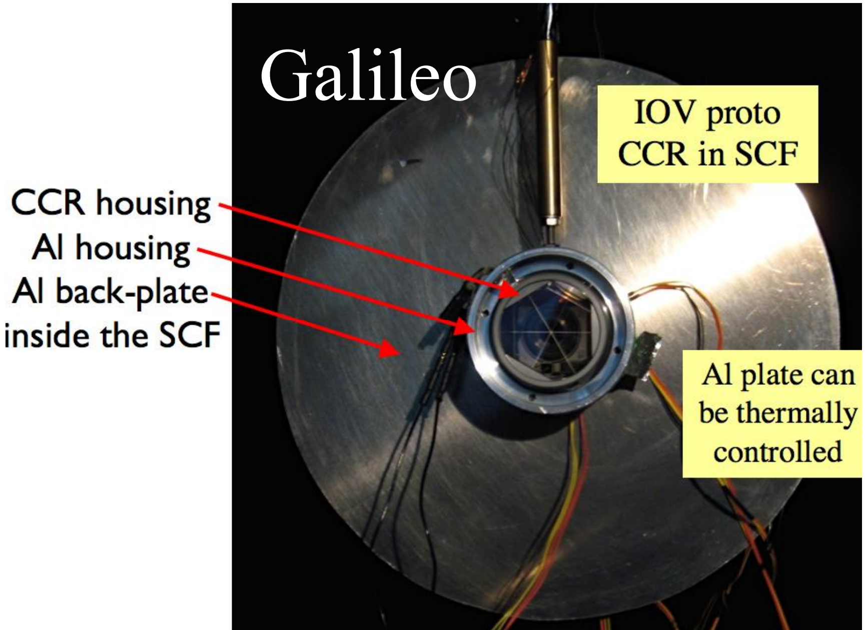
Comparison AM0 and SS spectra

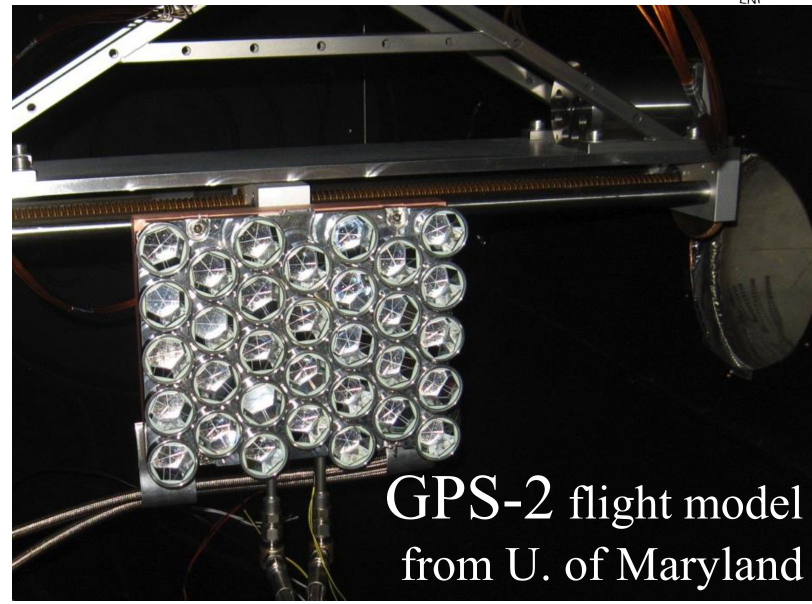


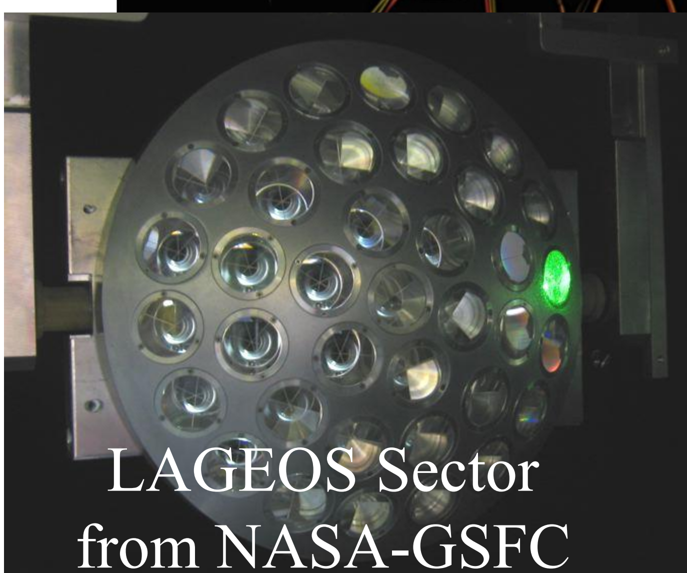
Default SCF-Test (background IP of INFN)

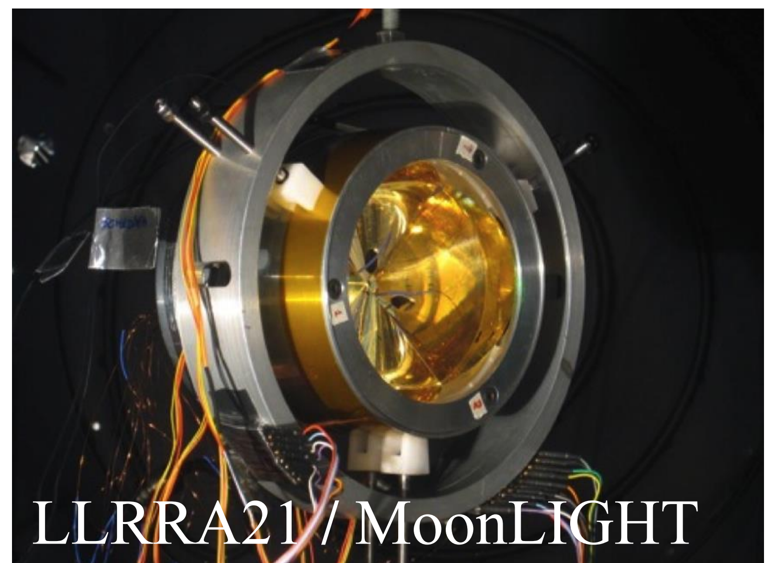
- Laboratory-simulated space conditions. Concurrent/integrated:
  - Dark/cold/vacuum
  - Sun (AM0) **simulator**
  - IR and contact **thermometry**
  - Payload **roto-translations**
  - Payload **thermal control**
  - **Laser interrogation and sun thermal perturbation at varying angles**
- Deliverables
  - **Array thermal behavior**
    - CCR thermal relaxation times ($\boldsymbol{\tau_{CCR}}$)
  - **Optical response**
    - **Far Field Diffraction Pattern (FFDP)**
- Also GRA invariant Optical Cross Section (OCS) in air/isothermal conditions
- Also integrated thermal-optical simulations.

