Galileo, the European GNSS program & LAGEOS

Authors: SCF_LAB team
Speaker: Simone Berardi

Les Rencontres de Physique de la Vallee d'Aoste
La Thuile March 3 2012

SCF_LAB team

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SCF_LAB
Satellite/lunar laser ranging
Characterization Facility
LABoratory

National Collaborations:

- ASI - Centro di Geodesia Spaziale - G. Bianco, C. Sciarretta, V. Luceri SLR/LLR station and orbit software
- AMI - Aeronautica Militare Italiana - R. Vittori, co-PI of ETRUSCO
- University of Bologna – S. Zerbini

International Collaborations:

- Univ. of Maryland at College Park - D. Currie, inventor LLR, Bradford Behr & C.O. Alley
- Harvard-Smithsonian Center for Astrophysics – D.A. Arnold & M.R. Pearlman
- GSFC/NASA - J.F. McGarry & T.W. Zagwodzki

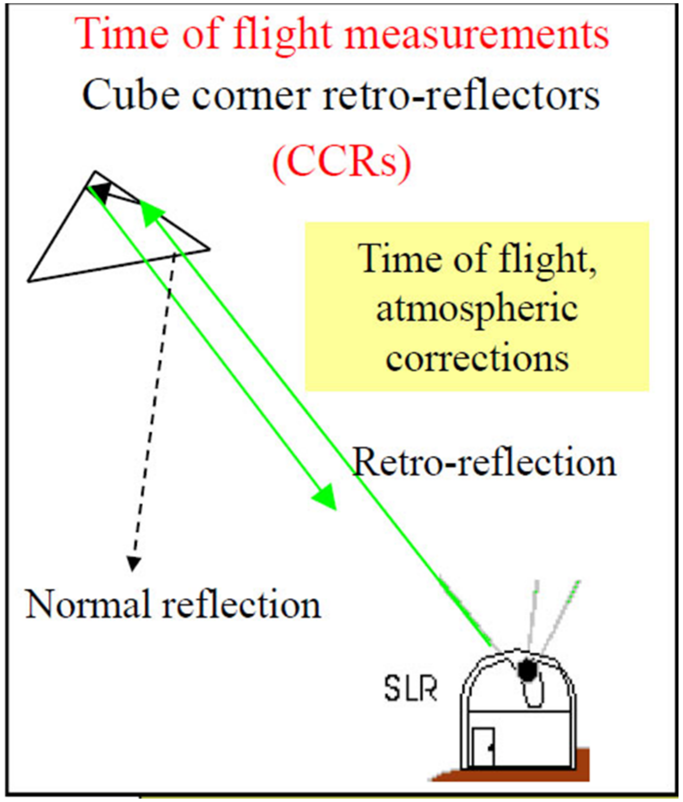
International Scientific Communities:

- ILRS - S. Dell'Agnello is member of Signal Processing WG

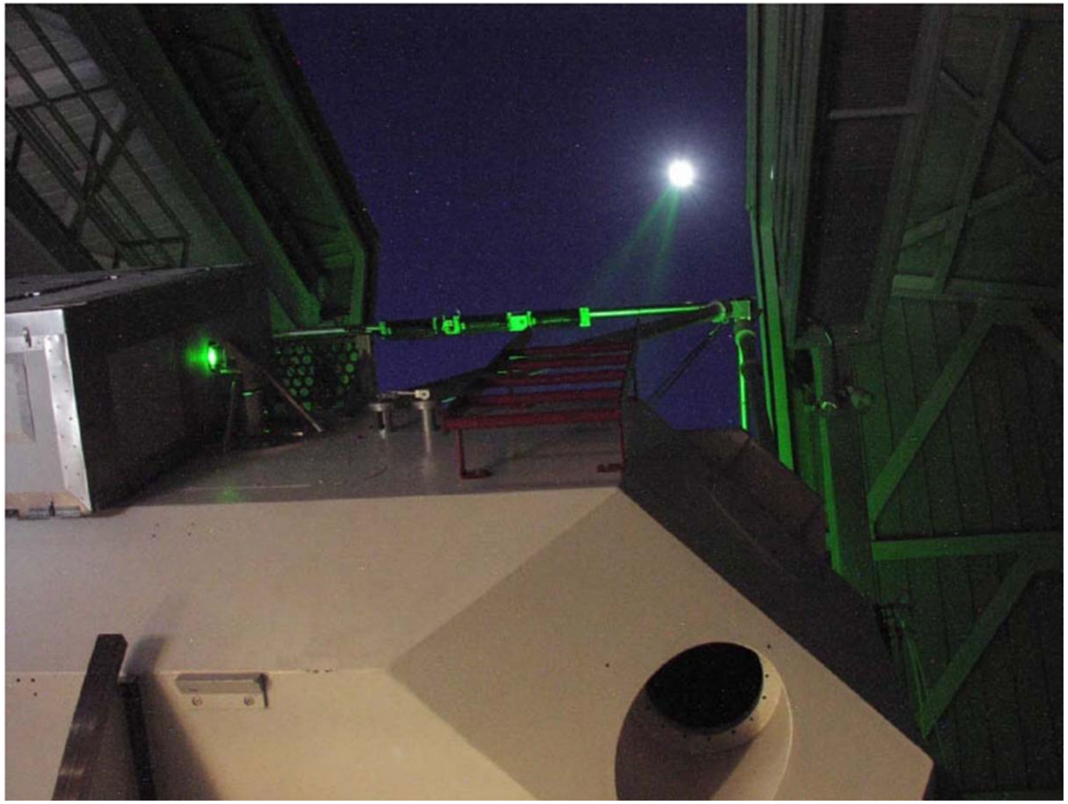
Outline

- Satellite Laser Ranging & International Laser Ranging Service
- Etrusco, the SCF_LAB & SCF_test
- LAGEOS SCF-Test
- Physics with Galileo
- Galileo IOV SCF-Test
- Conclusions & prospects

Satellite/Lunar Laser Ranging (SLR/LLR)



Satellite Laser Ranging (SLR)
Lunar Laser Ranging (LLR)



APOLLO LLR Station in New Mexico (USA)

The most precise and cost effective distance measurement in space
(few millimeters to few centimeters) and (100K€ to M€)

LAGEOS I (1976) and II (1992)

- Diameter 60 cm
- 426 CCR
- Weight ~ 400 kg
- Altitude ~ 6000 km

Main Physics Goal → "Frame Dragging" (39 mas/yr) by relative precision of ~ 1% → **LASER RANGING**

In the 1998, for the first time → **LENSE-THIRRING EFFECT**

ERROR FROM 40% (1998) TO 10% (2004)

The Largest errors are due to:
- **Error on Earth Geo-Potential**
- **NGPs (Thermal-Thrust)**

ITRF: space geodesy, GNSS, physics

Orbits: LEO, GNSS, GSO/GEO, Moon

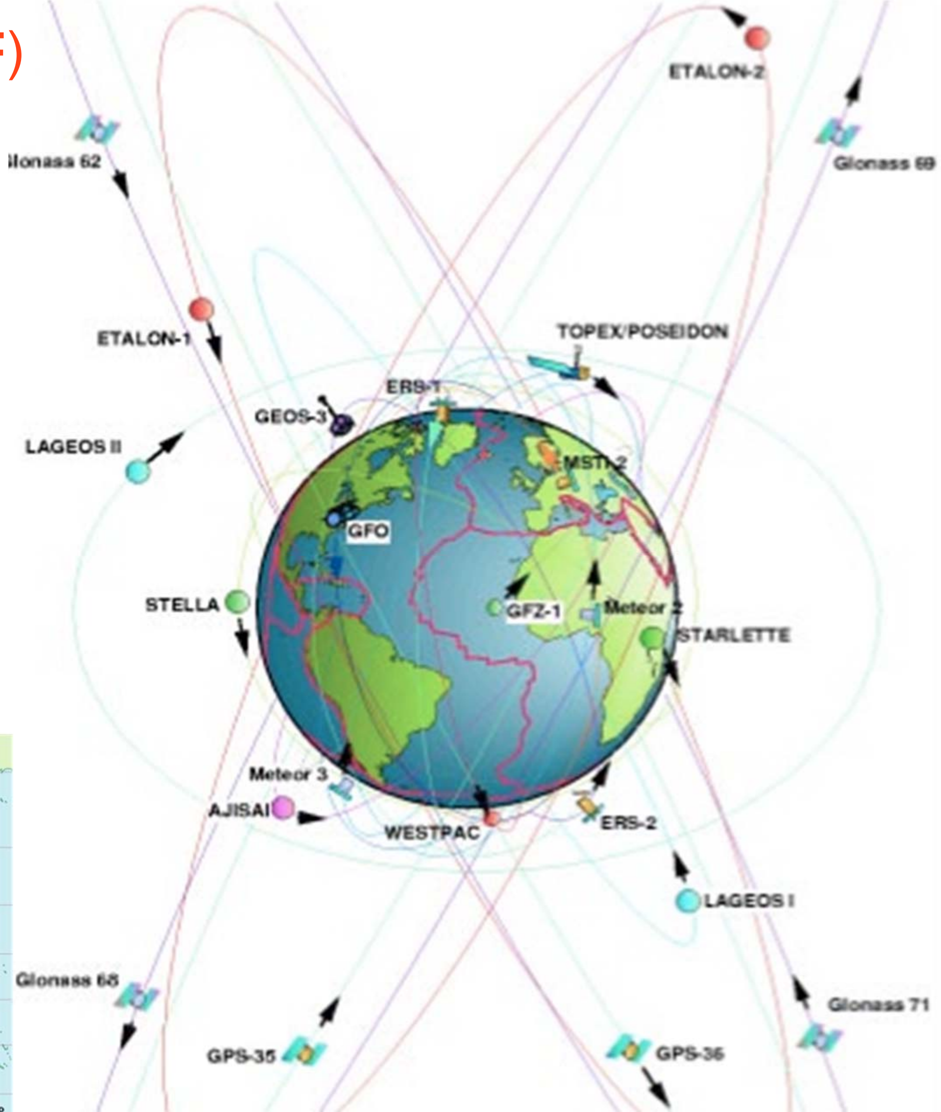
SLR constellation

Int. Terrestrial Reference Frame (ITRF)

- **Geocenter** from SLR (LAGEOS)
- **Scale** from SLR (LAGEOS) & VLBI
- **Orientation from** VLBI
- **Distribution w/**GNSS
- DORIS, …

