Satellite and Lunar Laser Ranging: Science and Technology Applications

Simone Dell'Agnello (INFN-LNF, Frascati National Labs)

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(www.lnf.infn.it/esperimenti/etrusco)

Winter College on Optics: **Light: a bridge between Earth and Space**

IYL-2015

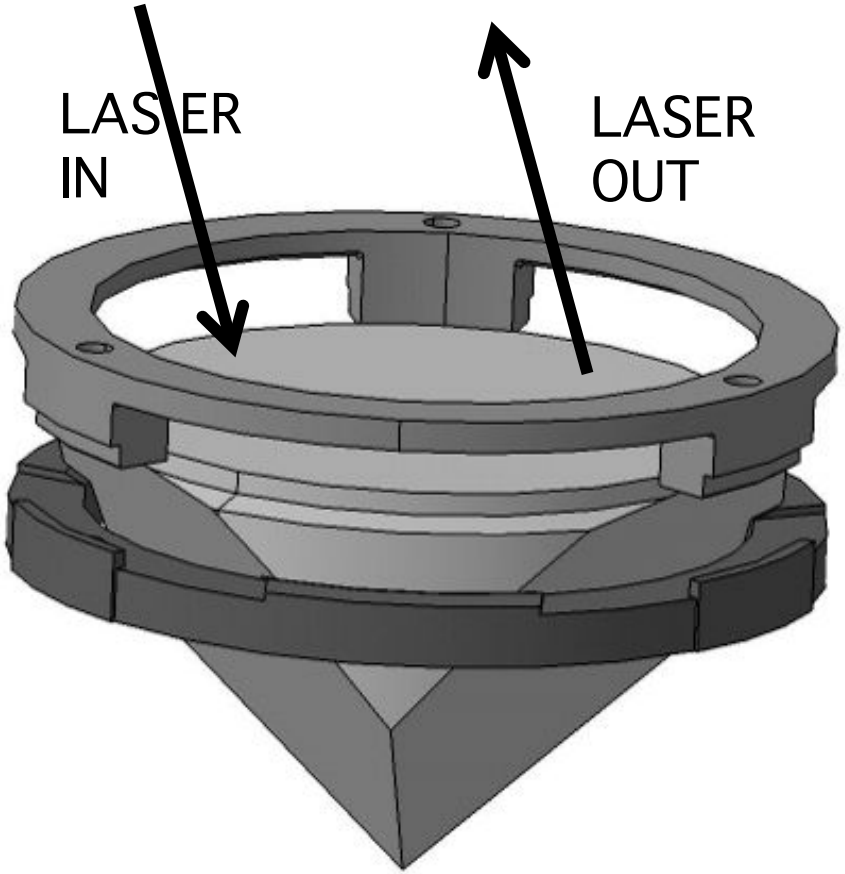
ICTP, Trieste, Italy - February 19, 2015

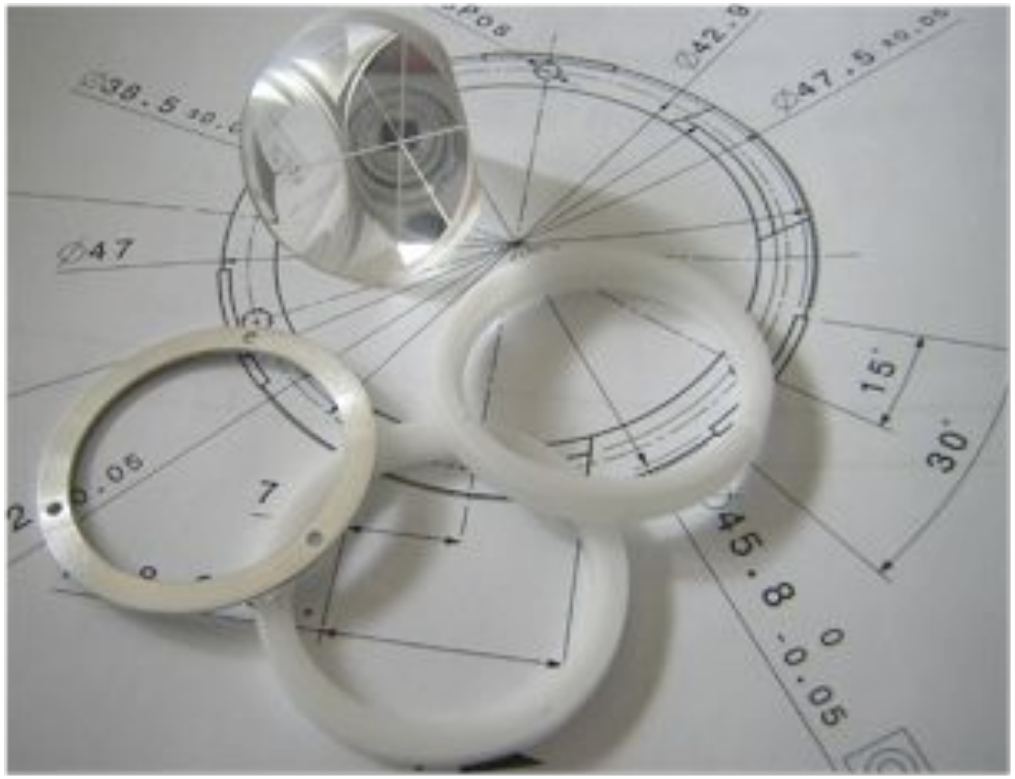
Outline

- Laser Retroreflectors and Laser Ranging in Space
- Satellite Laser Ranging Science application: International Terrestrial Reference System
- SCF_Lab @INFN, Italy: Unique Test Facility for Laser Retroreflectors in Space
- Technology Application: Global Navigation Satellite System
- Lunar Laser Ranging Science Application: Test of General Relativity
- Applications to Exploration of Mars System
- Conclusions and vision foreword

Laser retroreflector working principle

Cube Corner Retroreflectors (CCRs) made of special fused silica glass (Suprasil). Total internal reflection (TIR) on each of the faces causes Retroreflection in the same direction of incidence





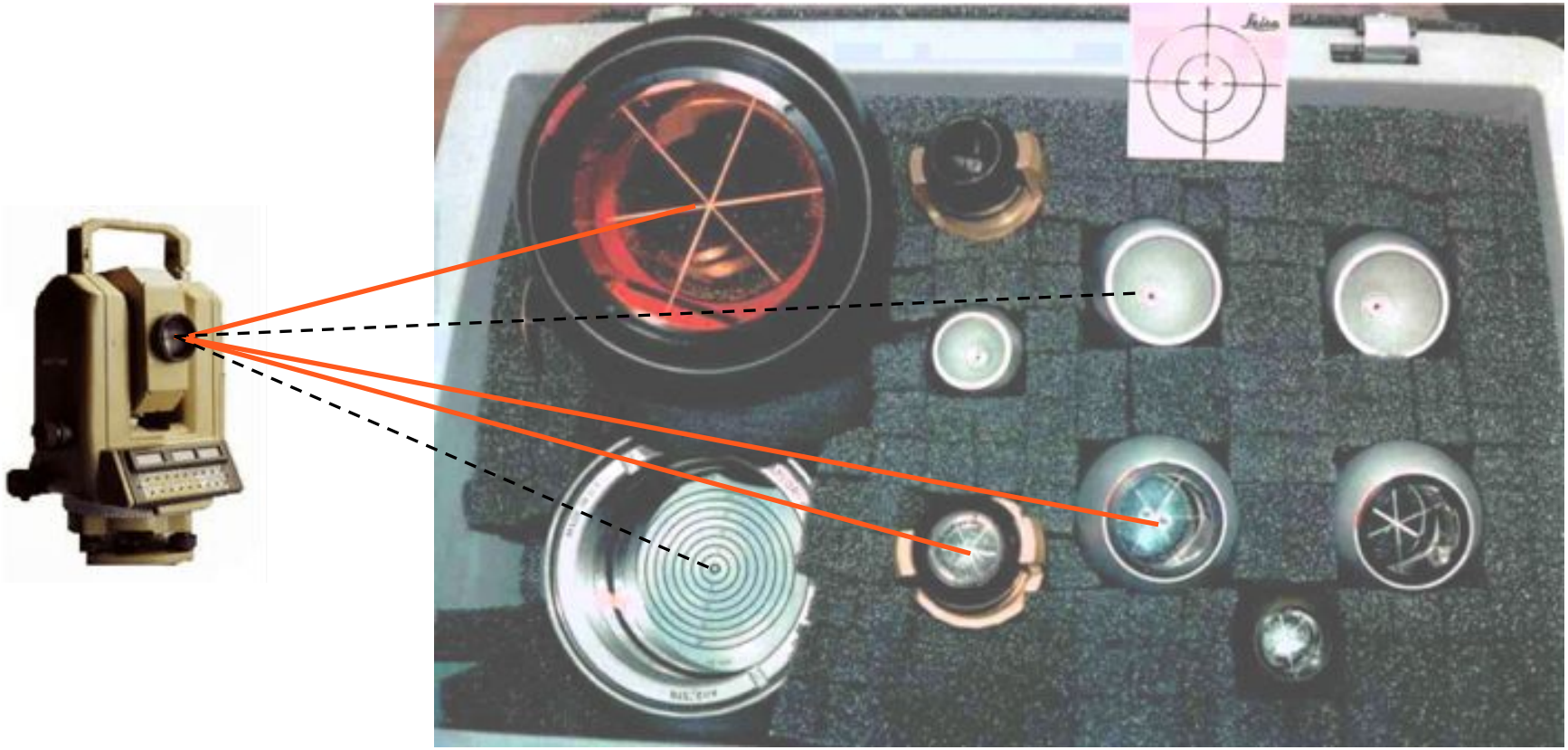
Triple (retro)reflection around the corner of the cube