World-first SCF-Tests

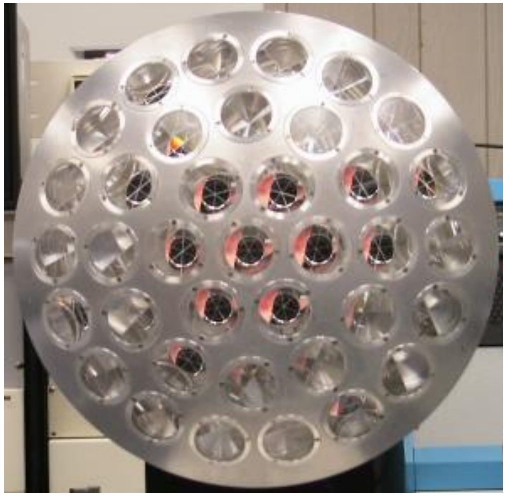


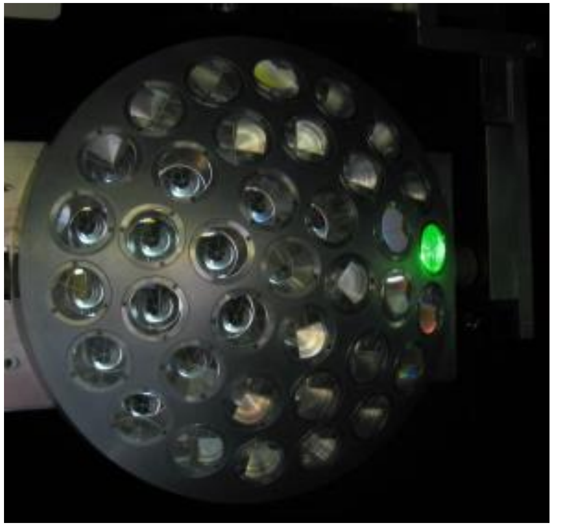


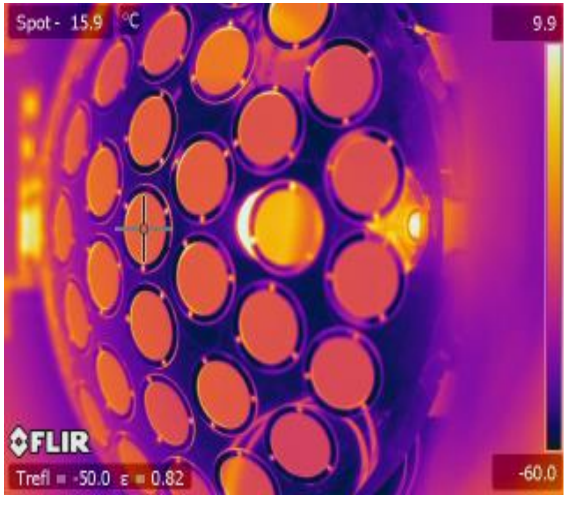


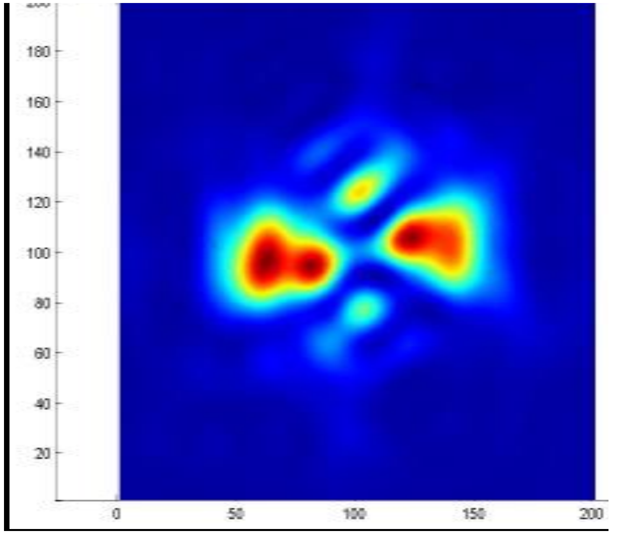


LAGEOS Sector



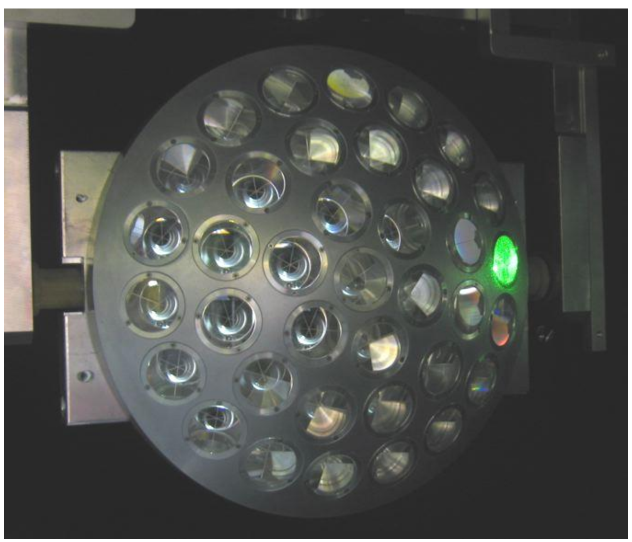






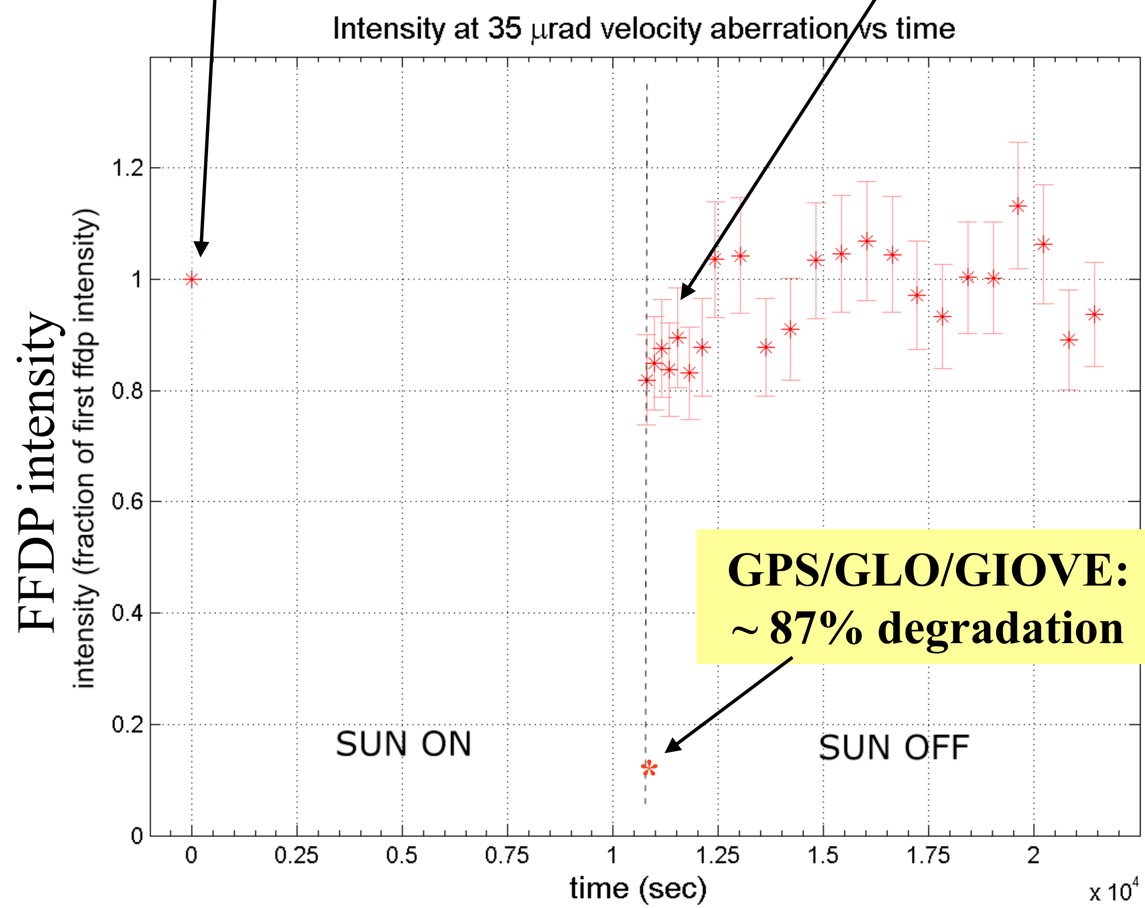
LAGEOS: uncoated SLR payload standard