LAGEOS

International Laser Ranging Service



ETRUSCO and ETRUSCO-2

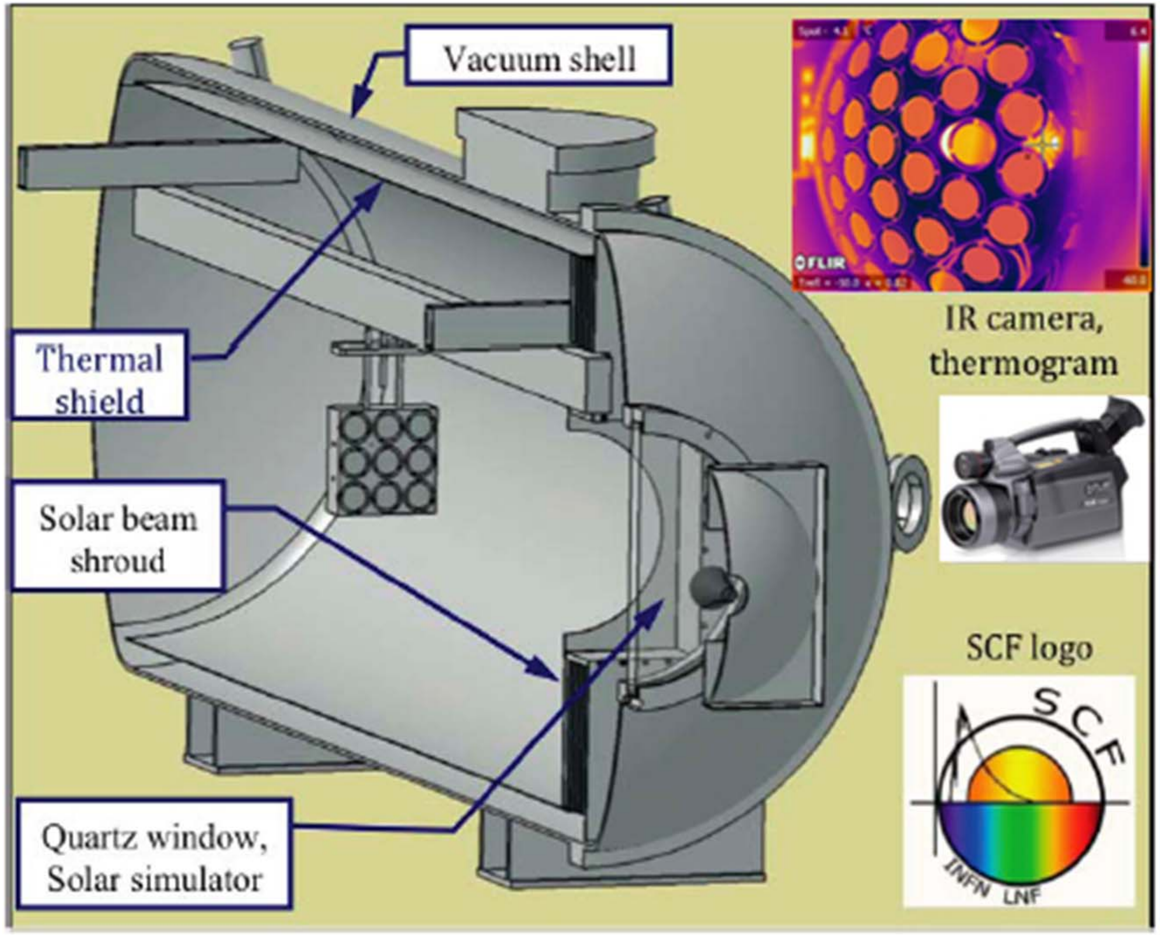
ETRUSCO (INFN): 2005-2010

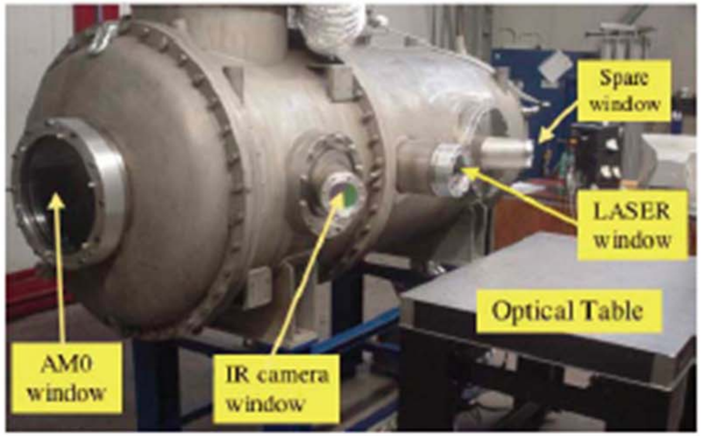
- development of a new industry-standard space test characterization of laser retroreflectors, the SCF-Test
- SCF-test of several optical payloads for GNSS

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

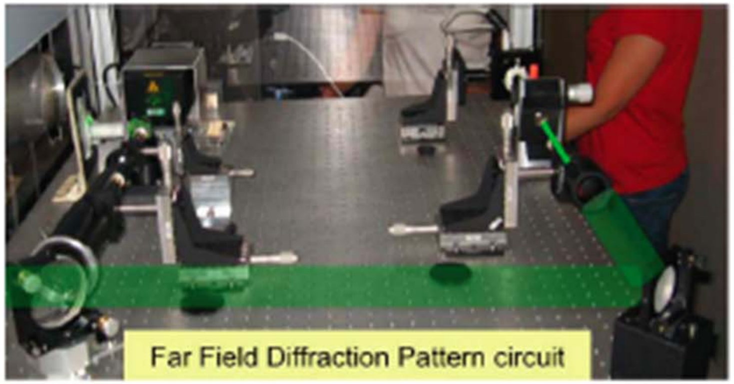
- New revision of the SCF-test
- Development and SCF-Test of GNSS Retroreflector Arrays (**GRA**)
- LAGEOS used as a reference, standard target

SLR/LLR Characterization Facility (SCF)



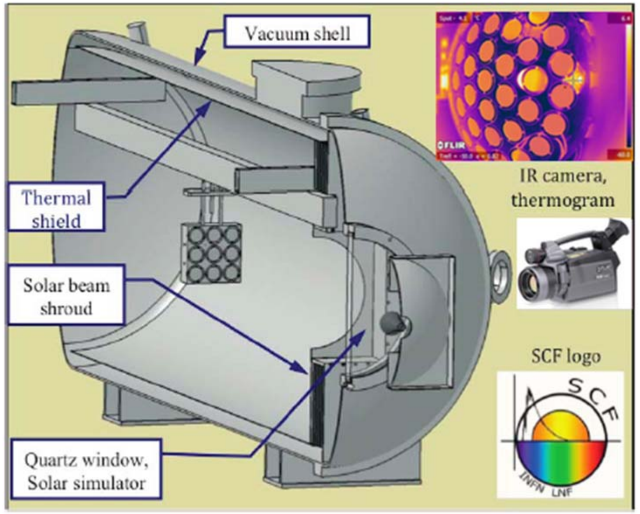


Optical circuit



Integrated and concurrent thermal and optical measurements in accurately laboratory-simulated space environment

SCF inside the Clean Room



Dedicated clean room environment

The SCF-Test (background IP of INFN)

- Accurately laboratory-simulated space conditions. Concurrent/integrated:
  - Dark/cold/vacuum, Sun (AM0) and Earth IR **simulators**
  - Non-invasive IR and contact **thermometry**
  - Payload **roto-translations** and **thermal control**
  - **Laser interrogation and sun perturbation at varying angle**

- Deliverables / Retroreflector Key Performance Indicators (KPIs)
  - **Thermal behavior**
    - Thermal relaxation time of retroreflector (τ_{CCR}) and its mounting elements
  - **Optical response**
    - Far Field Diffraction Pattern (FFDP)
      - Orthogonal polarizations for single uncoated reflectors
- Note: reduced, partial, incomplete tests (compared to the full space environment) are randomly misleading (either optimistic or pessimistic)

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

The SCF-Test (background IP of INFN)

Available online at www.sciencedirect.com

ScienceDirect

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Advances in Space Research 47 (2011) 822–842

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS

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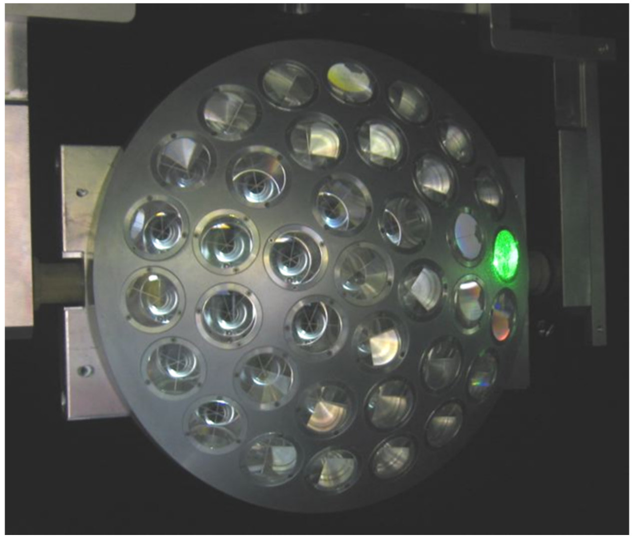
LAGEOS engineering model SCF-Test

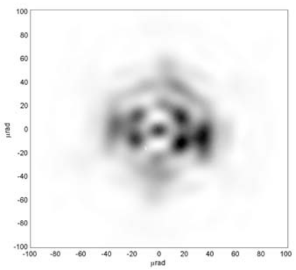
LAGEOS uncoated SLR payload standard

LAGEOS "Sector", engineering prototype property of NASA-GSFC. Inherits from Apollo.