Laser Retroreflectors

For ground positioning metrology: CCRs typically mounted inside half-spheres

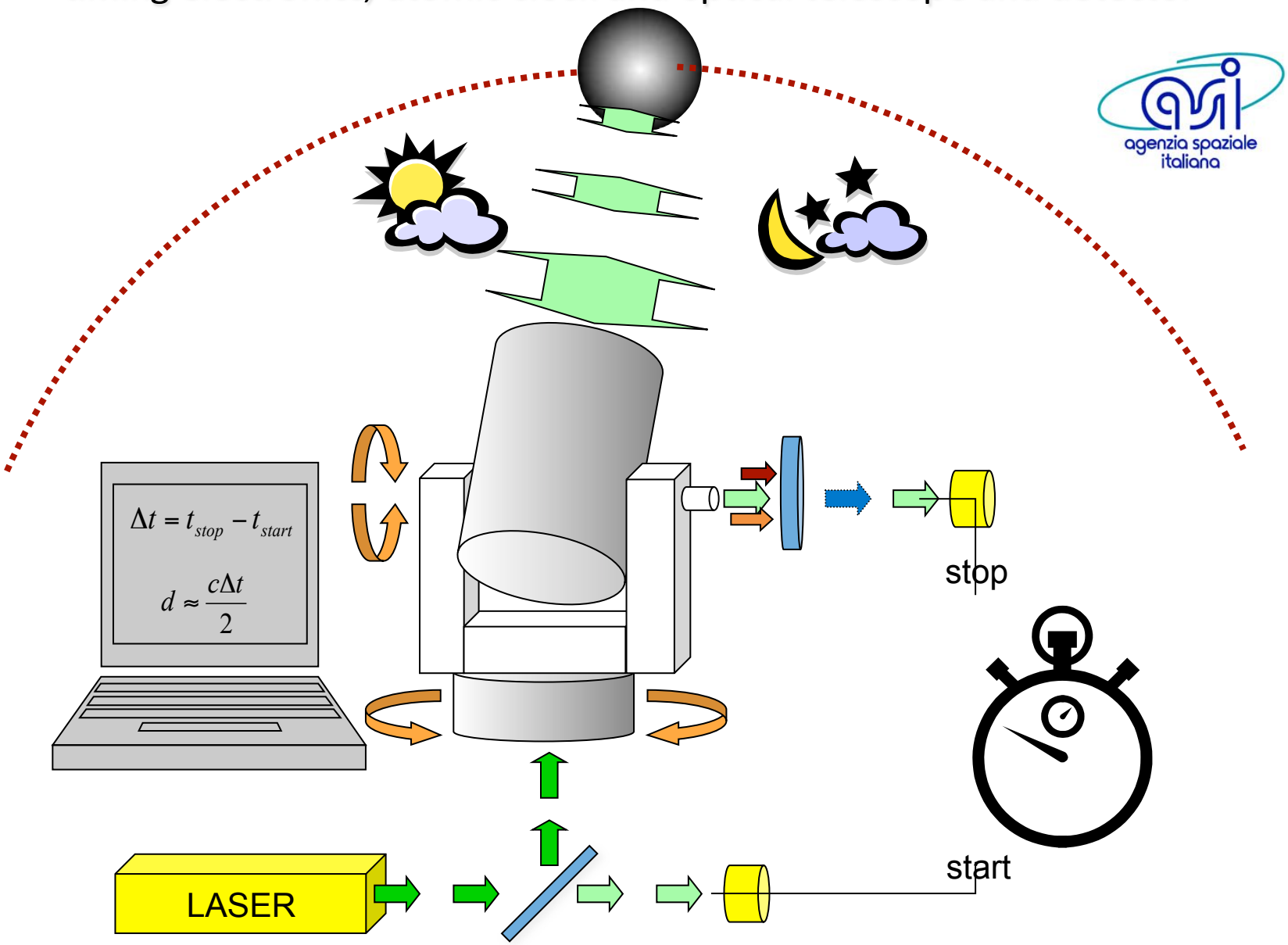
Taylor-Hobson sphere
For angular measurements

Laser-retroreflector ground applications:
theodolite (or laser "tracker"), retroreflector, time-of-flight



Used for positioning metrology of large physics installations, like Particle accelerators and particle physics experiments (at CERN in In Geneva, Fermilab in USA, Desy in Germany, DAΦNE in Italy …)

Laser Ranging in space: measurement of time-of-flight from ground laser station to satellite equipped with laser retroreflectors: pulsed laser, precision timing electronics, atomic clock and optical telescope and detector

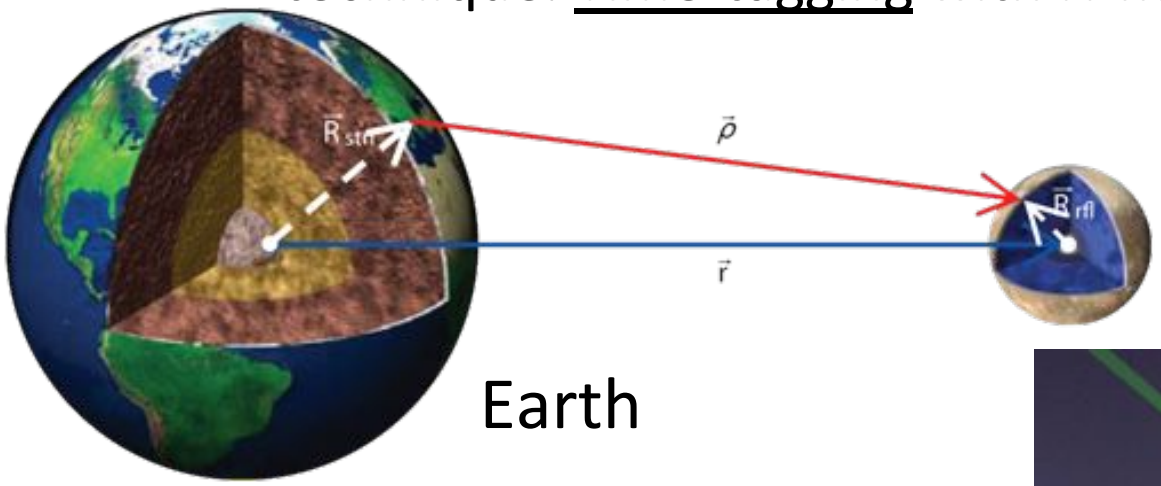


Matera Laser Ranging Observatory

Satellite/Lunar Laser Ranging (SLR/LRR)

Physical point-to- point link of laser pulses between ground and space

Unambiguous position/distance measurement ('laser range') to cube corner retroreflectors (CCRs) with short laser pulses and a time-of-flight technique. Time-tagging with H-maser clocks

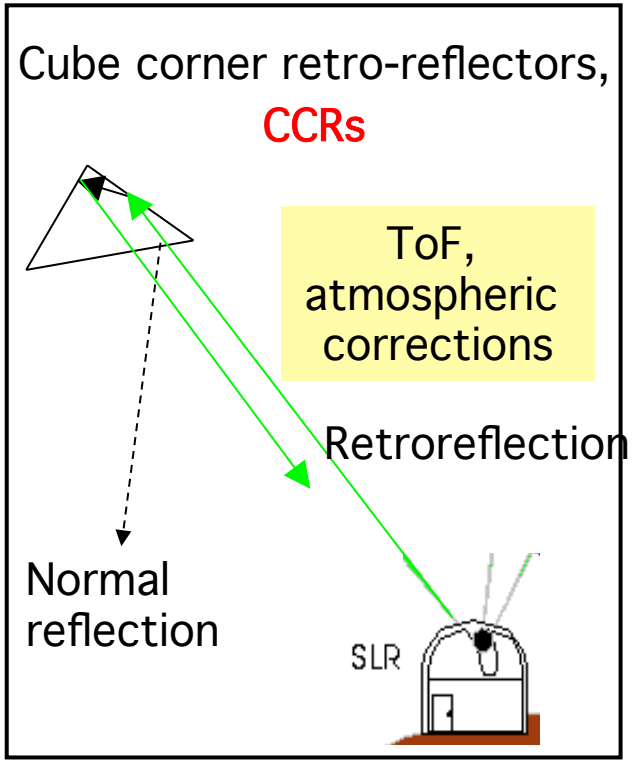


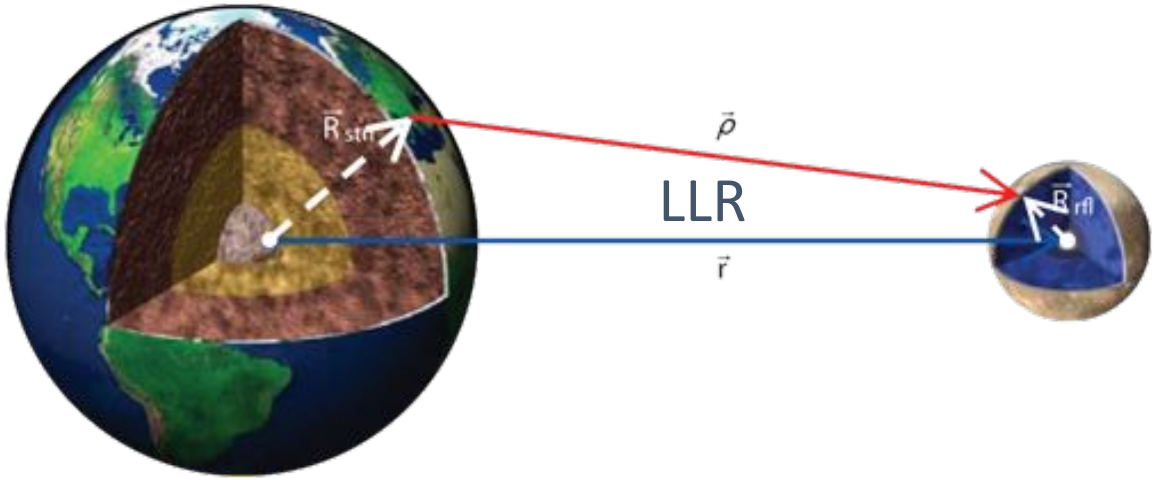
Moon

Earth

- **Precise** positioning (normal points at mm level, orbits at cm level)
- **Absolute** accuracy (used to define Earth center of mass, geocenter, and scale of length)
- **Passive**, maintenance-free Laser Retroreflector Arrays (**LRAs)**