LAGEOS "Sector", engineering prototype property of NASA-GSFC. Inherits from Apollo. **SCF-Tested @300K** at INFN-LNF

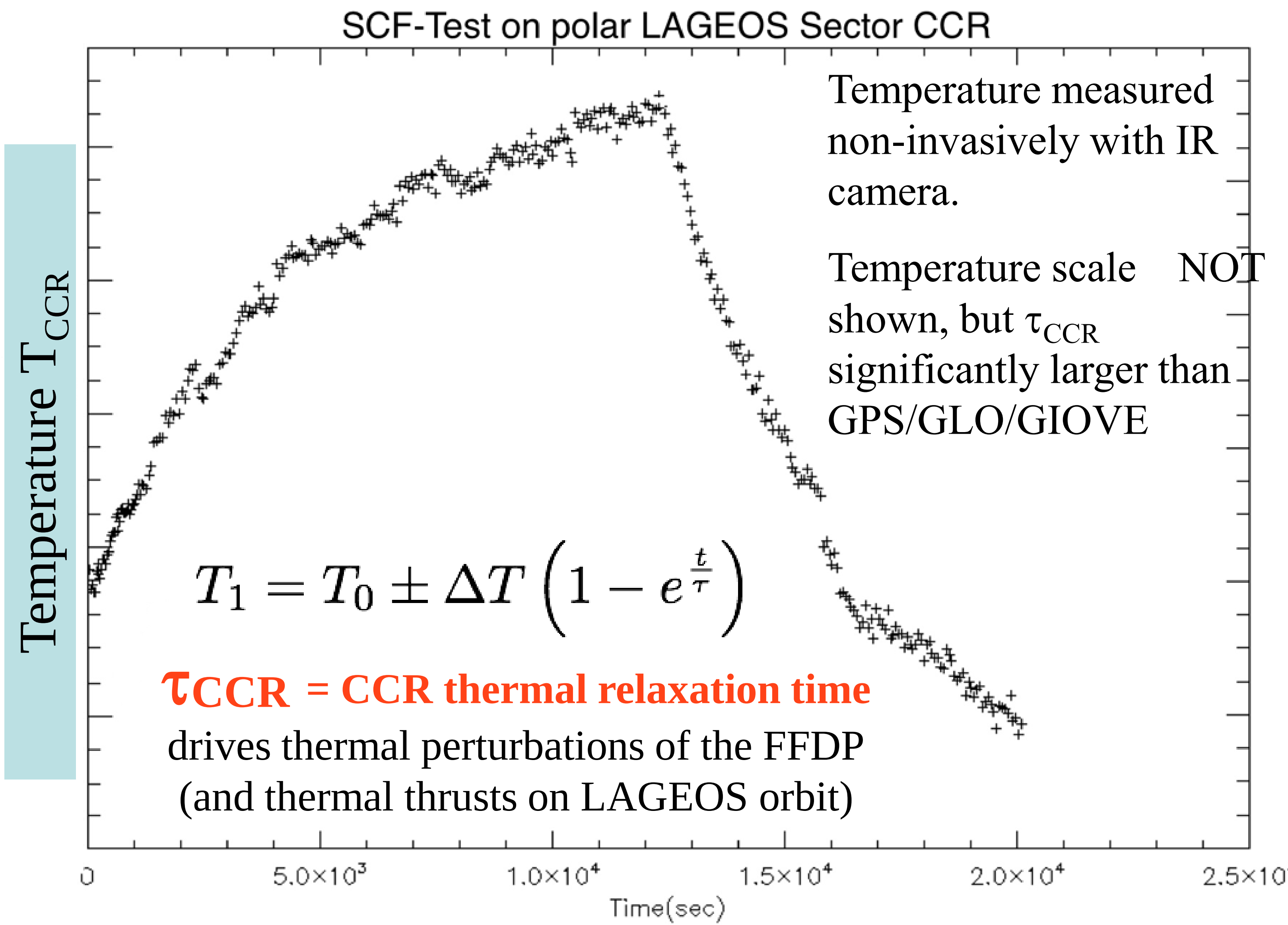


LAGEOS: laser return in space conditions not perturbed by Sun

LAGEOS: minimal degradation of laser return after 3 hr of Sun heating



LAGEOS Sector SCF-Test @300K



Temperature measured non-invasively with IR camera.