SCF-Tested @300K

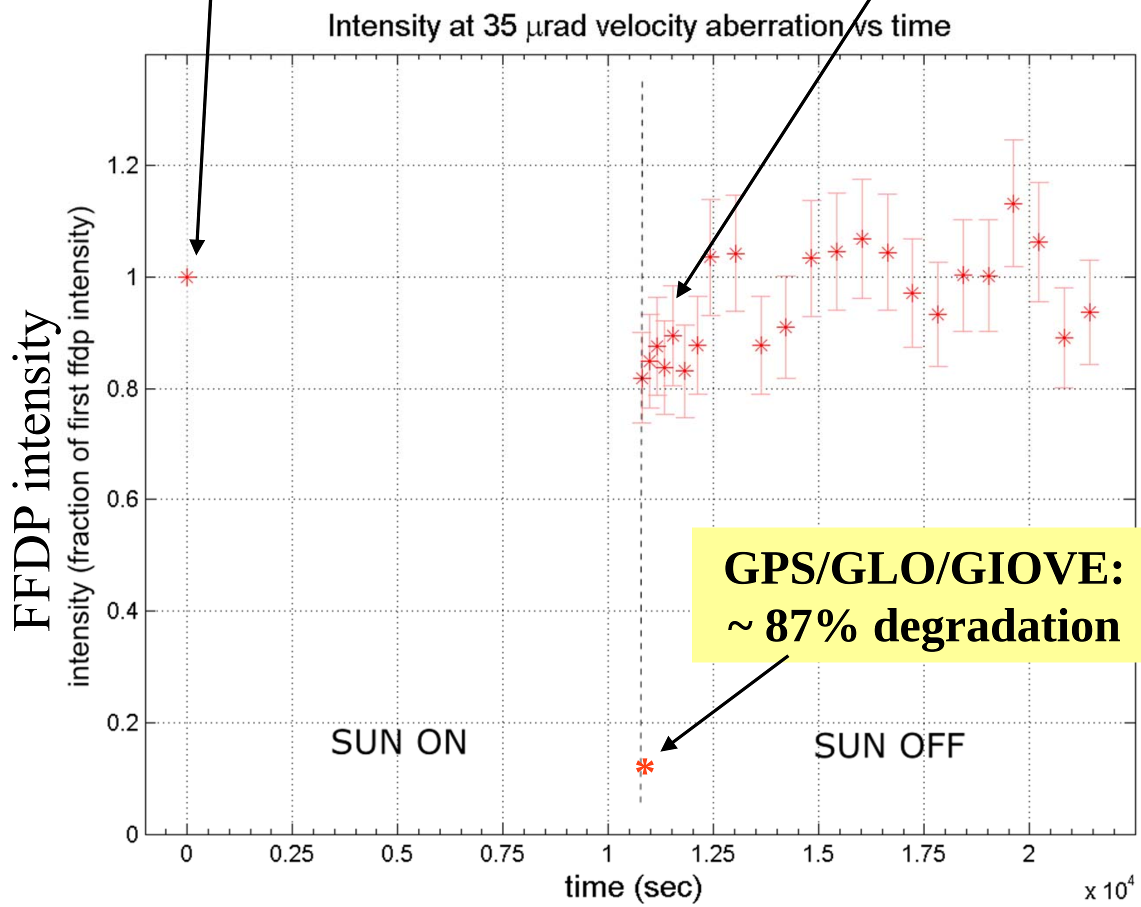
at INFN-LNF



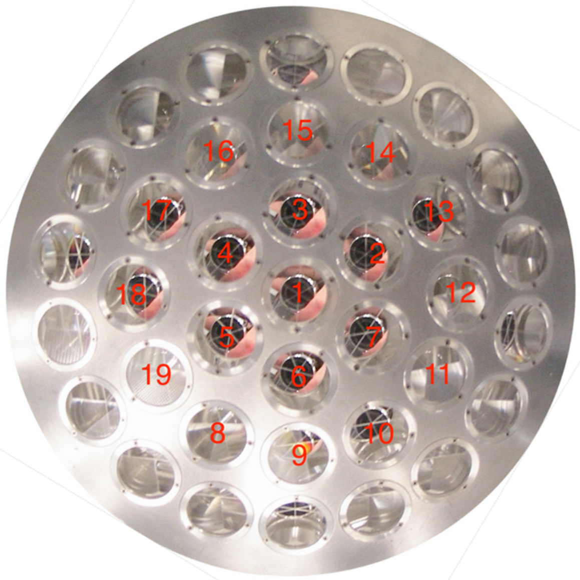


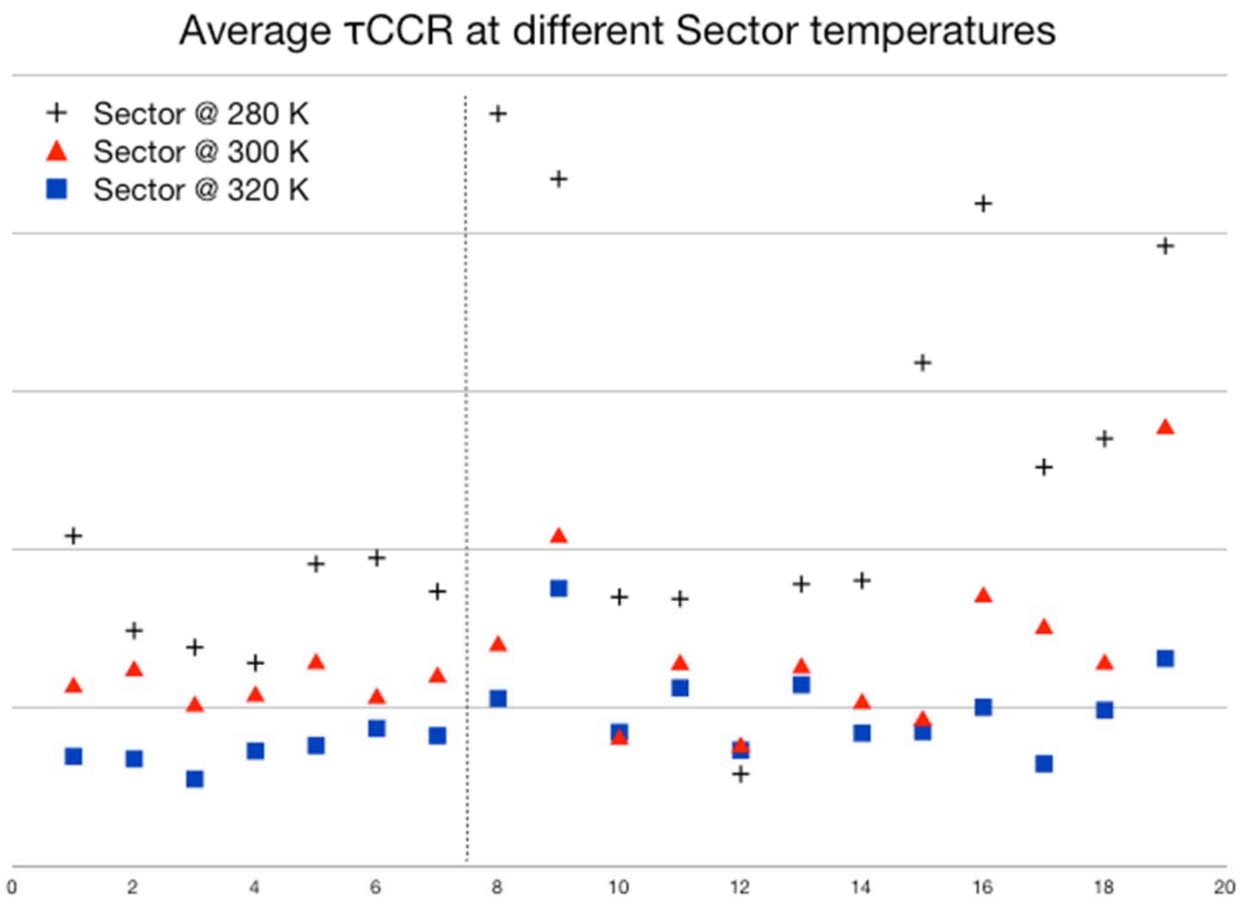
LAGEOS: laser return in space conditions not perturbed by Sun

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



LAGEOS sector – τ_{CCR} at different temperatures



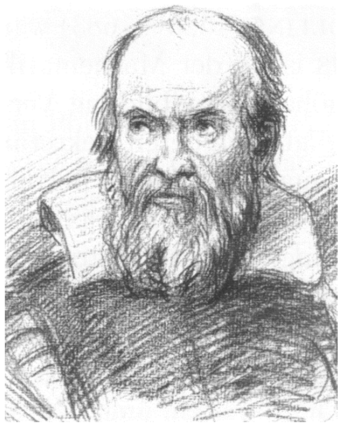


Characteristic heating and cooling time constants (τ_{CCR}) decrease with temperature.

$$\frac{\tau_{T_1}}{\tau_{T_2}} \cong \left(\frac{T_2}{T_1}\right)^3$$

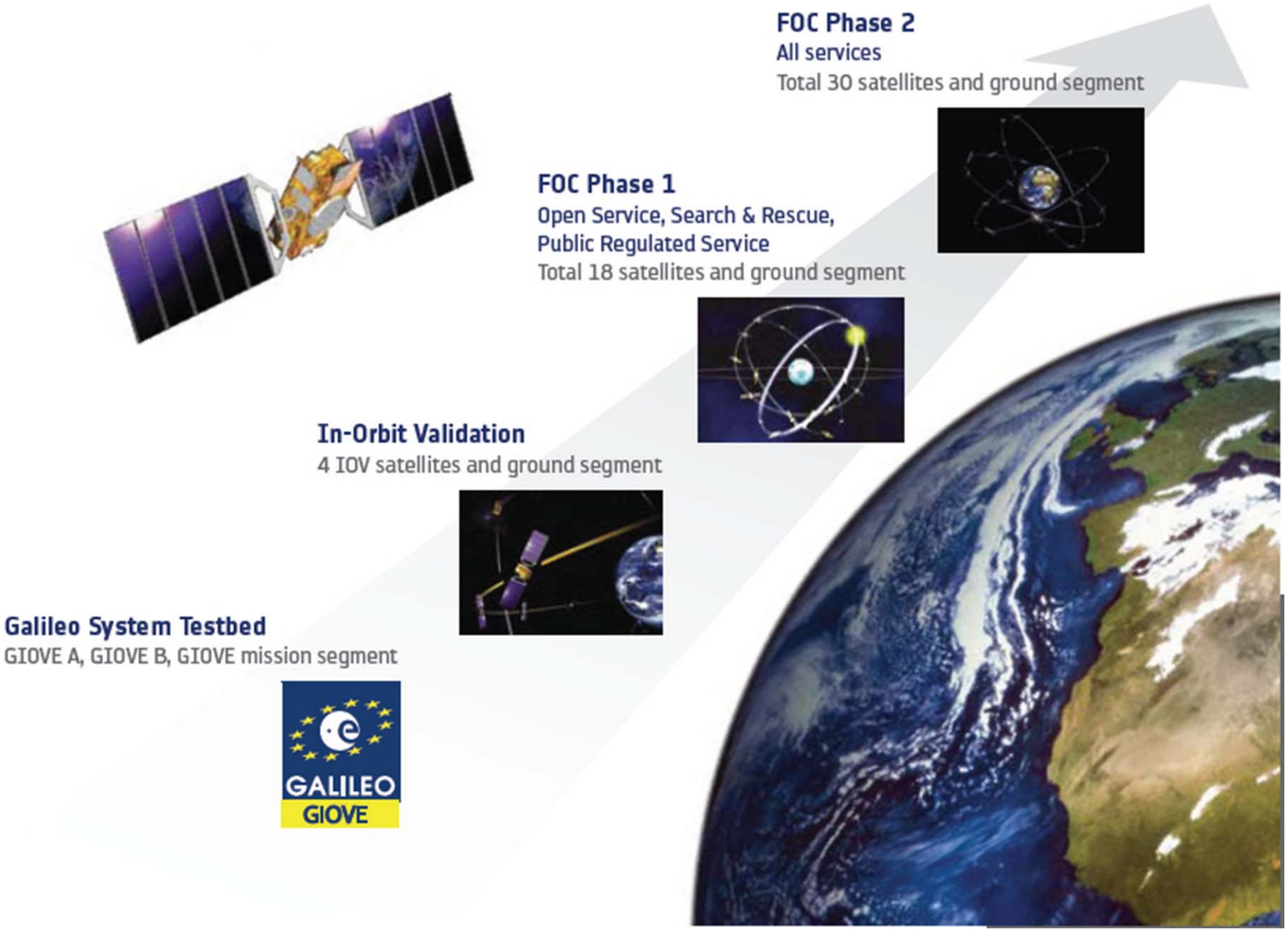
Galileo: European satellite navigation system