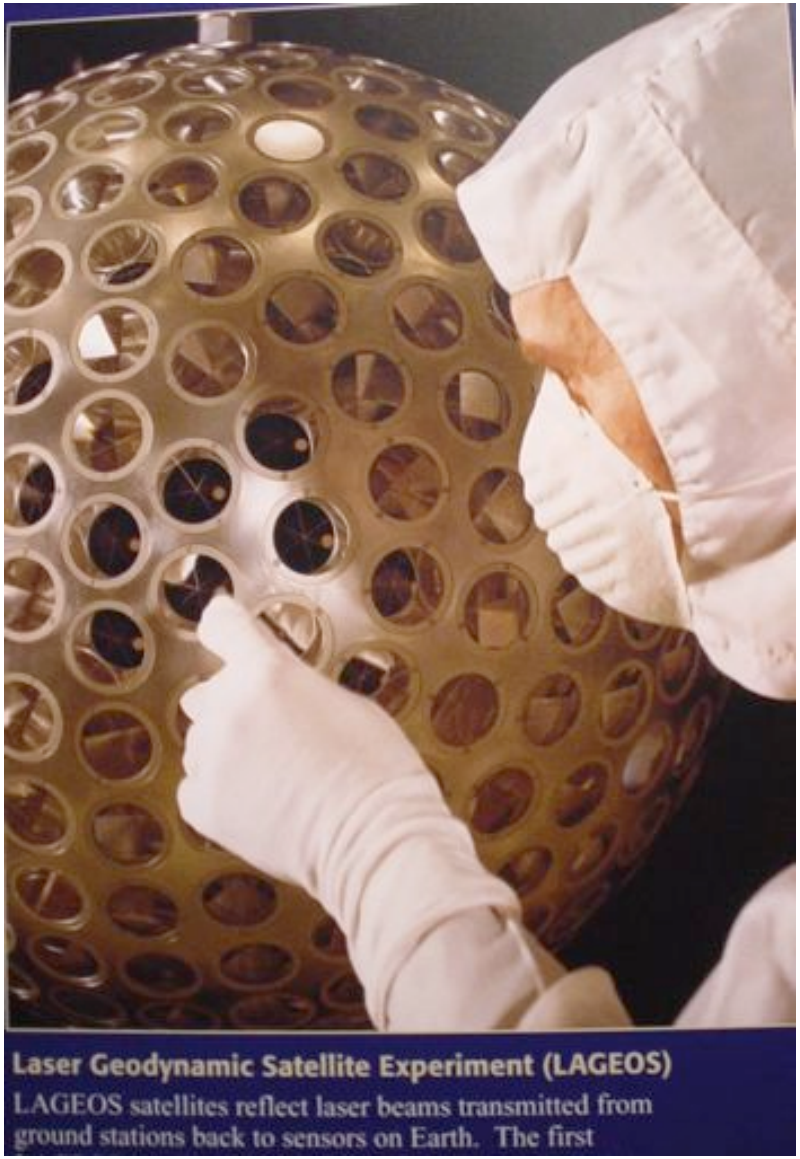
Lunar Laser Ranging (LLR)
Satellite Laser Ranging (SLR)
Time of Flight measurement (ToF)

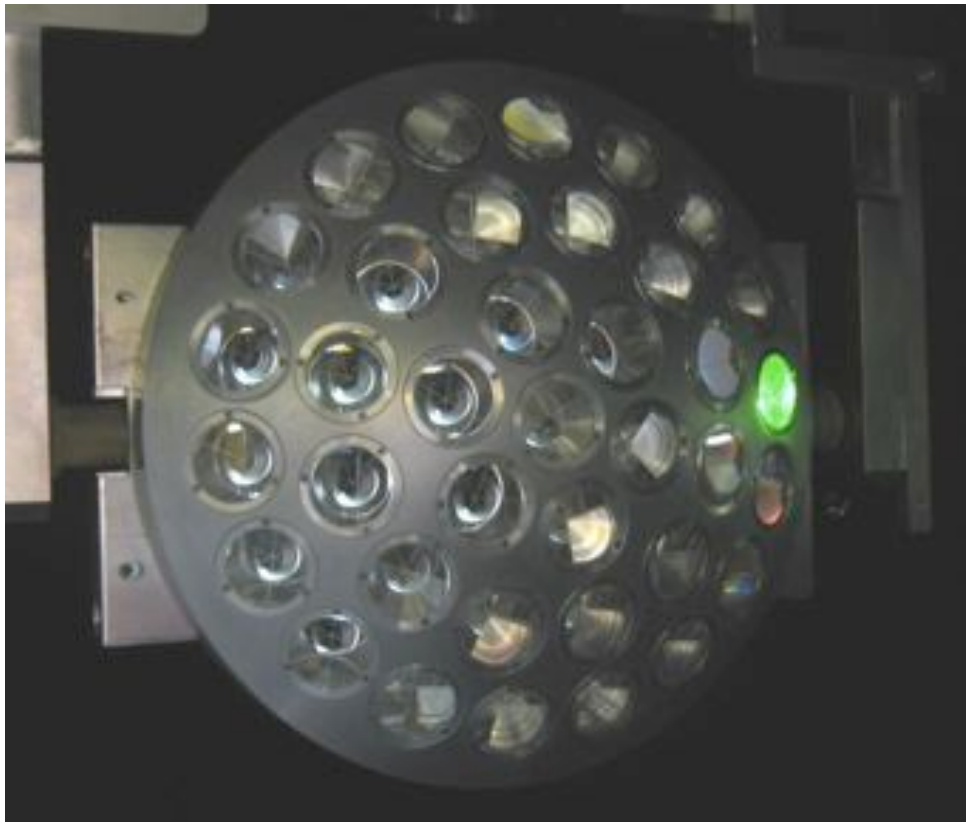




Laser Geodynamics Satellites (LAGEOS)

LAGEOS I (1976; NASA), LAGEOS II (1992; NASA/ASI)





LAGEOS "Sector", engineering prototype by NASA-GSFC, now at INFN-LNF Frascati for testing

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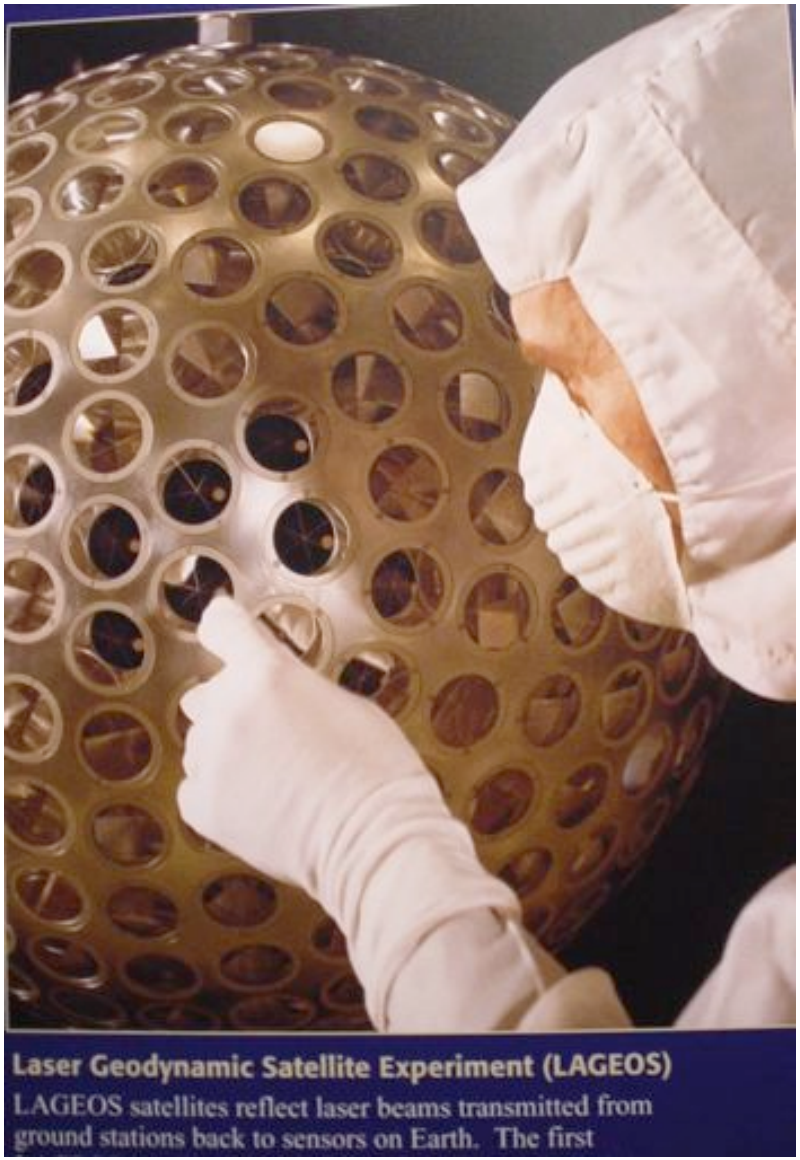
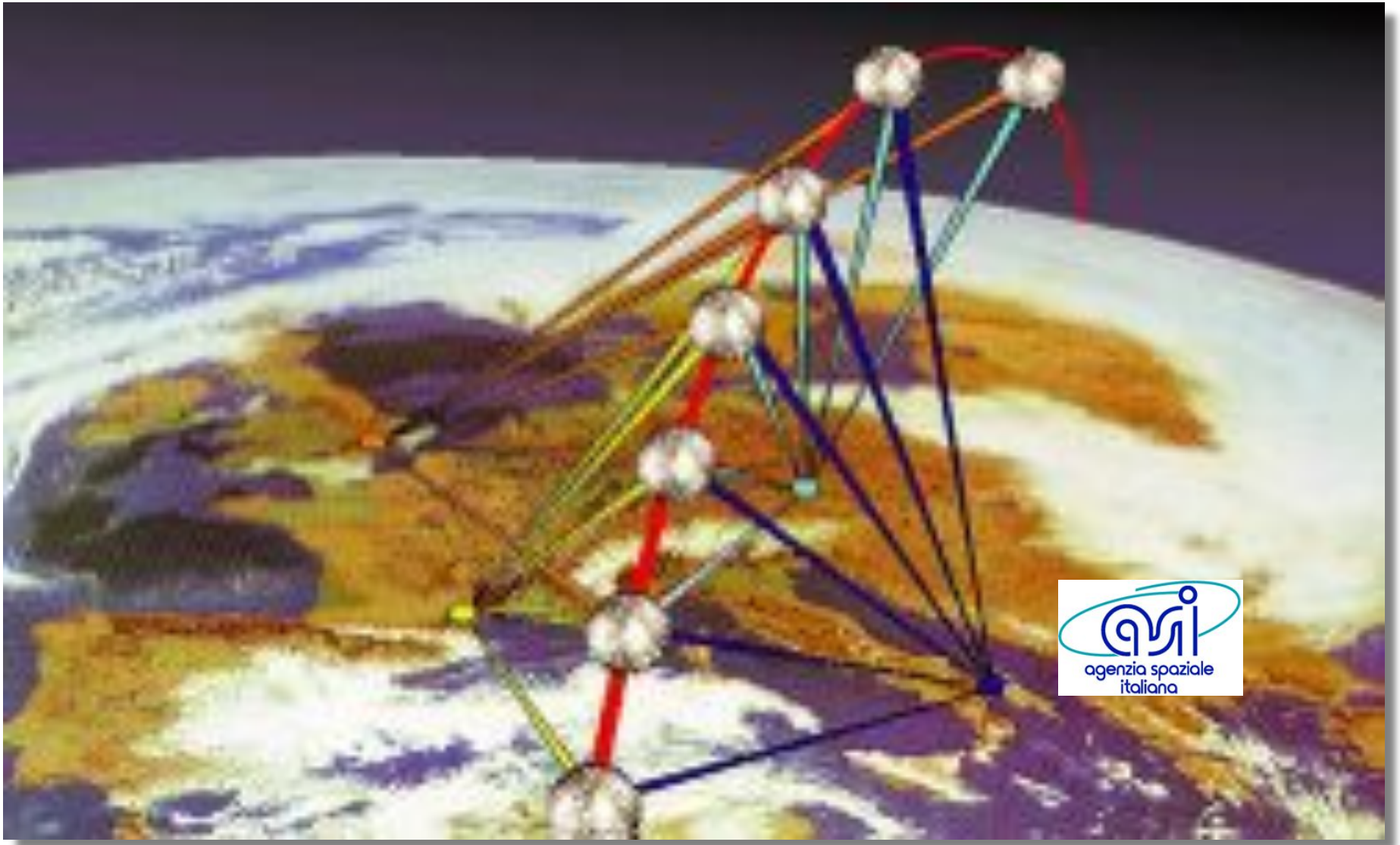