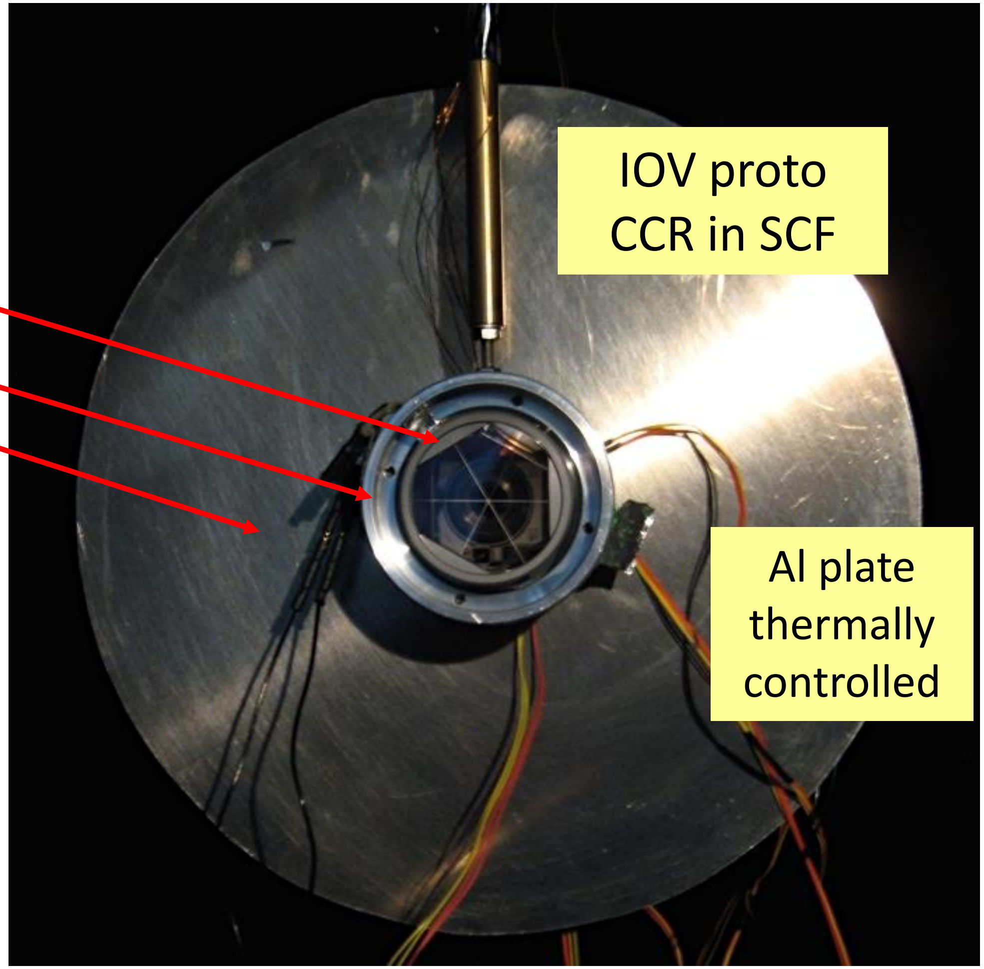
Temperature scale NOT shown, but τ_{CCR} significantly larger than GPS/GLO/GIOVE

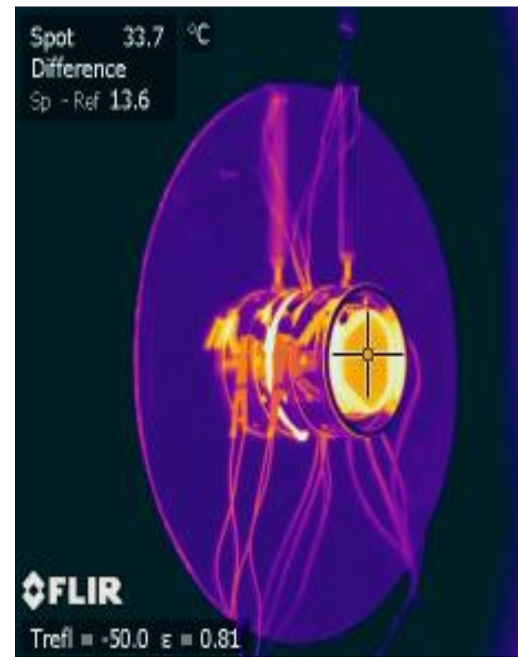
$$T_1 = T_0 \pm \Delta T \left(1 - e^{\frac{t}{\tau}}\right)$$

τ_{CCR} = CCR thermal relaxation time drives thermal perturbations of the FFDP (and thermal thrusts on LAGEOS orbit)