Galileo is a satellite navigation system currently being built by the European Union (EU) and European Space Agency (ESA). The €20 billion project is named after the famous Italian astronomer Galileo Galilei. One of the aims of Galileo is to provide a high-precision positioning system upon which European nations can rely, independently from the Russian GLONASS, US GPS, and Chinese Compass systems, which can be disabled in times of war or conflict

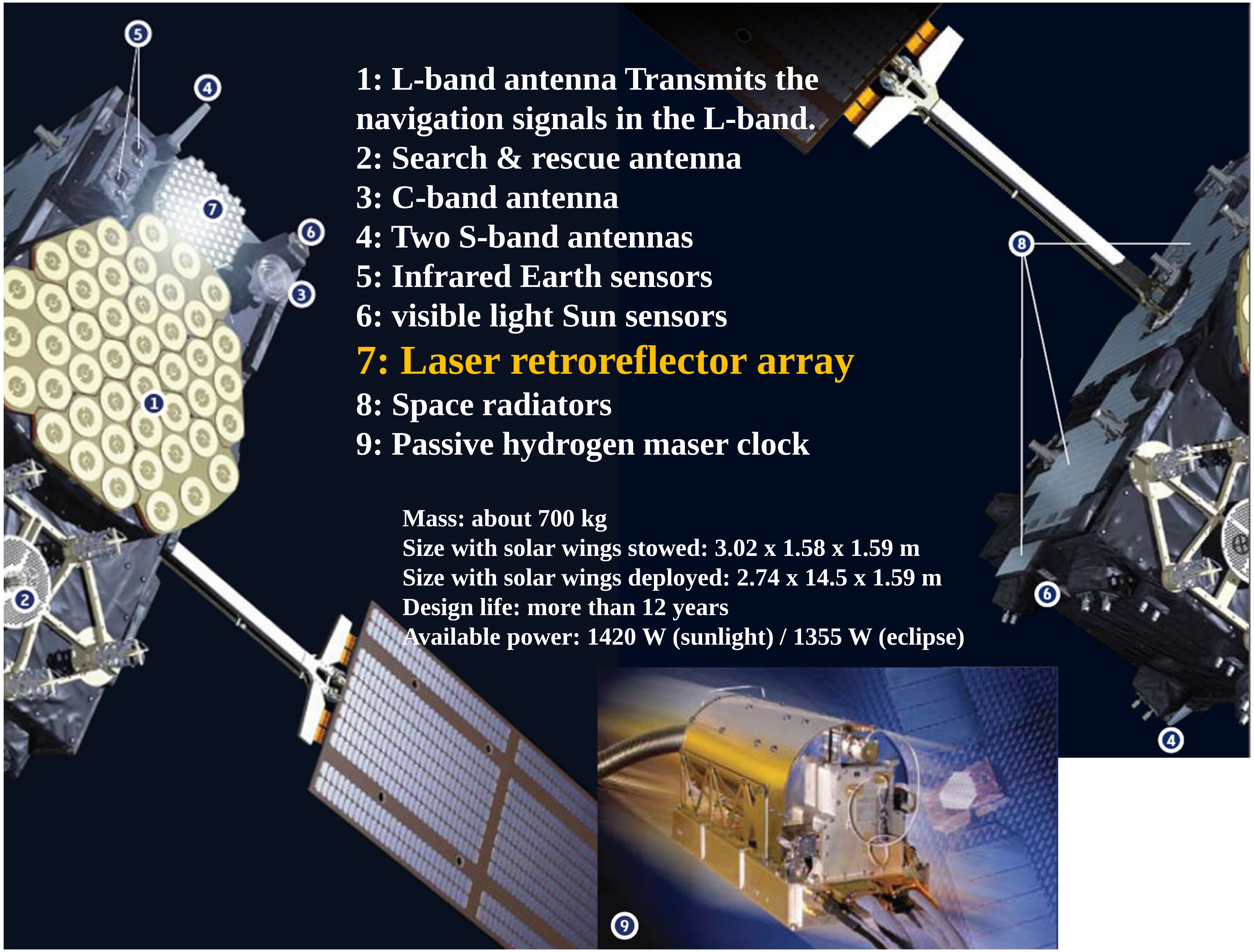


- The European Commission (EC) estimates that 6-7% of European GDP, around 800 billion by value, is dependent on satellite navigation.
- better coverage at high latitudes
- Interoperability with GPS and GLONASS: better signal strenght even with high buildings

Galileo Implementation Plan



External anatomy of the Galileo IOV satellite



1: L-band antenna Transmits the navigation signals in the L-band.
2: Search & rescue antenna
3: C-band antenna
4: Two S-band antennas
5: Infrared Earth sensors
6: visible light Sun sensors
7: Laser retroreflector array
8: Space radiators
9: Passive hydrogen maser clock

Mass: about 700 kg
Size with solar wings stowed: 3.02 x 1.58 x 1.59 m
Size with solar wings deployed: 2.74 x 14.5 x 1.59 m
Design life: more than 12 years
Available power: 1420 W (sunlight) / 1355 W (eclipse)

Galileo: beyond navigation

Available online at www.sciencedirect.com
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Advances in Space Research 47 (2011) 173
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Preface

Scientific applications of Galileo and other Global Navigation Satellite Systems (I)

In the last two decades, the Global Positioning System (GPS) has become a key tool for scientific applications in the field of geodesy/geophysics as well as for time and frequency monitoring. Europe is now on its way to launch a new enhanced navigation satellite system called Galileo, for which two test satellites (GIOVE-A and GIOVE-B) are already operational.

On October 14–16, 2009, the 2nd international colloquium on Scientific and Fundamental aspects of the Galileo programme was organized by the European Space Agency (ESA), the University of Padova, Italy and the Committee

the availability of future GNSS data, algorithms and models, constellation maintenance and space debris.

As only a small number of presentations were addressing directly the Galileo system itself (currently limited to the GIOVE satellites), it was also decided to expand the topics of this Special Issue more broadly to Global Navigation Satellite Systems (GNSS) scientific applications with regards to the future European Galileo navigation satellite system. Topics related to remote sensing with GPS were not considered for this Special Issue as papers on this topic are being assembled in another Special Issue of ASR.

Physics: Gravitational Redshift (GRS)

The GRS is a *classical* precision test of GR, originally proposed by Einstein.
It is a test of Local Position Invariance (LPI) of all metric theories of gravity.

Current experimental status, showing bounds on α, which measures degree of deviation of GRS from the formula

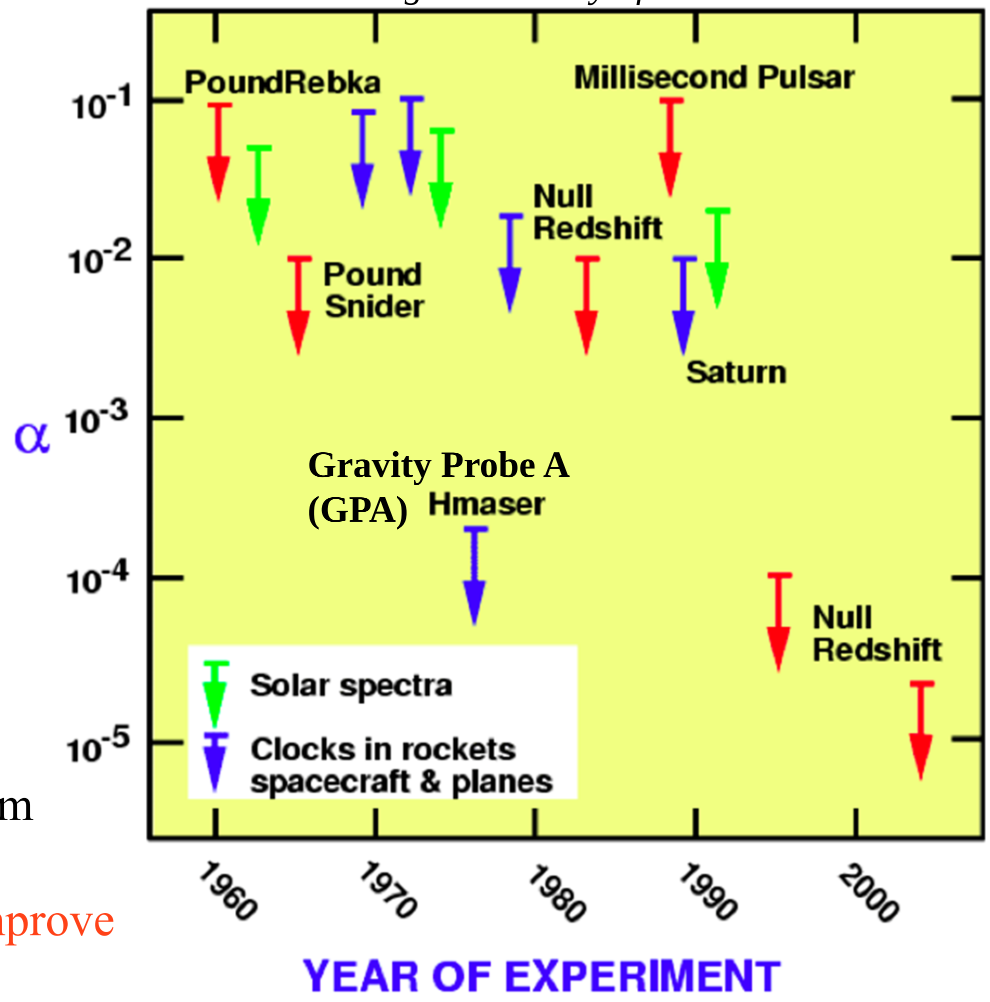
$$\Delta\nu/\nu = (1+\alpha) \times \Delta U(r)/c^2$$