Summers students

LAGEOS "Sector", engineering prototype by NASA-GSFC, now at INFN-LNF Frascati for testing

LAGEOS laser-tracked by ILRS stations of Matera (IT), Herstmonceux (UK), Graz (AT), OCR (FR)



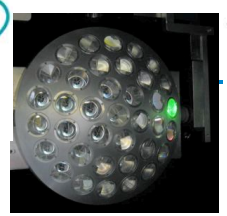
SLR/LLR examples

S

L

R

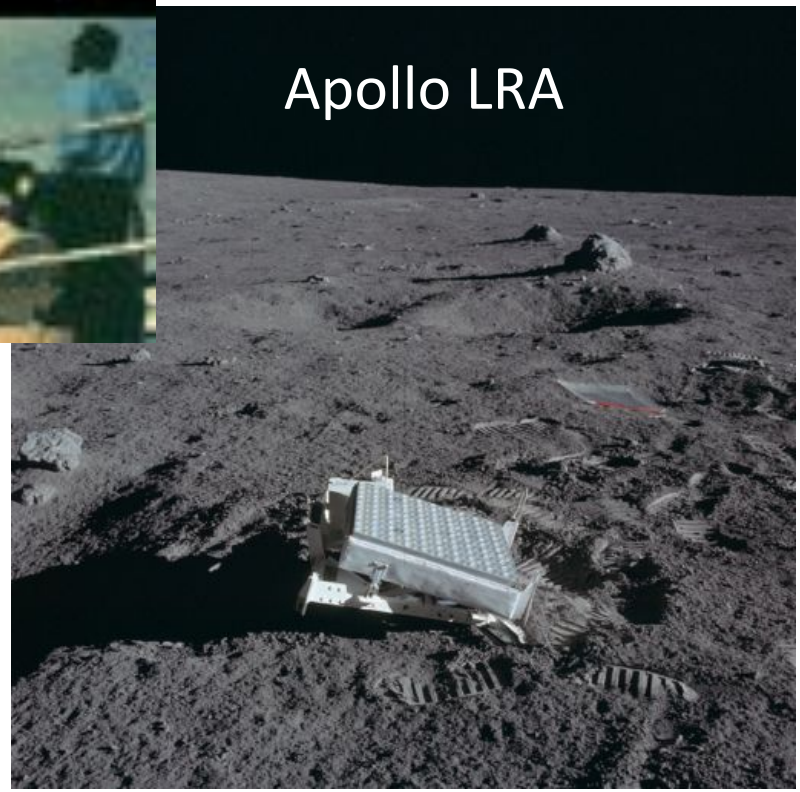
LAGEOS



(altitude ~6000 km):

ToF ~ 0.05 sec

Apollo LRA



Moon

(d ~ 380000 km):

ToF ~ 2.5 sec

Centro di Geodesia Spaziale *Giuseppe Colombo*
Matera, Italy
Site position known by SLR, VLBI, GNSS (“tri-located”)

MLRO,
Matera Laser Ranging Observatory
LLR since 2010

Satellite/Lunar Laser Ranging (SLR/LLR)

Time of Flight (ToF) measurements of short laser pulses

1st SLR to cube corner retroreflectors (CCRs):
October 31, 1964 from NASA-GSFC, by H. Plotkin et al

Intern. Terrestrial Reference System (ITRS)

- **Geocenter** from SLR/LAGEOS
- **Scale** from SLR and VLBI
- **Orientation** from VLBI
- **Distribution w**/GNSS. Also DORIS

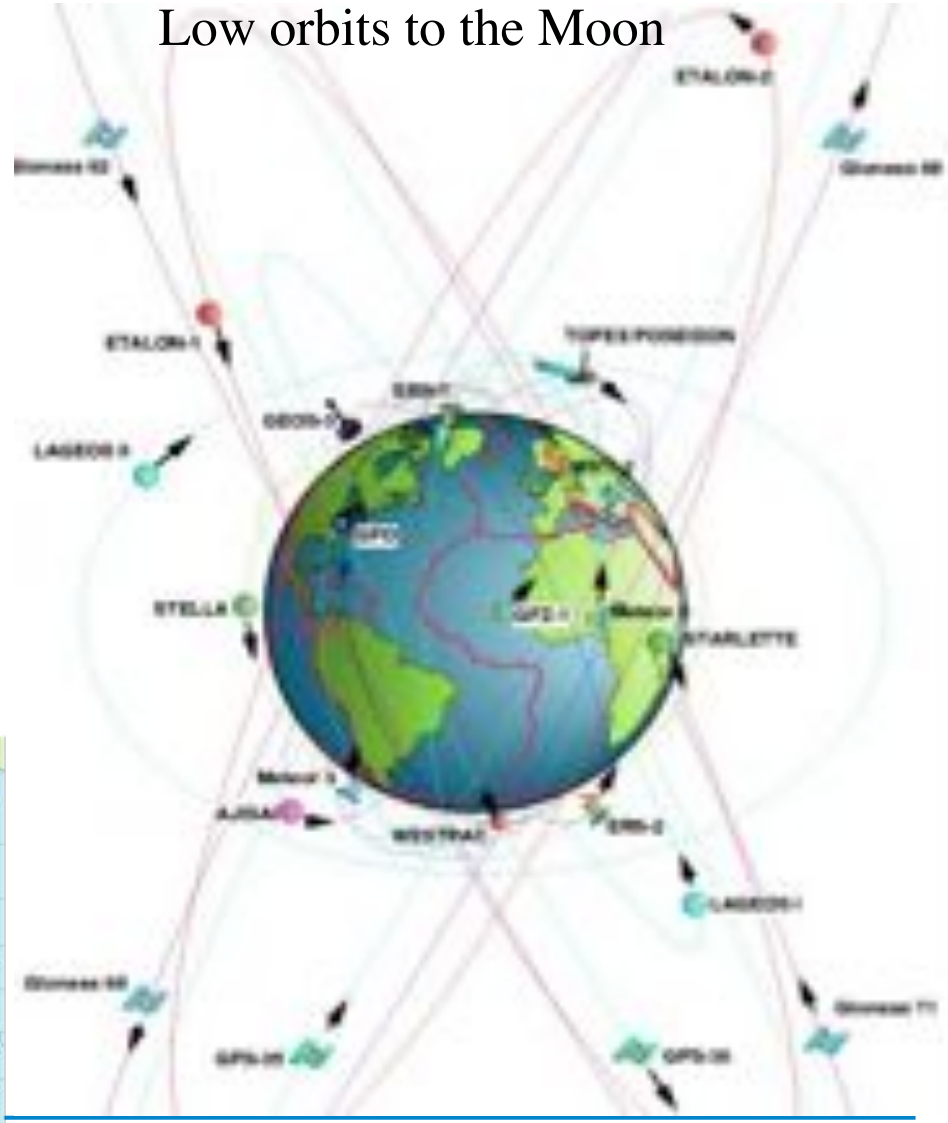
For Geodesy, GNSS, Gravity, Earth Observation