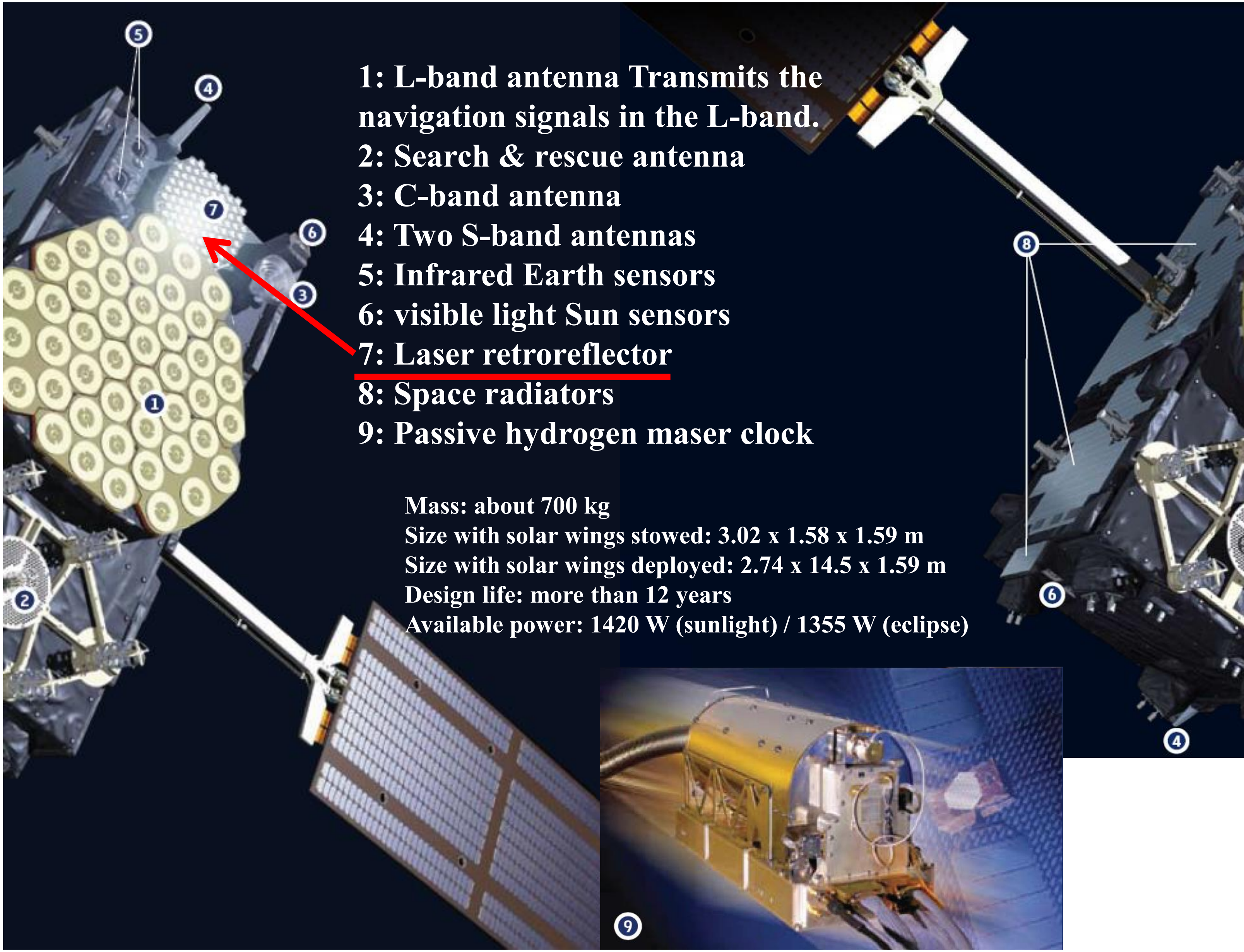
GALILEO IOV CCR SCF-Test configuration

CCR housing
Al housing
Al back-plate
inside the SCF





First 4 Galileo IOV satellites

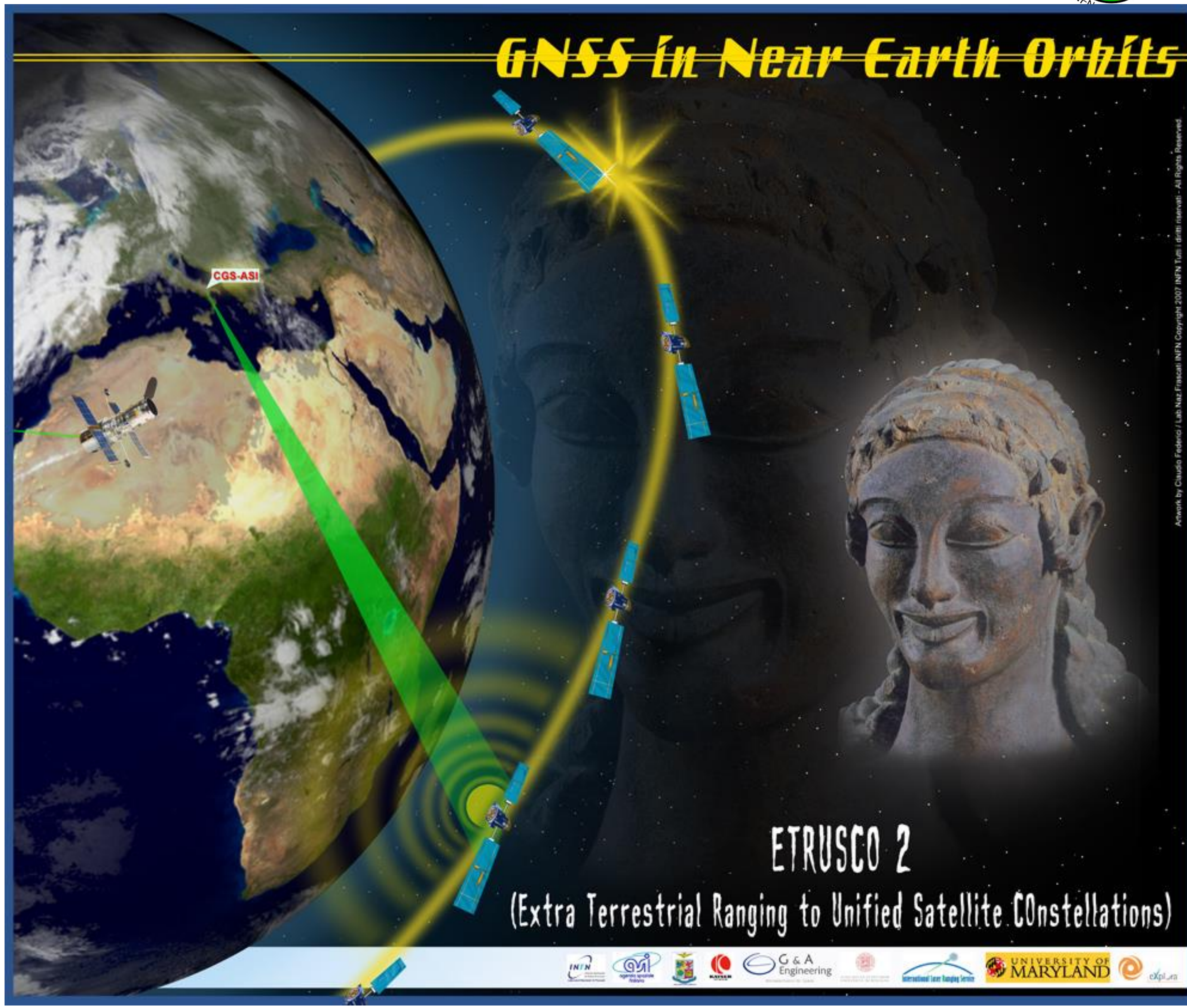


ETRUSCO-2: ASI-INFN Program for GNSS (May 2010 April 2013)

Optimized for Galileo and GPS-3

PI:
S. Dell' Agnello

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



ETRUSCO-2

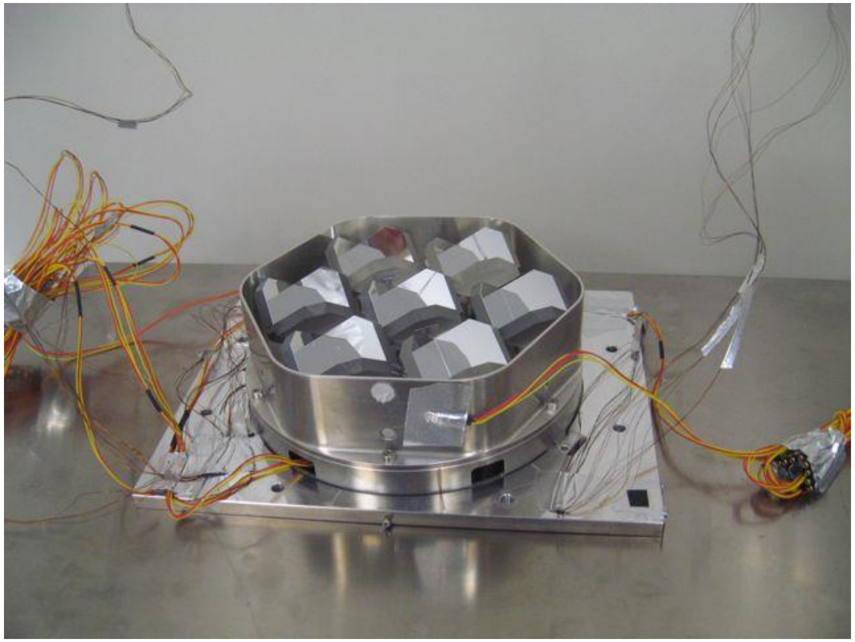
- Continuation of ETRUSCO-1 INFN R&D (2006-2010) with a full-blown ASI-INFN project of technological development