where:
U is the gravitational potential
ν is the clock frequency

Best GRS measurement:
$|\alpha| < 2 \times 10^{-4}$ from GPA in 1976

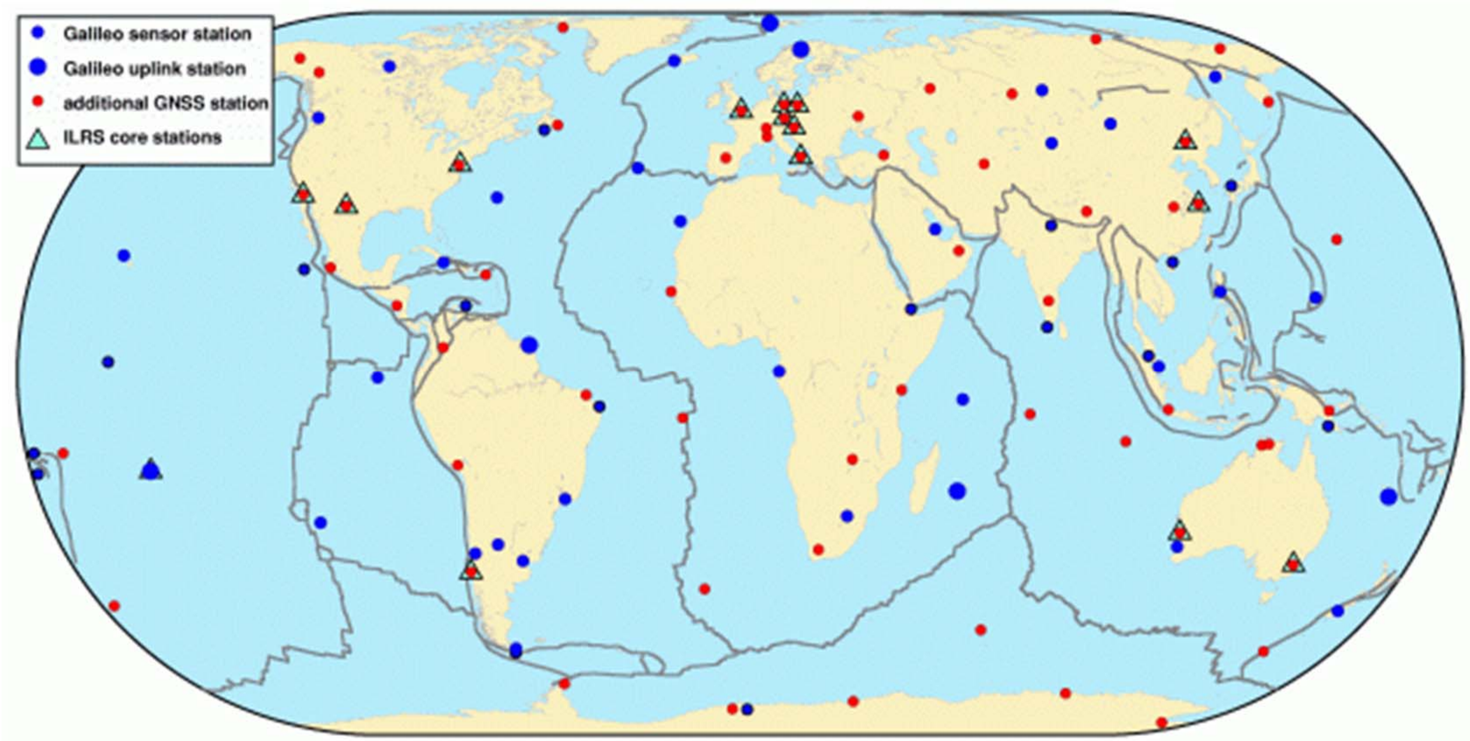
- 1 Hydrogen-maser clock
- Maximum orbital height of 10000 Km
- Took data for ≈ 2h
- With Galileo (30 Hmaser) we can improve over GPA up to a factor 100

Figure courtesy of C. Will

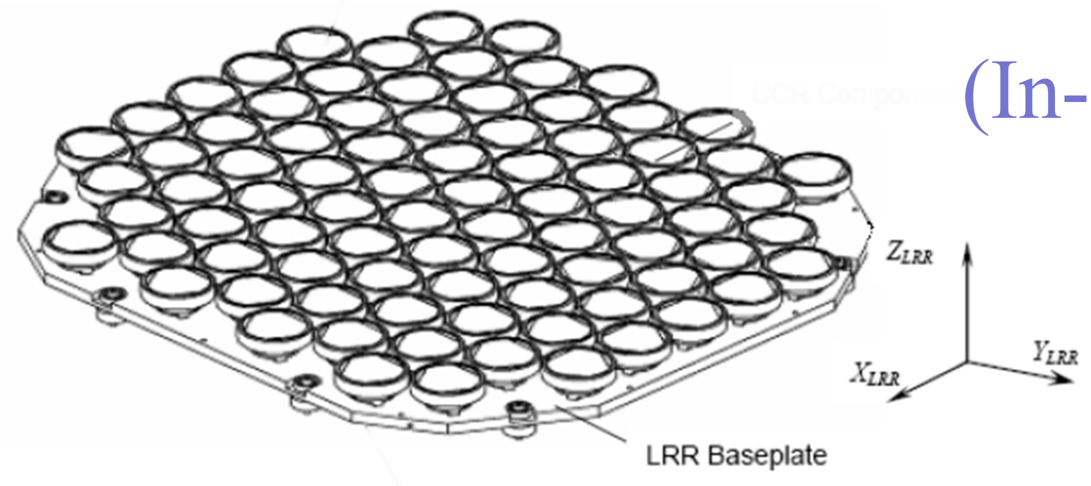


Geodesy : 'Galileo' Terrestrial Reference System

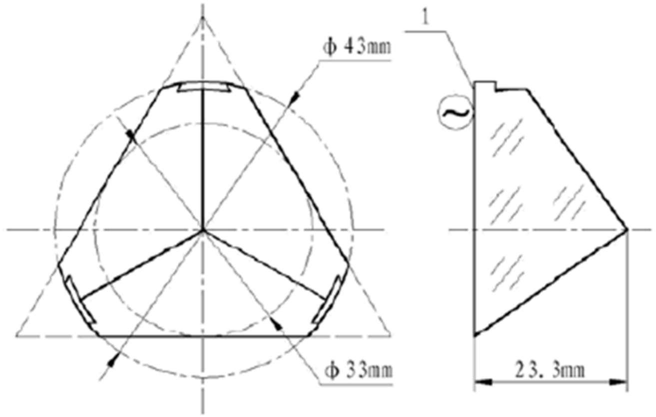
In the future: the GTRF realisation and long-term maintenance will follow the state of the art of TRF implementation. For the determination of the Galileo Sensor Station (GSS) positions a global free network adjustment is applied, avoiding any tensions by fixing of station positions, and providing this way the highest internal network quality



Satellite Laser Ranging payload of Galileo IOV



(In-Orbit Validation)
IOV array

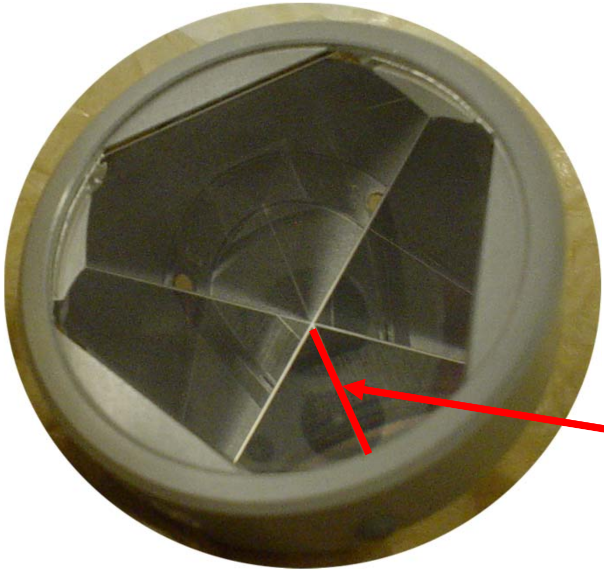


84 Corner Cube Retroreflectors (CCR)

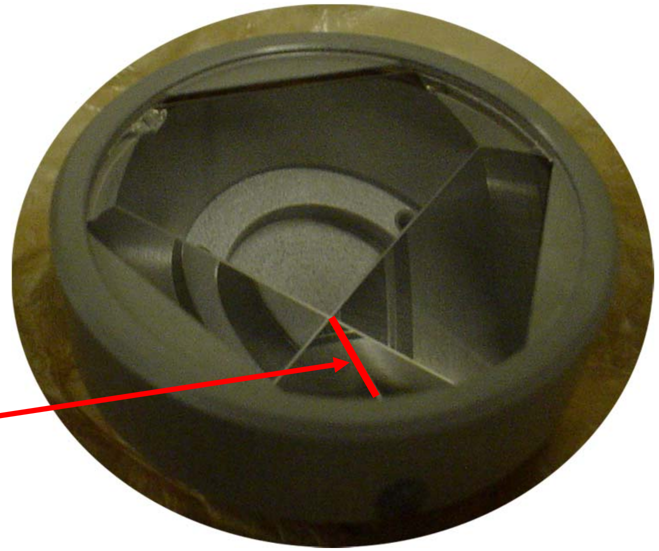
- doped fused silica (Suprasil 311) glass tetrahedron
- no metallic coating on reflective surfaces
- front surface coated with ITO (Indium Tin Oxide)
- aperture face is included in a circle of 43 mm diameter
- Minimum aperture 33 mm diameter
- height of the tetrahedron is 23.3 mm
- Iso-static mounting to plate
- Velocity aberration compensation 24 μrad
- CCR are randomly oriented

This information will be published in an update to "Specification of Galileo and GIOVE Space Segment Properties Relevant for Satellite Laser Ranging" (ESA-EUING-TN-10206) and in the "Mission Support Request Form"

Preliminary results from SCF-Testing of a prototype uncoated cube corner retroreflector (CCR) for Galileo IOV satellites provided by ESA



Optical breakthrough (BT) = loss of total internal reflection (TIR). **Left** photo: camera barely visible indicates beginning of BT at ~17^{o} light inclination towards physical edge. **Right**: full BT above 17^{o}



The INFN-LNF SCF Team

Istituto Nazionale di Fisica Nucleare (INFN) - Laboratori Nazionali di Frascati (LNF)

Frascati (Rome), Via E. Fermi n. 40, 00044, Italy

Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali di Frascati

ESA request for Galileo laser tracking approved

International Laser Ranging Service

http://ilrs.gsfc.nasa.gov/

Testing of SLR payload by LNF indicated as reference by ESA

RetroReflector Array (RRA) Characteristics:

Additional information about the Galileo retroreflector array can be found in the Galileo-101 and -102 ILRS SLR Mission Support Request Form. Specifications for the Galileo retroreflector array have been extracted from this support request form:

- Number of CCRs: 84
- CCR size: 33 mm diameter, 23.3 mm height
- Material: Doped fused silica (Suprasil 311)
- Coating: Reflective surface uncoaded, incident surface coated with indium tin oxide

Additional information:

- ESA presentation on Galileo retroreflector design
- "ETRUSCO-2: An ASI-INFN Project of Technological Development and SCF-TEST of GNSS LASER Retroreflector Arrays"

SCF-Test/Revision-ETRUSCO-2

New retroreflector Key Performance Indicators (KPIs):

GRA Optical response along the GCO (GNSS Critical half-Orbit)

- **Far Field Diffraction Pattern** (FFDP) => laser return, to ground
- **Wavefront interferogram** (WI) => retroreflected laser wavefront, onboard (WI is under development and one of the true novelty of ETRUSCO-2)

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)

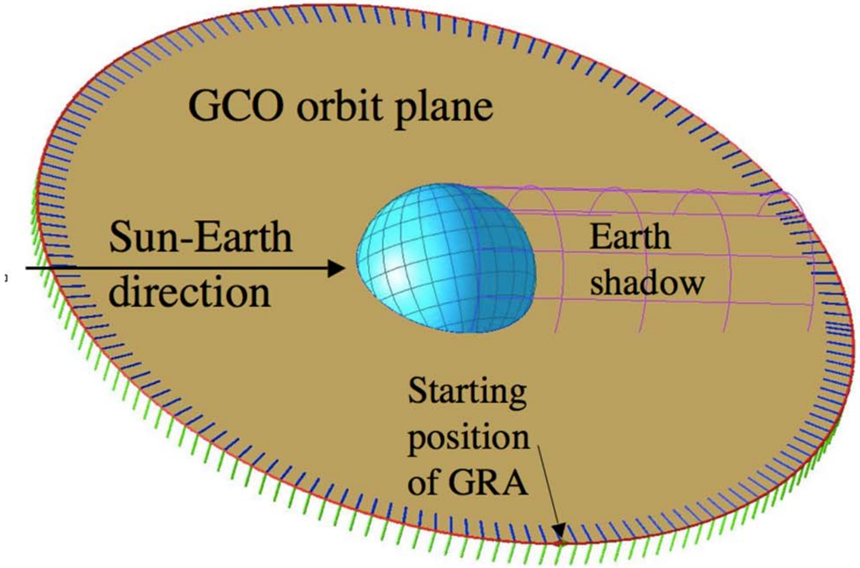
SCF-Test of GNSS Critical half-Orbit (GCO)

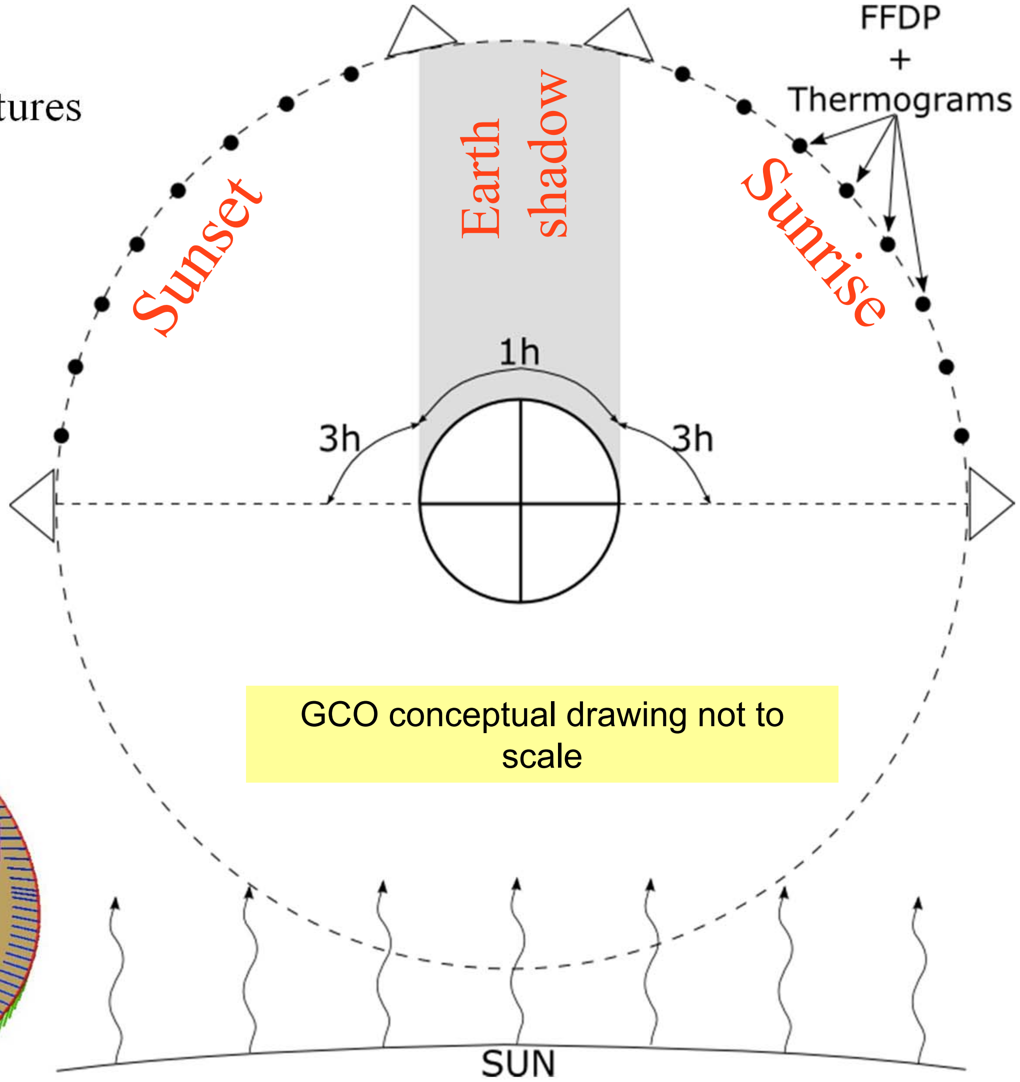
GCO: GNSS orbit with nodal line parallel to Sun-Earth direction.

Sunrise-Eclipse-Sunset probes critical features of the thermal and optical behavior of the CCR, including optical and thermal breakthrough.

Galileo orbit:

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

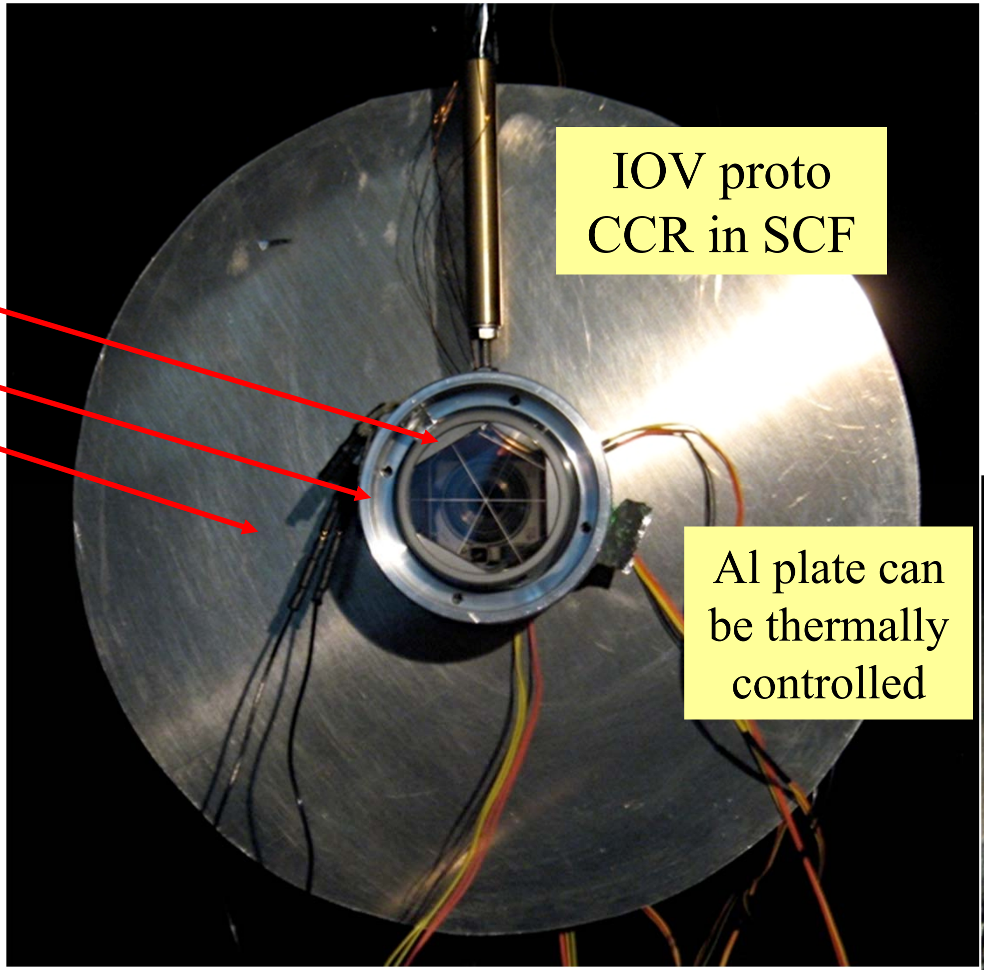




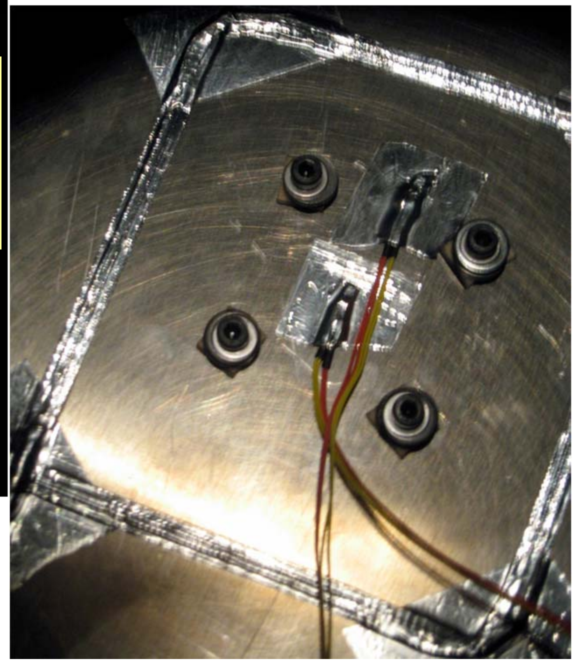
Galileo IOV SCF-Test

Galileo IOV CCR SCF-Test configuration

CCR housing
Al housing
Al back-plate
inside the
SCF



Rear side of
Al back-plate

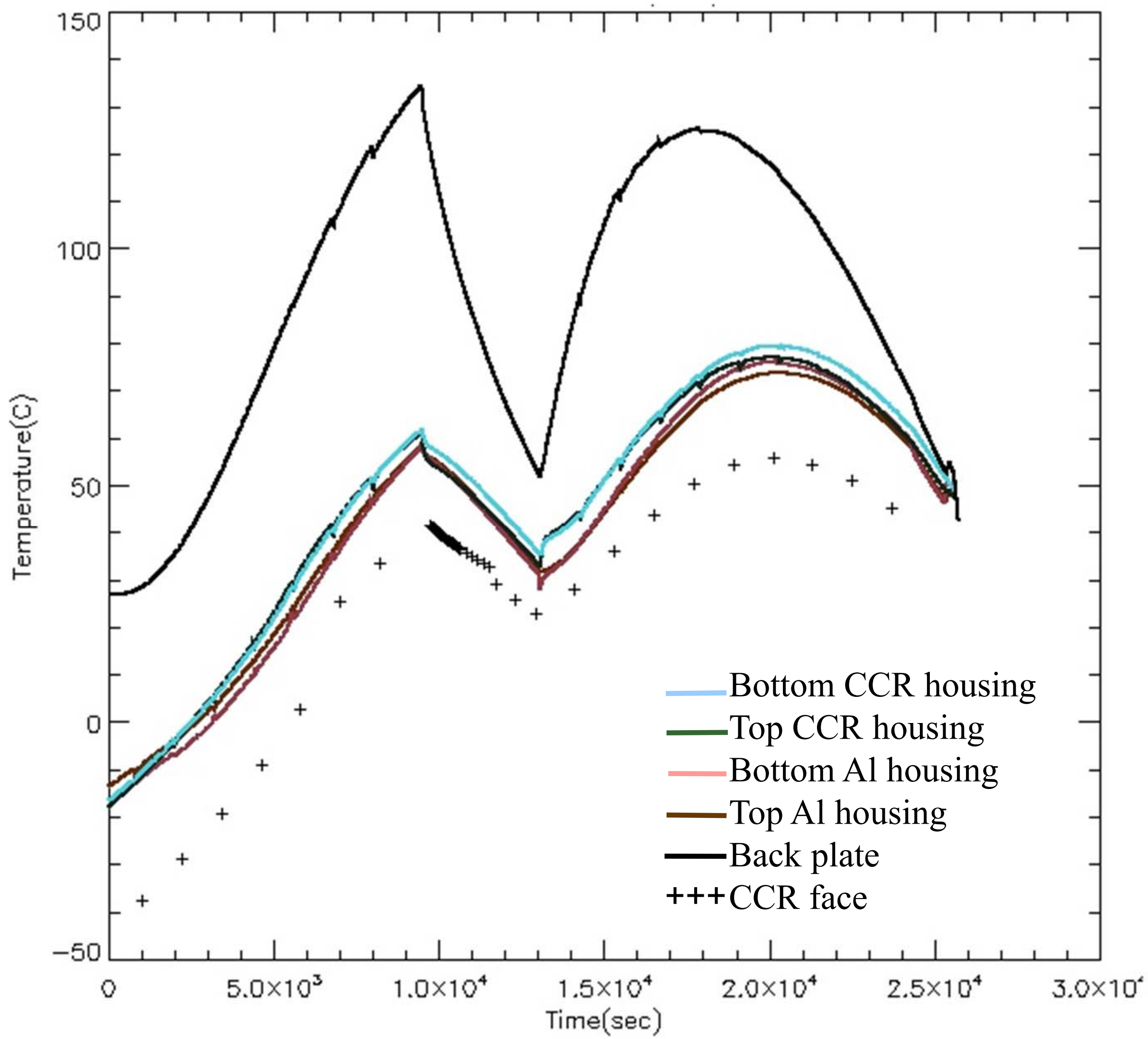


IOV CCR temperature measurements

Measured temperatures vs. time (& sun inclination):

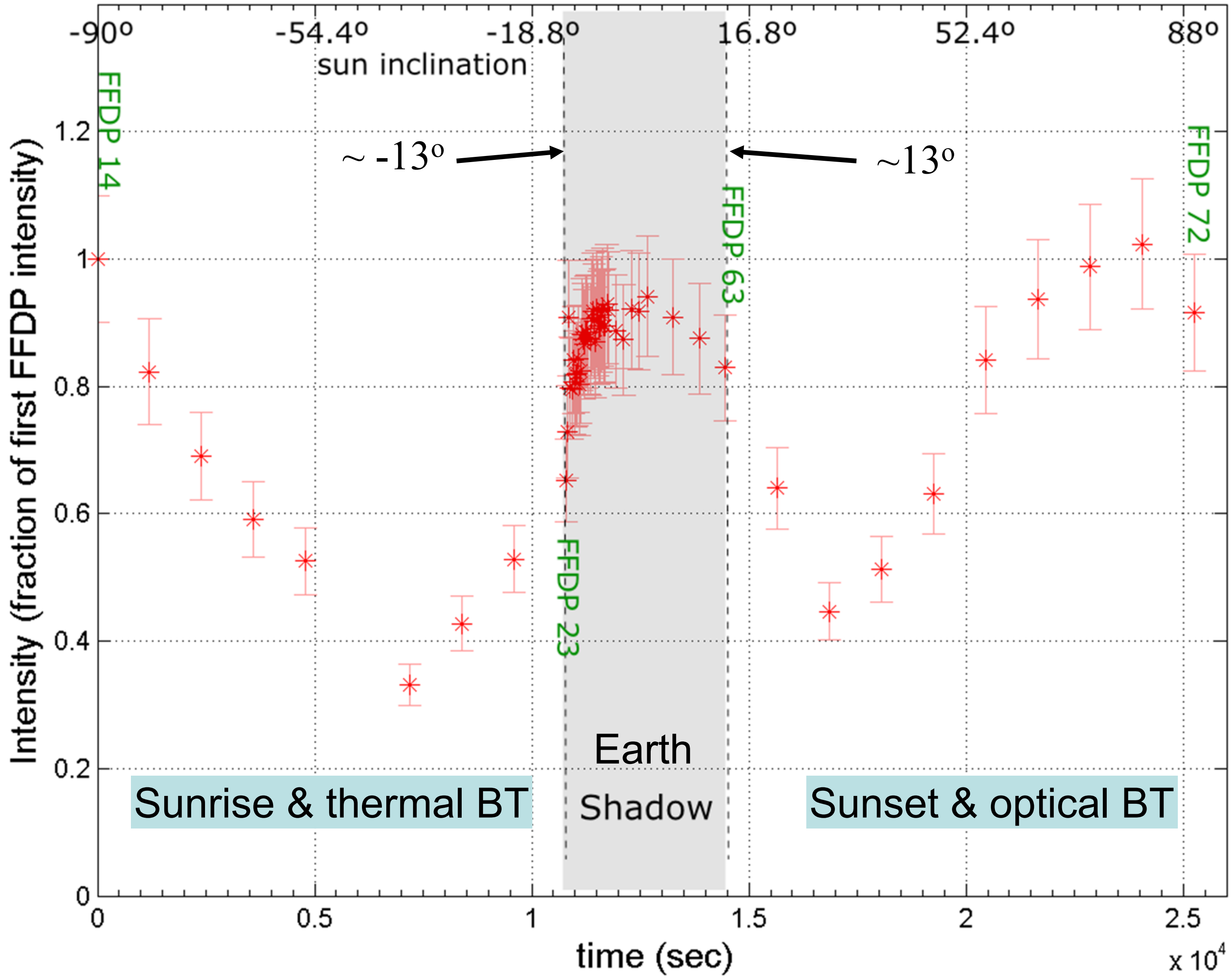
- 2 probes on CCR housing
- 2 probes on Al housing
- 1 probe on the back-plate
- IR camera thermograms of the outer CCR face

Note the very large temperature excursion, >100 K



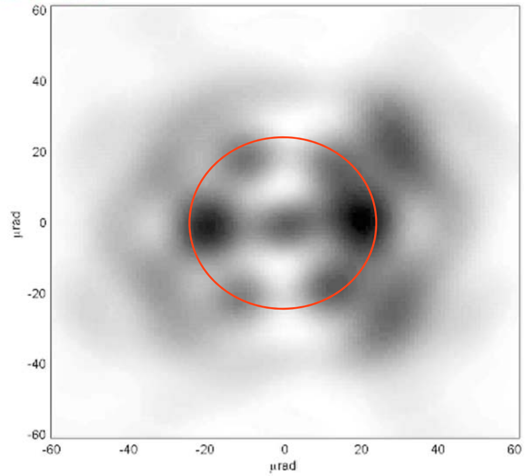
Average relative FFDP intensity at 24 μrad

"velocity aberration"