LAGEOS

International Laser Ranging Service

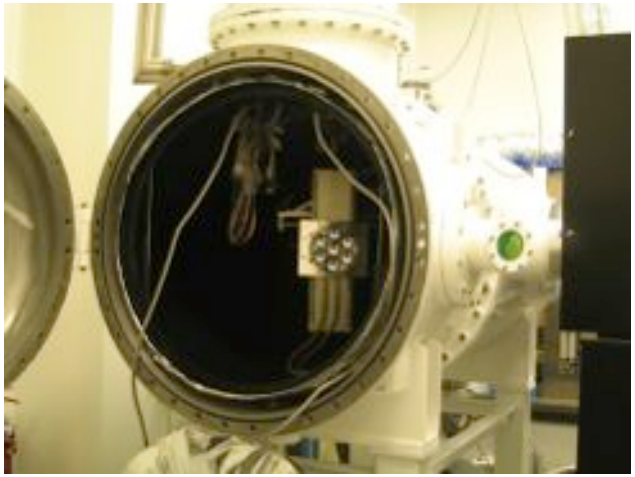
SLR CONSTELLATION

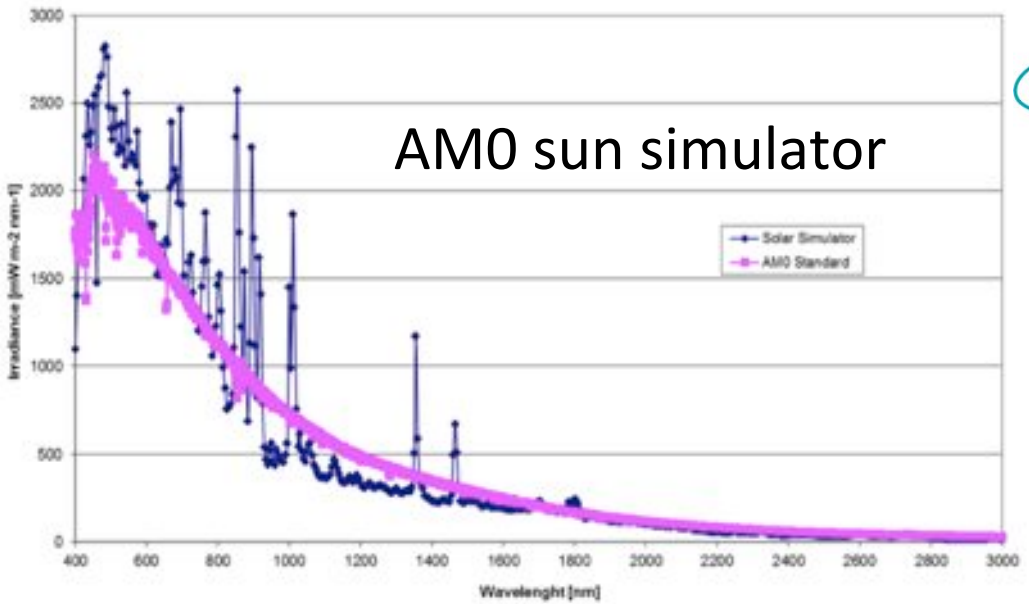
Low orbits to the Moon



SCF_Lab: retroreflector characterization

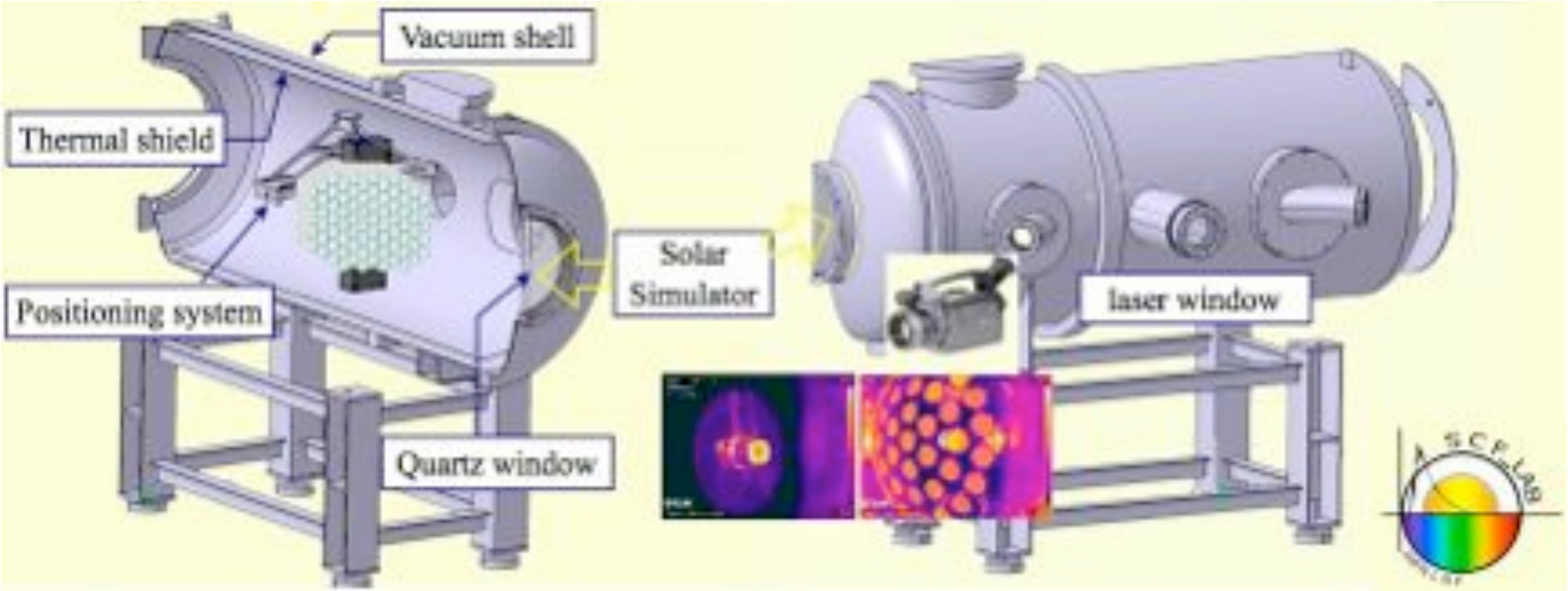
- Two Optical Ground Support Equipment (OGSE)
- SCF (top right) SCF-G (bottom right) dedicated to Galileo, other GNSS
- Two AM0 sun simulators, IR thermometry
- Detailed optical testing
- J. Adv. Space Res. 47 (2011) 822–842





SCF_Lab: retroreflector characterization

- Two Optical Ground Support Equipment (OGSE)
- (Better than) Class 10000 (ISO 7) Clean Room



SCF-Test: Retroreflector characterization

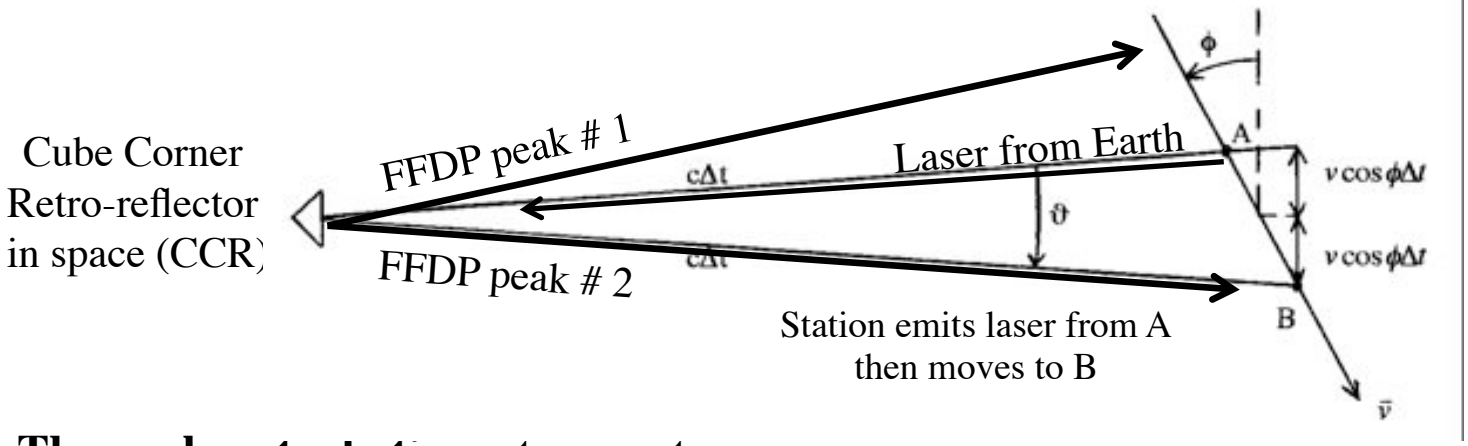
- Accurately laboratory-simulated space conditions
  - TV + Sun (AM0) **simulators**
  - IR and contact **thermometry**
  - Payload **roto-translations** and **thermal control**

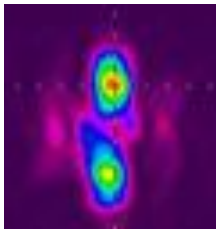
- Deliverables / Retroreflector Key Performance Indicators
  - **Thermal relaxation** time of retroreflector (τ_{CCR})
  - **Optical response**
    - Far Field Diffraction Pattern (**FFDP**)
    - Wavefront Fizeau Interferometer (WFI), vibe-insensitive

- Invariant lidar Optical Cross Section, OCS, in air/ isothermal conditions

CCRs in space: thermal & optical issues

- **Compensation of station-satellite Velocity Aberration (or "point-ahead" effect)**: requires accurate dihedral angle offsets w/0.5 arcsec accuracy to control shape (angle θ) and intensity of laser return (FFDP, Far Field Diffraction Pattern) to ground





FFDP peaks back to ground

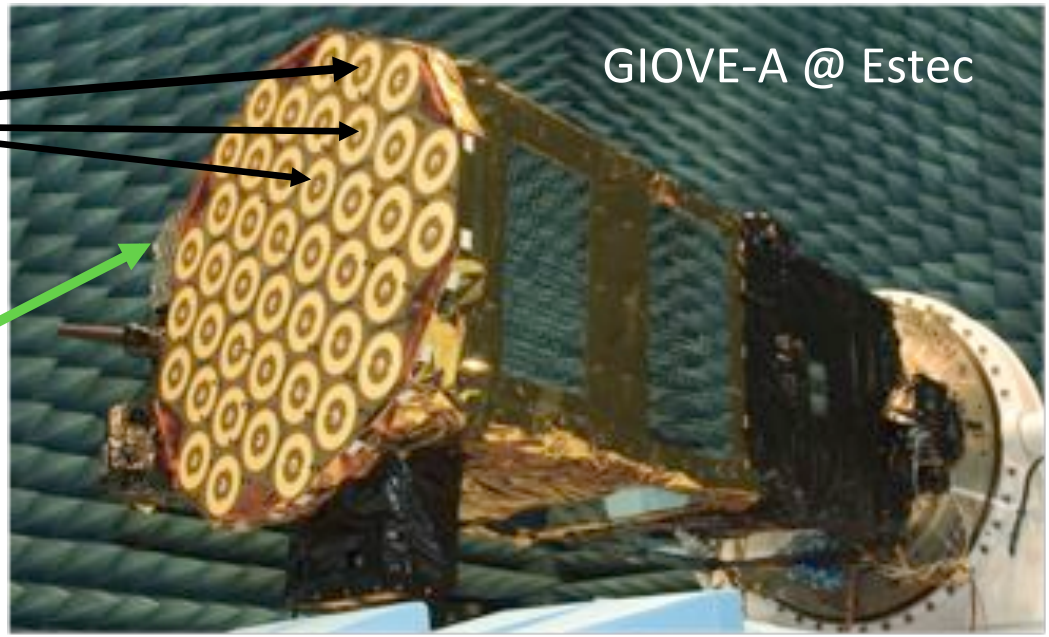
- **Thermal perturbations:** temperature gradients across CCR can degrade laser performance
  - A CCR could work at STP, BUT not in space for thermal reasons
- **Design** CCR array to control thermal and optical properties
- **SCF-Test**: characterize performance at dedicated INFN-LNF facility