- Targeted to Galileo and GPS-3, open to other GNSS constellations
  - INFN is Prime Contractor
  - Partners:
    - ASI-CGS (G. Bianco et al), Univ. of Bologna (S. Zerbini)
    - Three Italian SMEs

ETRUSCO-2 (ASI-INFN): 2010-2013

- New SCF-G, optimized for GNSS
- Two new GNSS retroreflector payloads

Small, hollow reflector prototype model, GRA-H, delivered and fully SCF-Tested with SCF in 2011



Full size model, GRA, of solid fused silica

SCF-Test/Revision-ETRUSCO-2

- Accurately laboratory-simulated space conditions

- Deliverables / Retroreflector Key Performance Indicators (KPIs)
  - **GRA Thermal behavior:** thermal relaxation time of retroreflector (τ_{CCR}) and its mounting elements starting from hot/cold case (typical span of 100 K for GNSS)
  - **GRA Optical response along the GCO**
    - **Far Field Diffraction Pattern** (FFDP) => laser return to ground
    - **Wavefront Fizeau Interferogram** (WFI) => retroreflected laser wavefront onboard vibration and air turbulence insensitive

Note: the GCO is a very powerful, sensitive KPI. Instead, reduced, partial, incomplete tests (compared to the full space environment) are randomly misleading (either optimistic or pessimistic)

- GRA invariant Optical Cross Section (OCS) in air/isothermal conditions

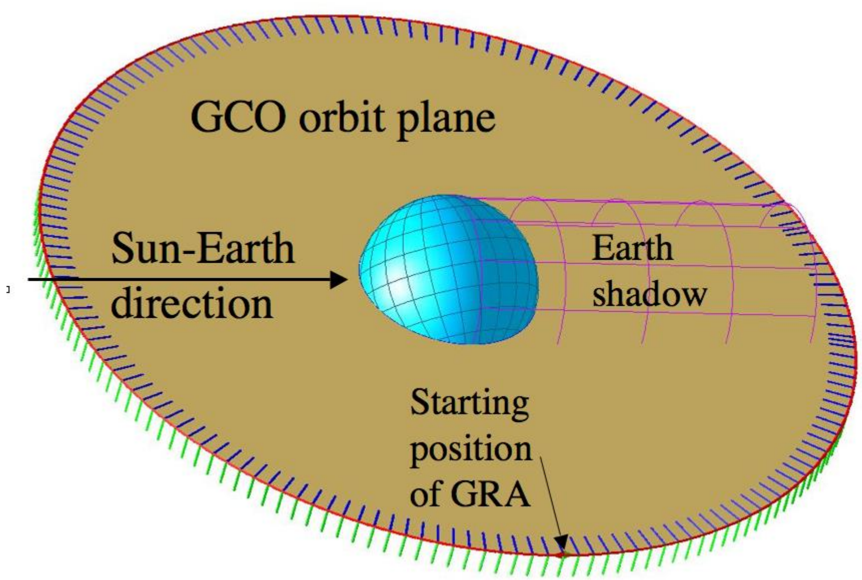
SCF-Test of Galileo Critical half-Orbit (GCO)

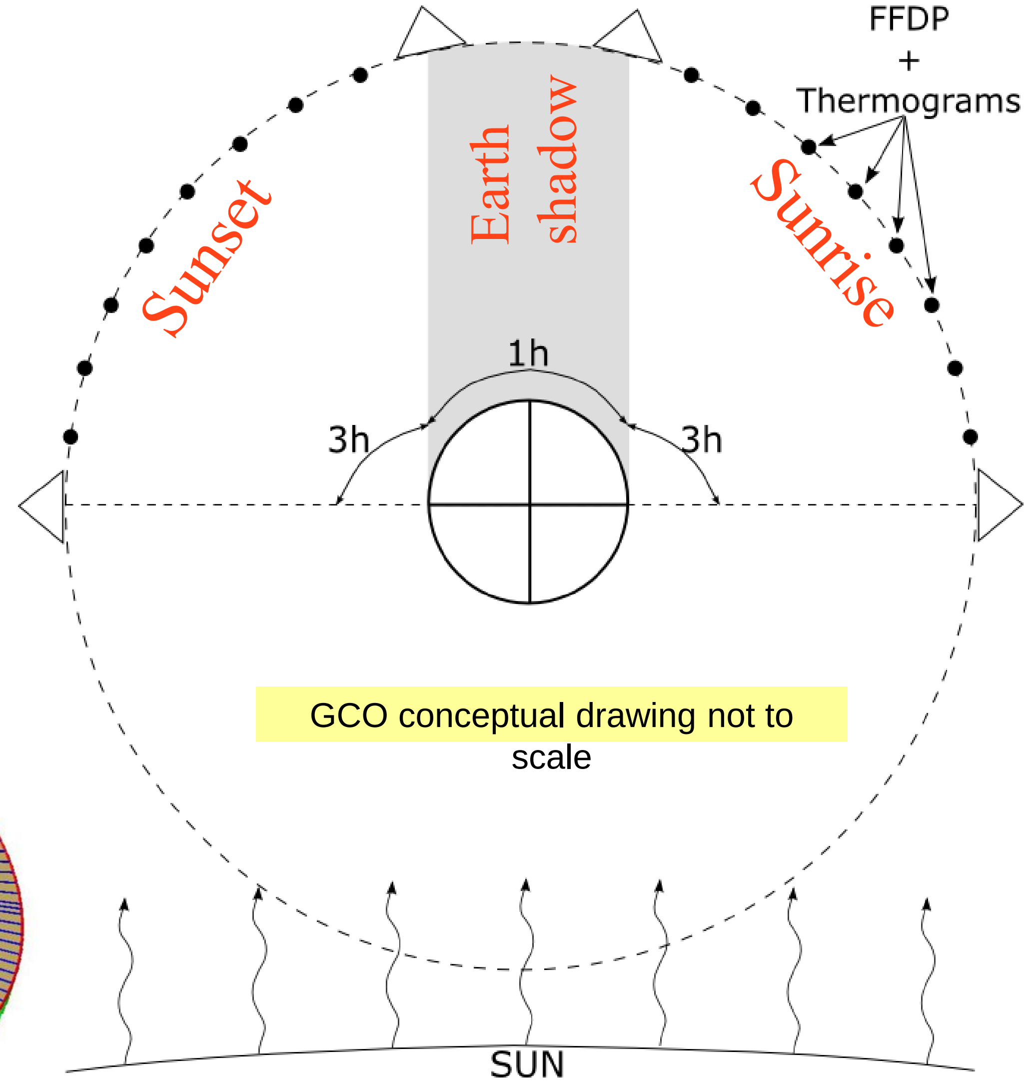
GCO: angular momentum normal to Sun-Earth direction.