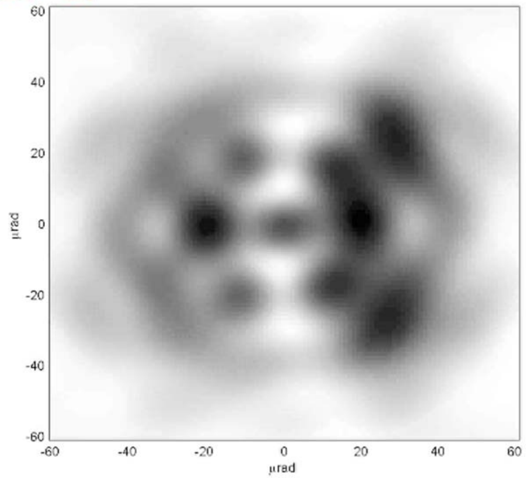


Some IOV FFDPs of previous plots

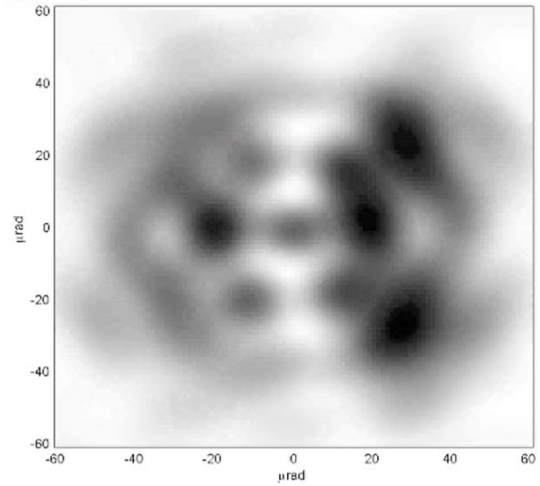
FFDP 16



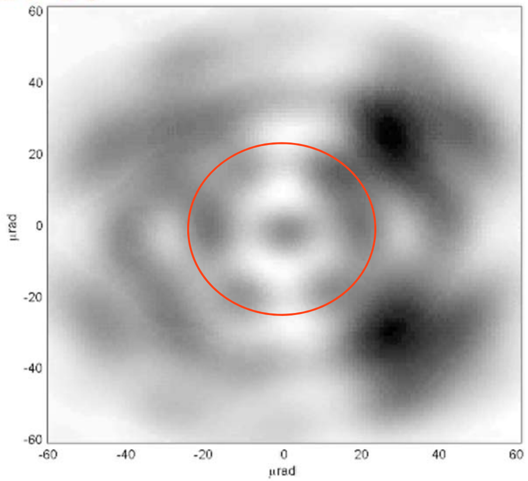
FFDP 17



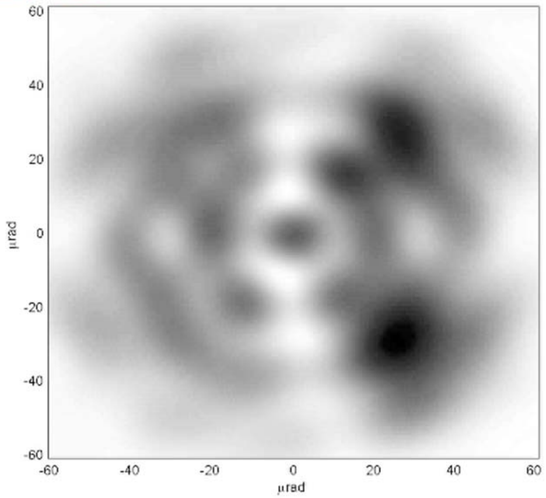
FFDP 18



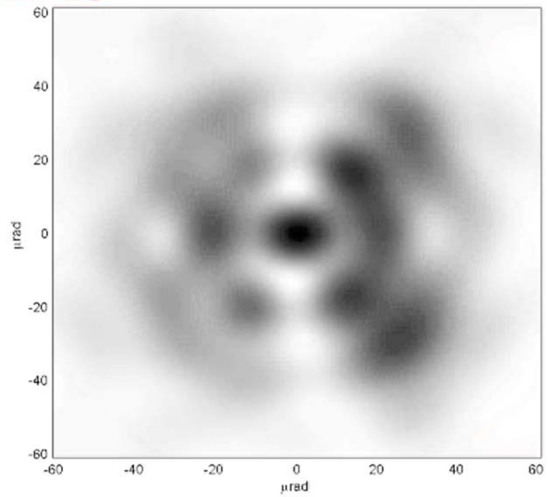
FFDP 20



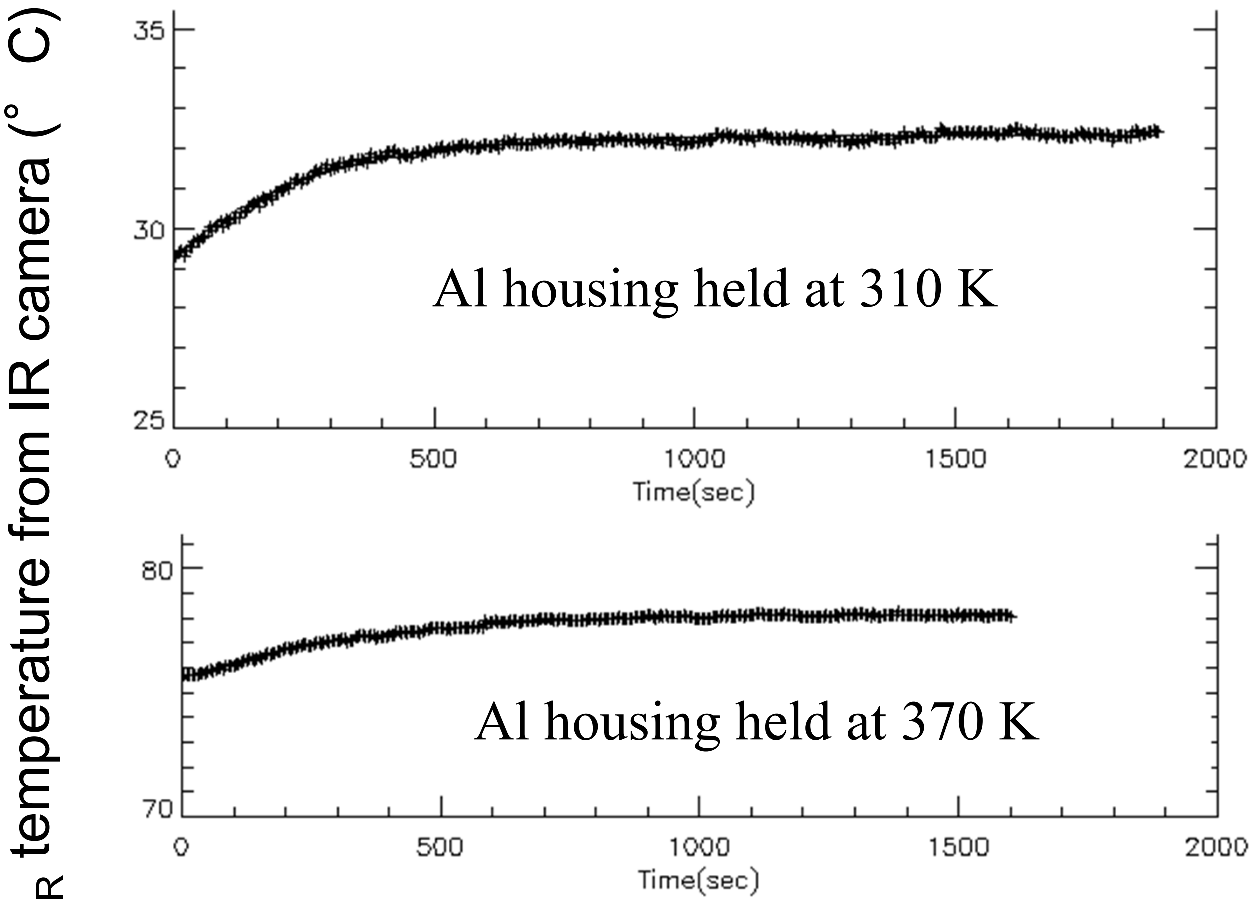
FFDP 21



FFDP 23



Measurement of IOV τ_{CCR}



Exponential fits:

τ_{CCR}(T~310K) = **245** s
ΔT = 3.0 ° C
T_i = 25.8 ° C

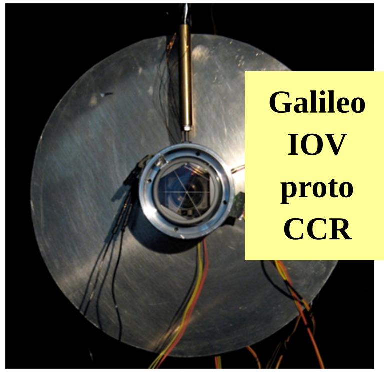
τ_{CCR}(T~370K) = **341** s
ΔT = 2.6 ° C
T_i = 75.5 ° C

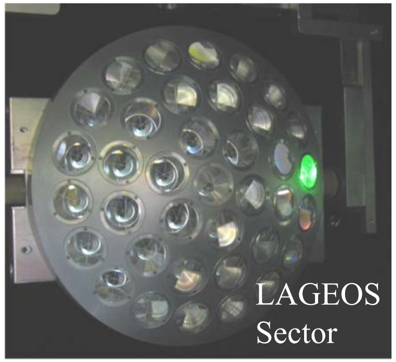
IOV τ_{CCR} increases with T of the Al-housing by ~30%

Instead, LAGEOS τ_{CCR} decreases with T of the bulk Al, as $1/T^3$

Preliminary indications from IOV τ_{CCR}

- IOV τ_{CCR}~250 sec at 310 K, shorter than previous SCF-Test measurements
  - ✓ Al-coated GPS/GLO/GIOVE CCRs of flight array and a prototype CCR: τ_{CCR}~700-1100 sec
  - ✓ Many uncoated CCRs of the LAGEOS "Sector", for which τ_{CCR}~ thousands of seconds
- IOV τ_{CCR} increases from 310 K to 370 K by ~30%; this indicates that in the CCR mounting heat conduction dominates.
- For LAGEOS we measured $\tau_{CCR} \sim 1/T^3$; this indicates that radiative heat exchange dominates in an optimized CCR mounting (confirmed by simulations)





Conclusions and prospects

- New SCF-Test/Revision-ETRUSCO-2 (except for the WI) applied to a prototype Galileo IOV CCR
- **This specific IOV CCR better than GLONASS/GPS/GIOVE in terms of optical degradation**
  - Al-coating removed, finally, on modern GNSS, after 30 years, thanks to our SCF-Test results.
- <u>Important</u> to SCF-Test more IOV retroreflectors
- <u>Mandatory</u> to SCF-Test FOC-1 retroreflectors, which are different from IOV (different makers)
- <u>Ultimate goal</u>: develop and SCF-Test best possible GRA for FOC-2, with a pan-European effort, to reduce dependence of Europe's flagship programme from non-European laser retroreflector technologies
- Discussions underway for GPS-3 and other GNSS constellations: IRNSS, COMPASS, QZSS

Acronyms and definitions

1. AM0: Air Mass Zero
2. ASI: Agenzia Spaziale Italiana
3. BT: Break Through
4. CCR: Cube Corner Retroreflector
5. ESA: European Space Agency
6. ETRUSCO: Extra Terrestrial Ranging to Unified Satellite Constellation
7. FFDP: Far Field Diffraction Pattern
8. FOC: Full Orbit Capability
9. GCO: GNSS Critical half Orbit
10. GNSS : Global Navigation Satellite System
11. GPS: Global Positioning System
12. GRA: GNSS Retroreflector Arrays
13. GTRF: Galileo Terrestrial Reference Frame
14. ILRS: International Laser Ranging Service
15. IOV: In Orbit Validation
16. IP: Intellectual Property
17. ITRF: International Terrestrial Reference Frame
18. ITRS: International Terrestrial Reference System
19. KPI: Key Performance Indicator
20. OCS: Optical Cross Section
21. LAGEOS: LAser GEOdynamics Satellite
22. SCF: Satellite/lunar laser ranging Characterization Facility
23. SLR: Satellite Laser Ranging
24. TIR: Total Internal Reflection
25. WI: Wavefront Interferogram

Questions or comments?