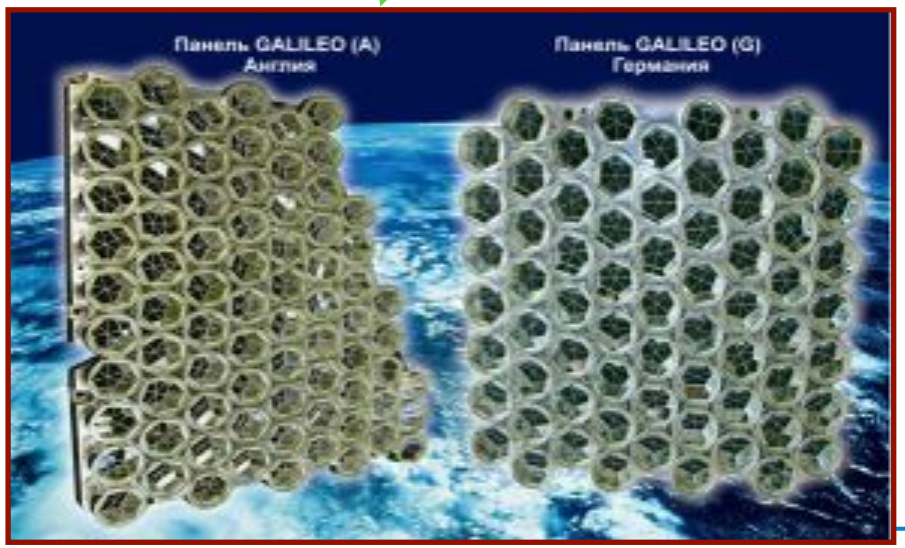
GNSS velocity aberration is
$\theta \sim 2\ v/c \cos\phi \sim 25\ \mu rad$ (~ 500 m on the ground)
Achievable with choice of CCR diameter or variety of dihedral angle offsets from 90°
Nominal distance between FFDP peaks is
$2 \times \theta = 50\ \mu rad \Rightarrow 1$ Km

GLONASS, GPS and GIOVE-A/B CCRs

Microwave antennas

LRA





Benefits of LRAs on GNSS

- Only independent validation/calibration of GNSS orbits, with 2-4x better precision
- Absolute positioning, ie, wrt ITRS
- Long term stability & geodetic memory
- Therefore: **combining SLR+GNSS data will improve orbit reconstruction**

Russian GLONASS/GPS/GIOVE-A/B reflectors

Al-coated fused silica laser retroreflector technology, with thermal mounting not optimized as LAGEOS and Apollo Technology used since the 1980s until 2010s.
Coating now abandoned due to SLR return inefficiencies experienced by ILRS and due to SCF-Test results

Third and last GPS flight array ever made by USSR for GPS

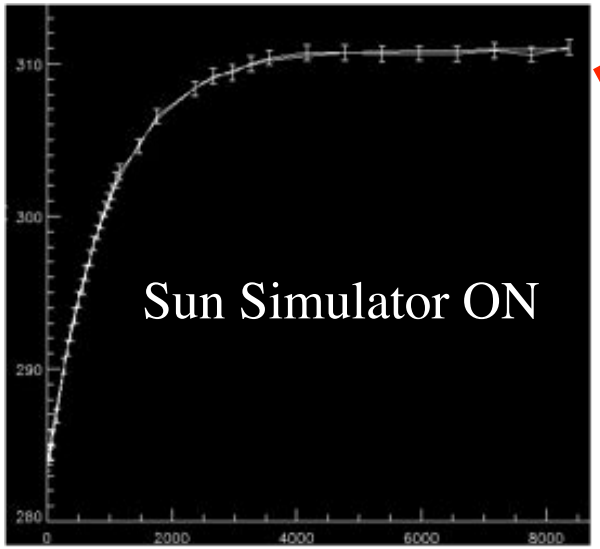
~19 x 24 cm^2

~1.3 Kg,

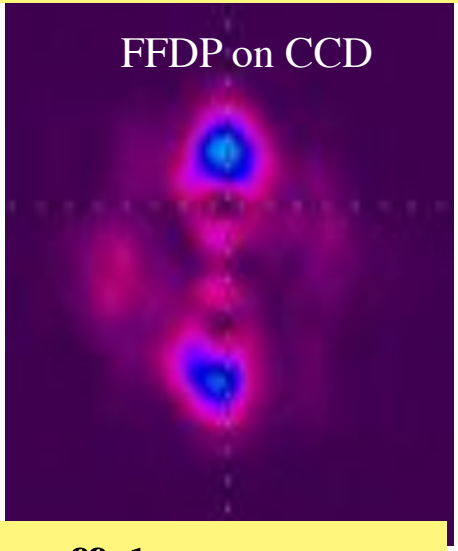
32 CCRs.

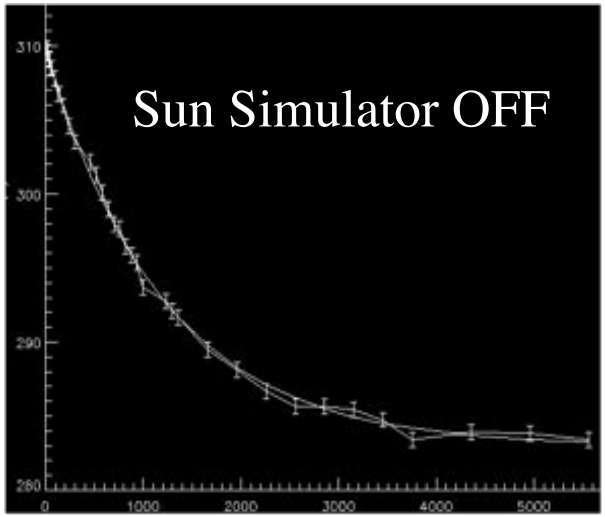
Property of University of Maryland (C. Alley, D. Currie), SCF-Tested at INFN-LNF

SCF-Test of GLO/GIOVE: **de-qualification** of Al coating

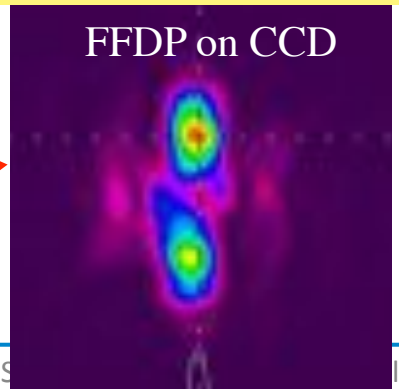


Sun on: laser return (FFDP) severely degraded (2 km distance)



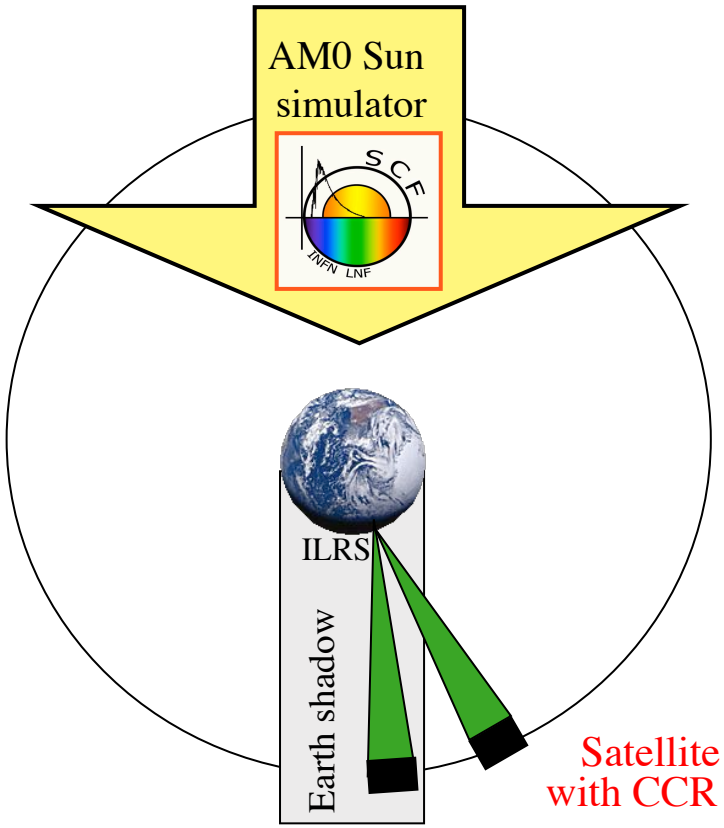


Sun off: laser return (FFDP) peaks restored at 1km distance



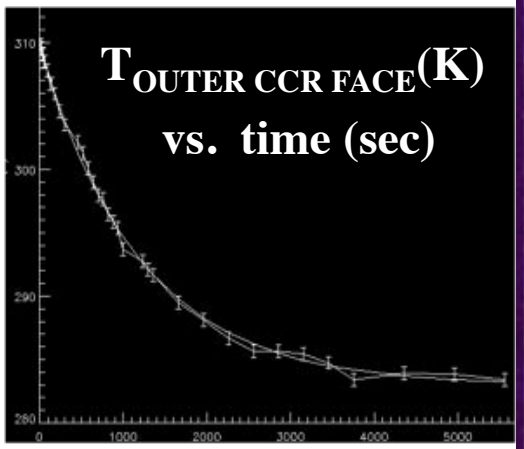
IR $T_{OUTER\ CCR\ FACE}$(K) vs t (sec)

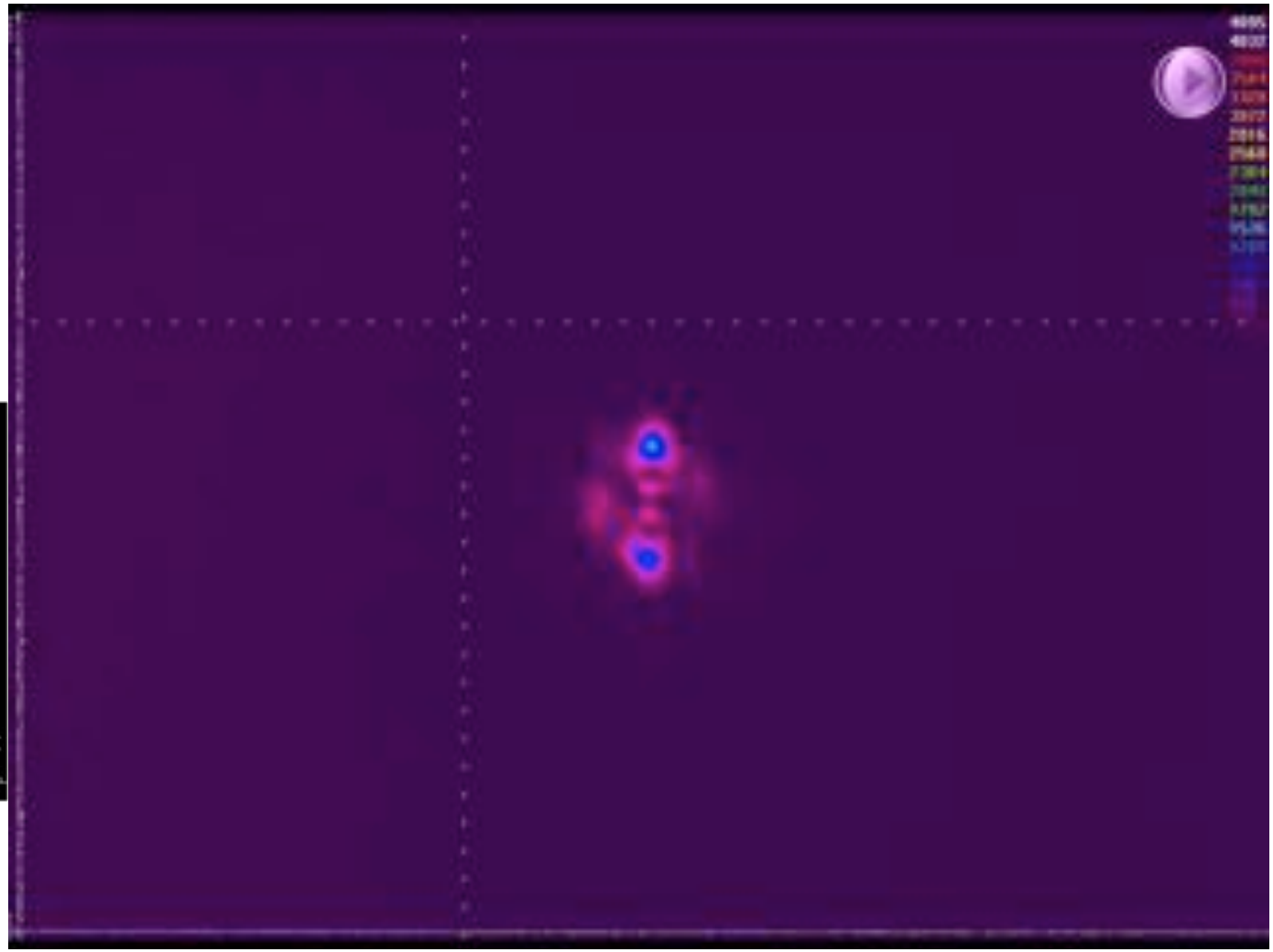
Factor ~7 reduction of FFDP at GNSS velocity aberration