Sunrise-Eclipse-Sunset probes critical features of the thermal and optical behavior of the CCR

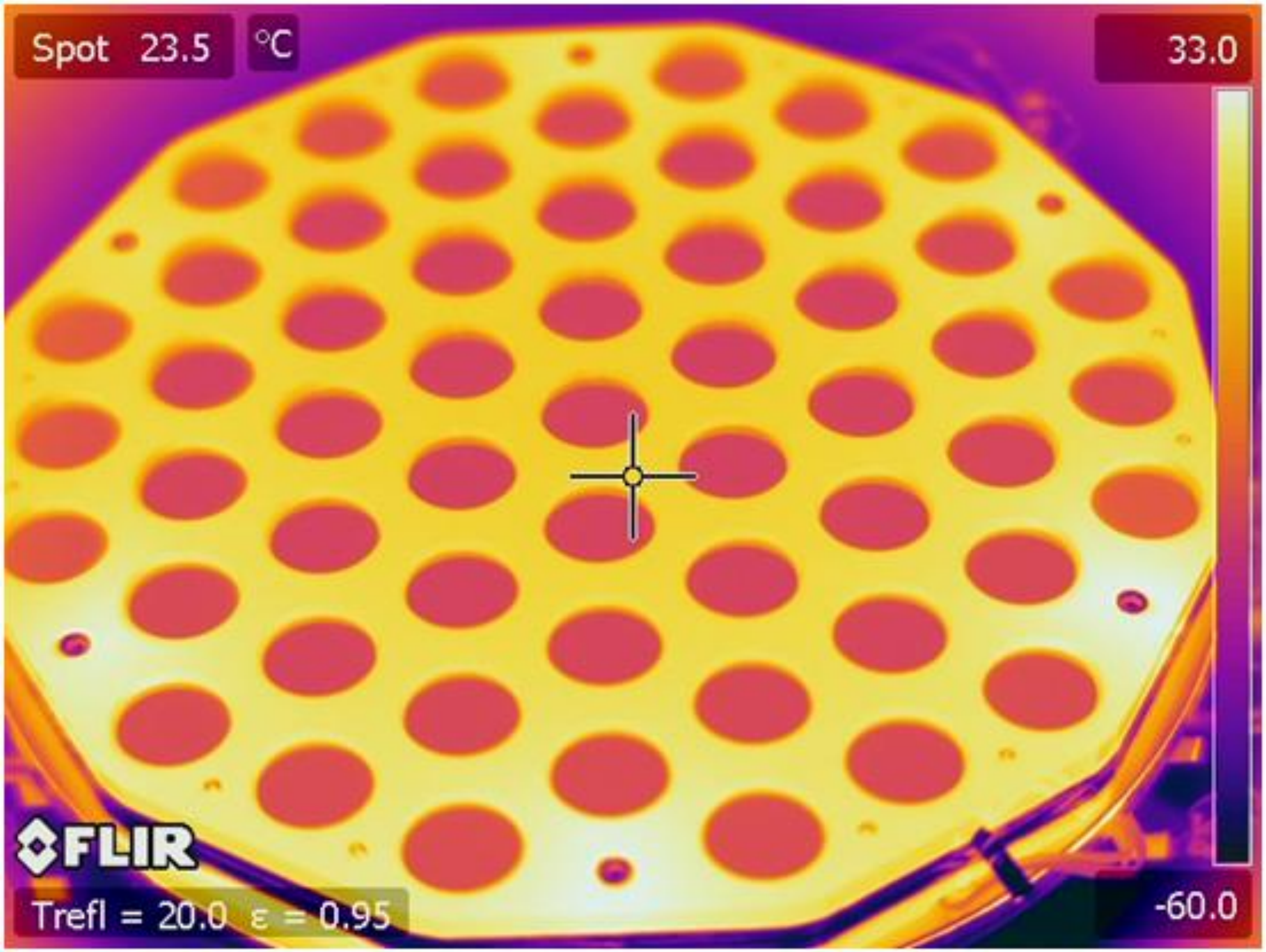
Galileo orbit:

- Altitude = 23222 km
- Period ~ 14 hr, shadow ~ 1hr

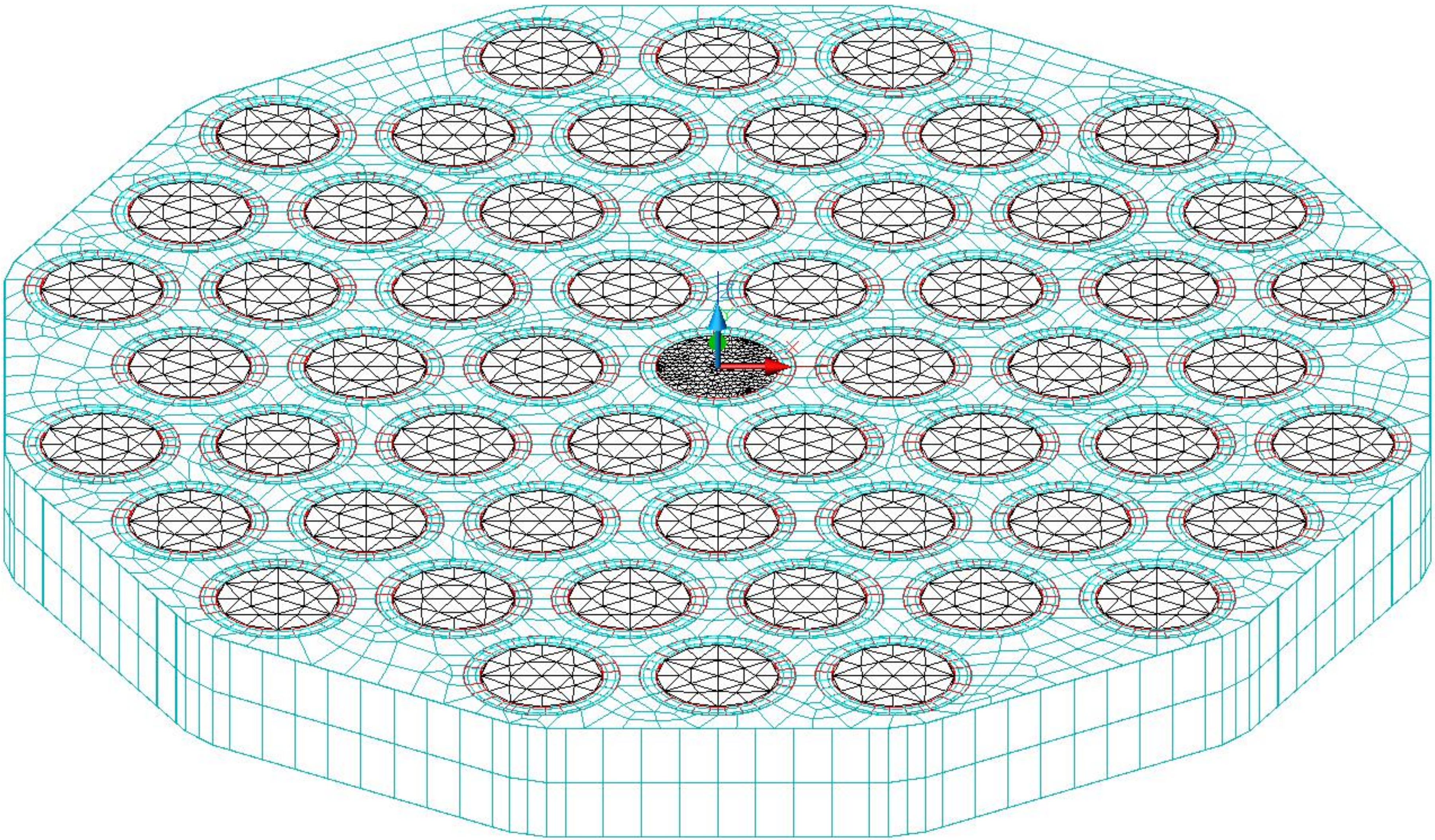




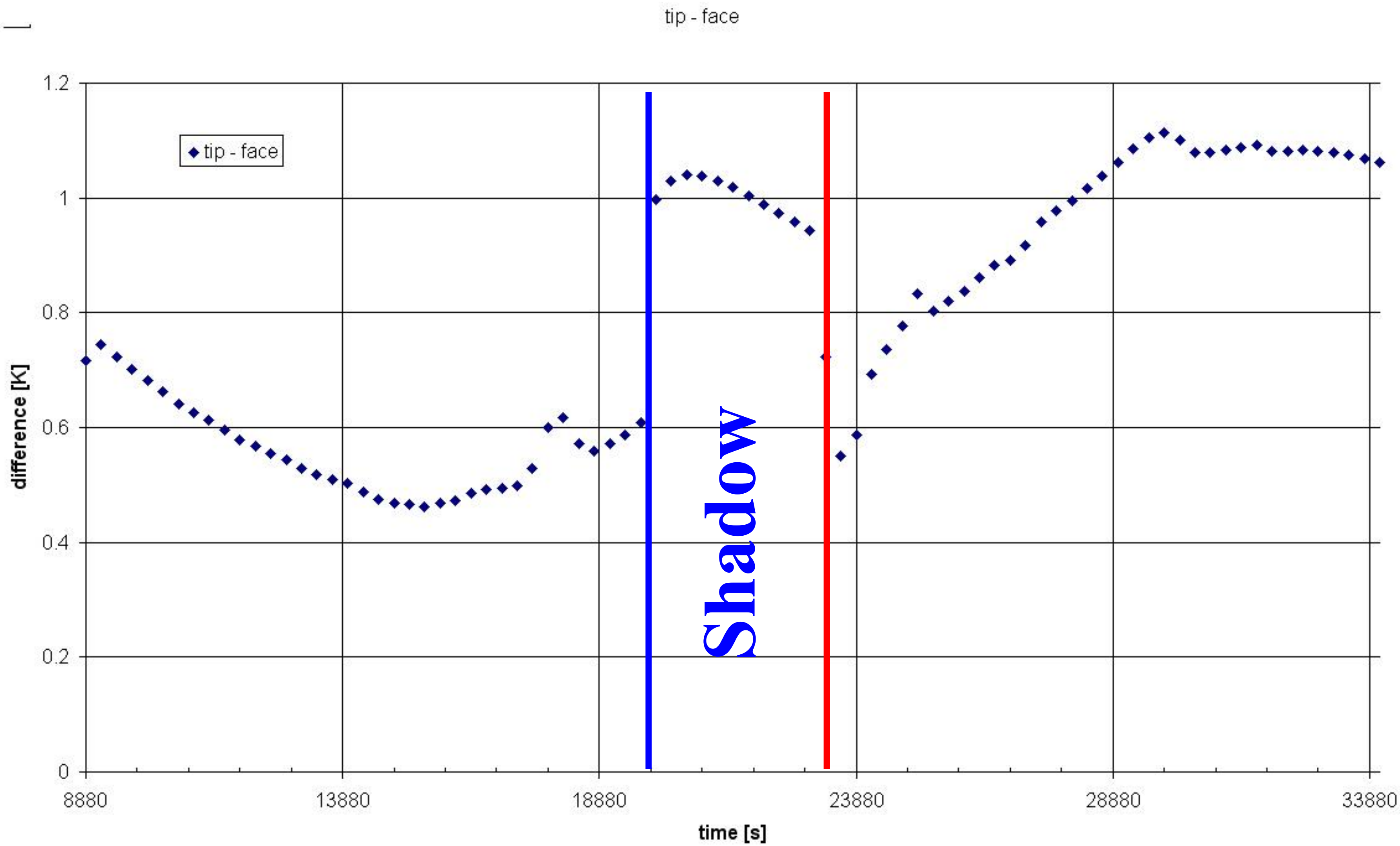
IR thermograms



GRA Thermal model



Tip-Face temperature difference for CCR 1



Conclusions and prospects

- New infrastructure SCF_Lab with two unique OGSEs
- SCF: Satellite/Lunar/GNSS laser ranging/altimetry
- SCF-G: optimized for GNSS
- SCF-Test of: GPS/GLONASS/GIOVE, LAGEOS, Galileo IOV
- New SCF-Test/Revision-ETRUSCO-2 applied to a prototype Galileo IOV CCR
- GRA for next coming Galileo Satellites

Thank you for your attention

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