Making SCF movies (of laser return)

SCF-Test of GLONASS, GIOVE

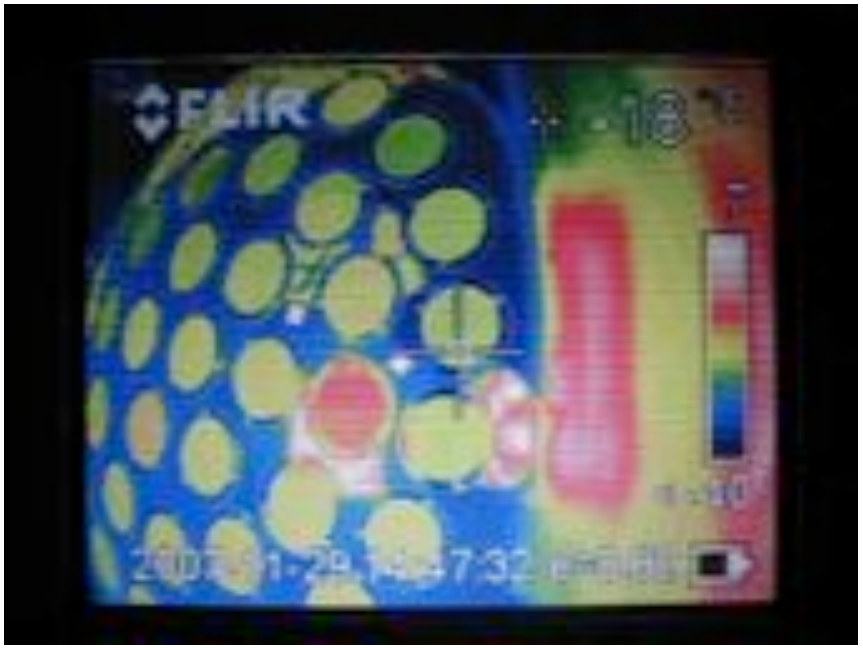




SCF movies (of thermal behaviour)

SCF-Test of LAGEOS Sector:

IR movie of Sector moving from AM0 (sun simulator) window to laser window at 90°. IR camera is in between

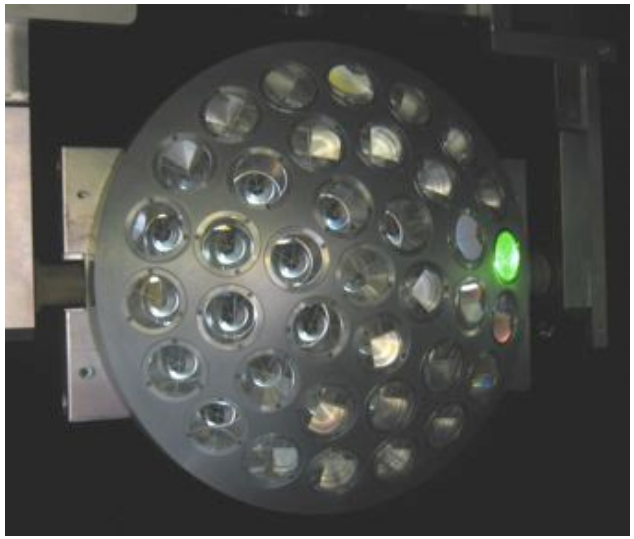


For ESA's test of Galileo reflectors, rotation accomplished in ~few seconds

SCF-Test of LAGEOS GLO/GPS/Giove

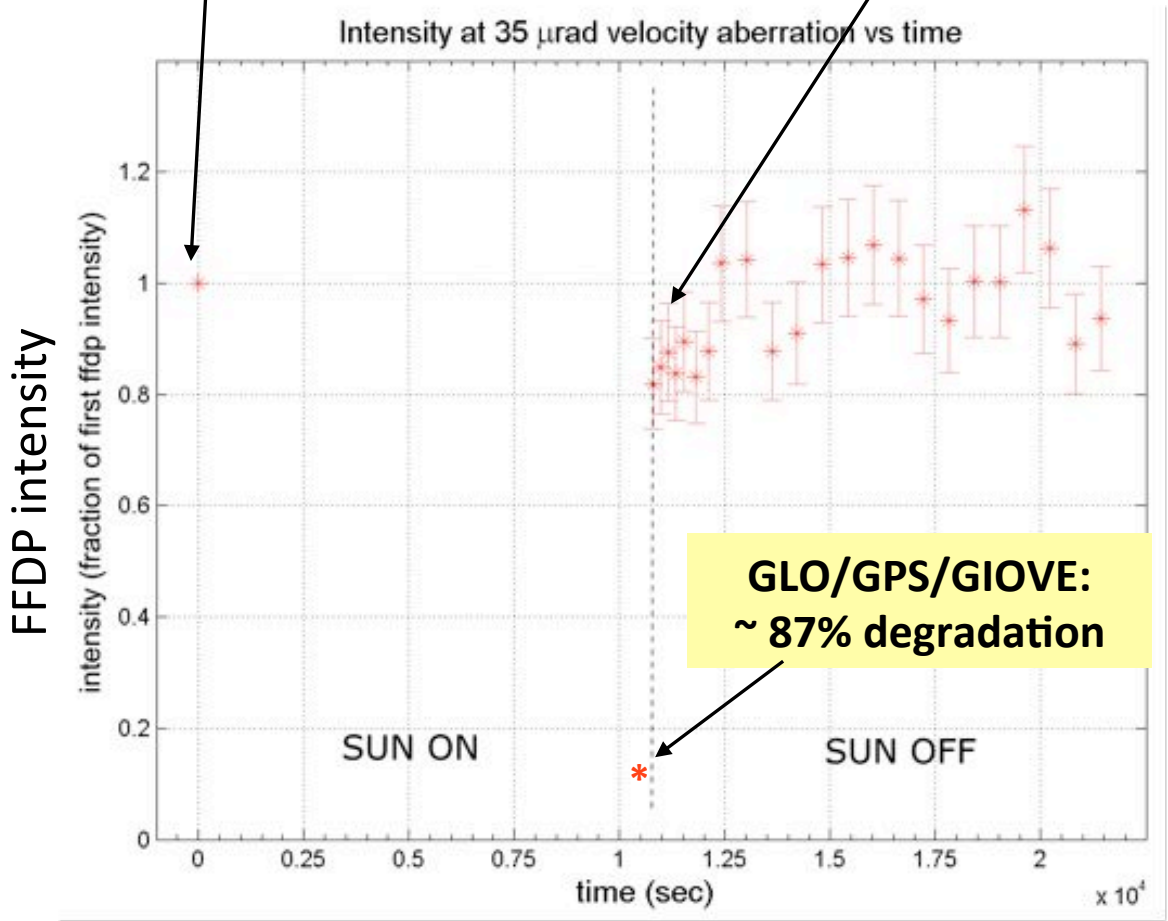
LAGEOS IS THE ILRS REFLECTOR STANDARD

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



LAGEOS: unperturbed laser return

LAGEOS: 20% degradation of laser return after 3 hr exposure to Sun simulator



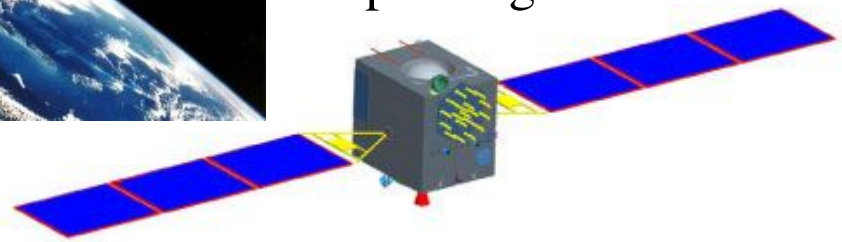
GLO/GPS/GIOVE: ~ 87% degradation

SCF_Lab with Elachi (JPL) & Flamini (ASI)

GNSS, Global Navigation Satellite System

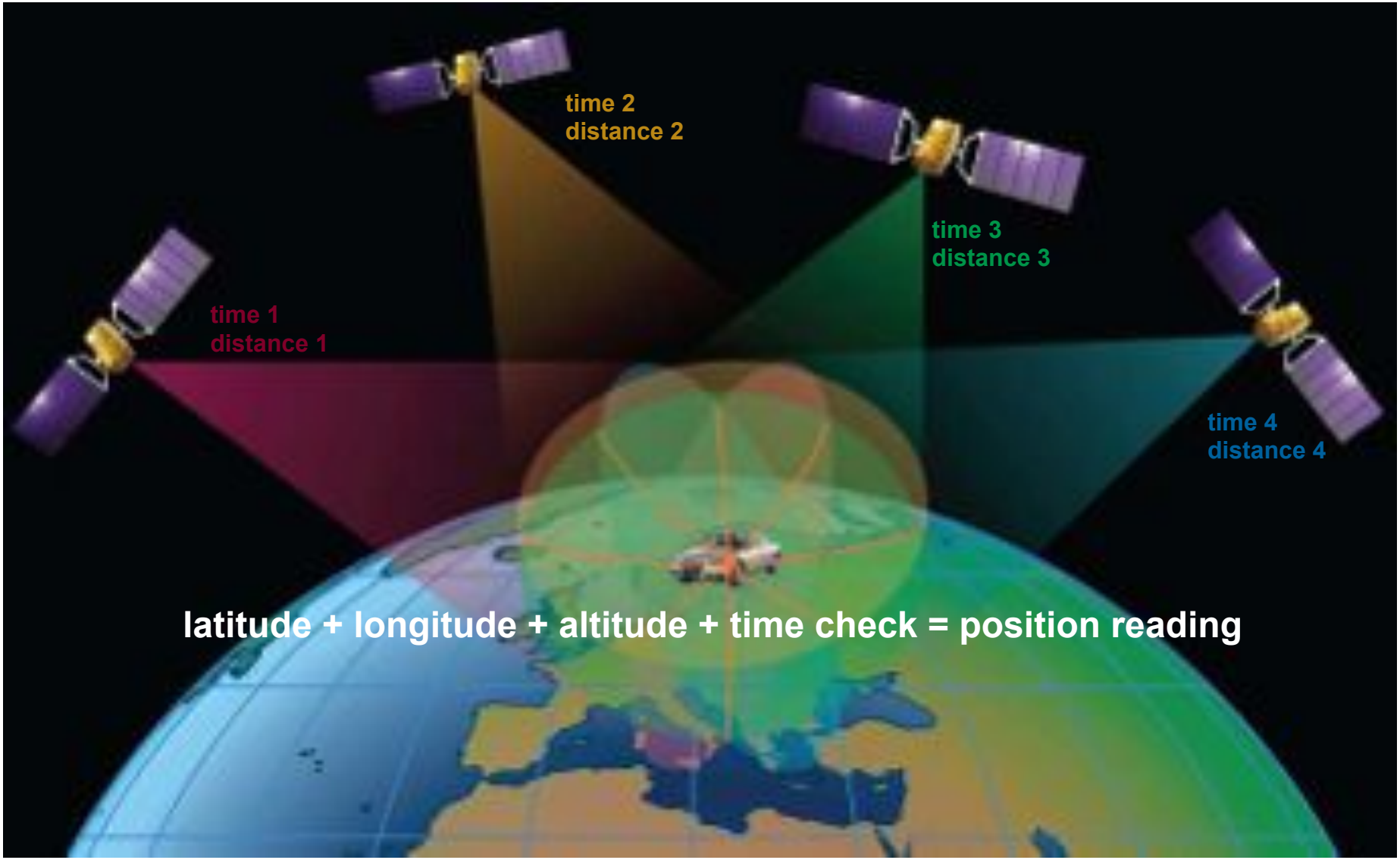
~100 satellites, with laser retroreflectors

Chinese Compass/
Beidou: 20 global,
plus regional satellites

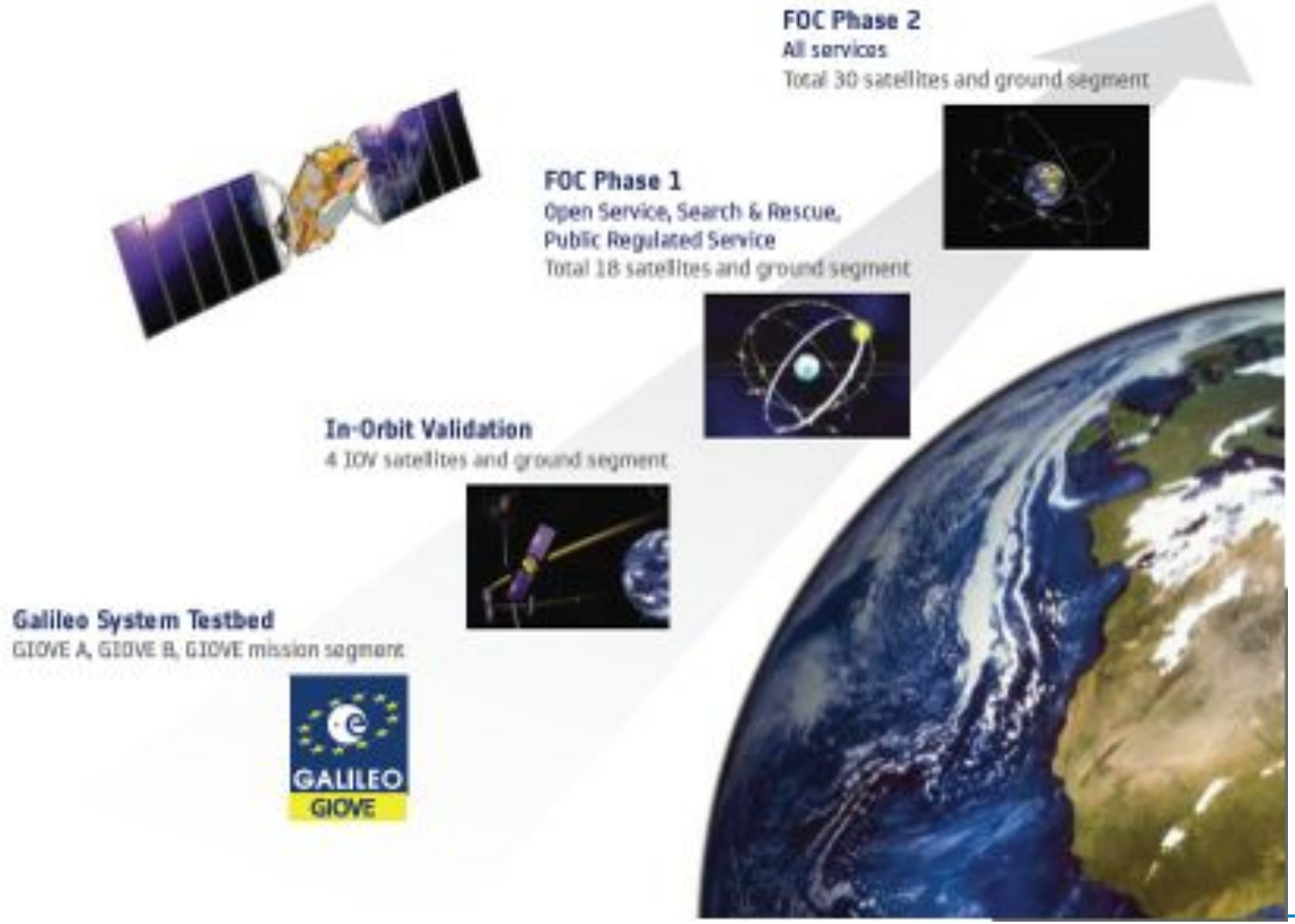


Russian GLONASS:
24 global satellites

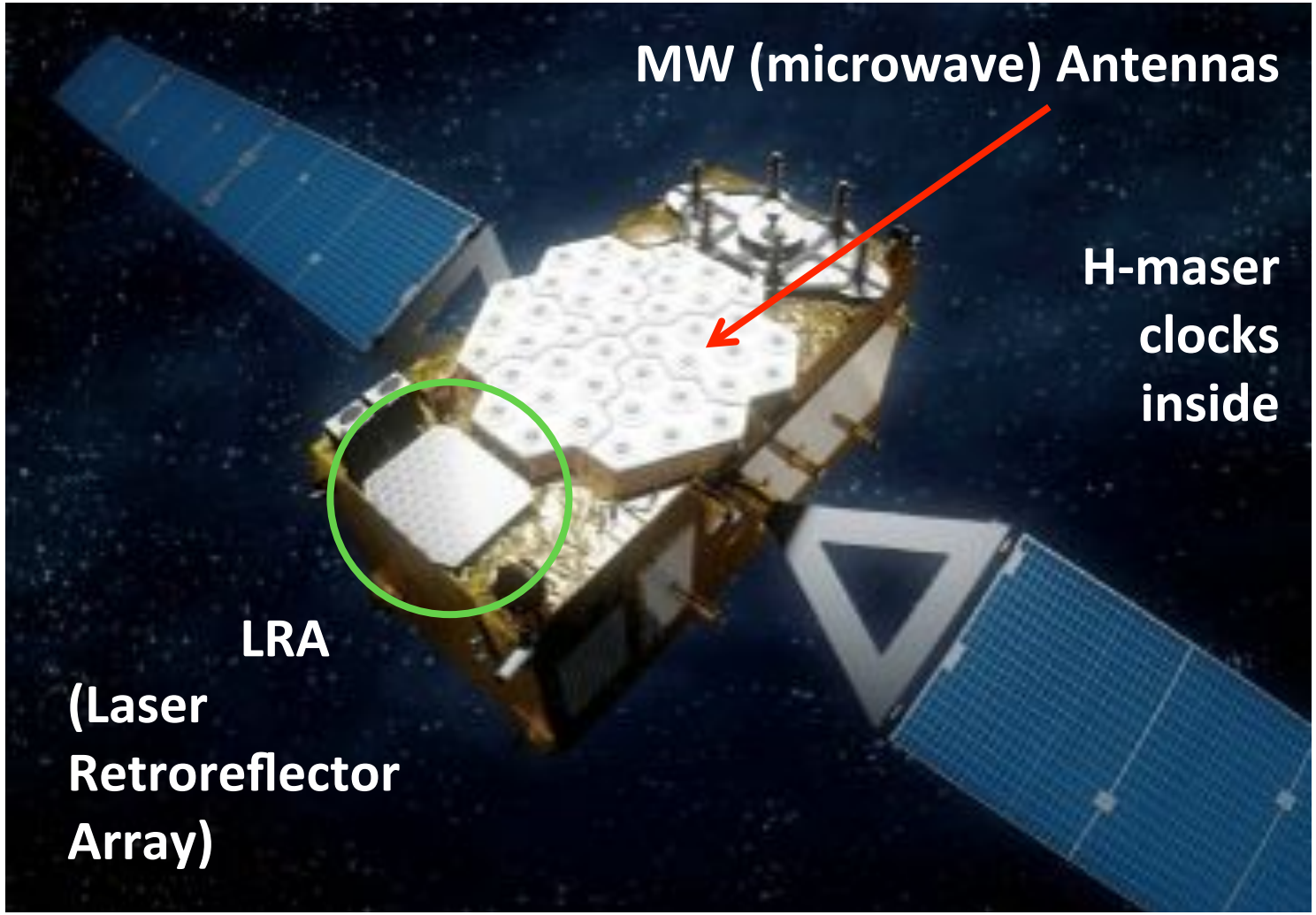
How satellite navigation works



Galileo implementation plan

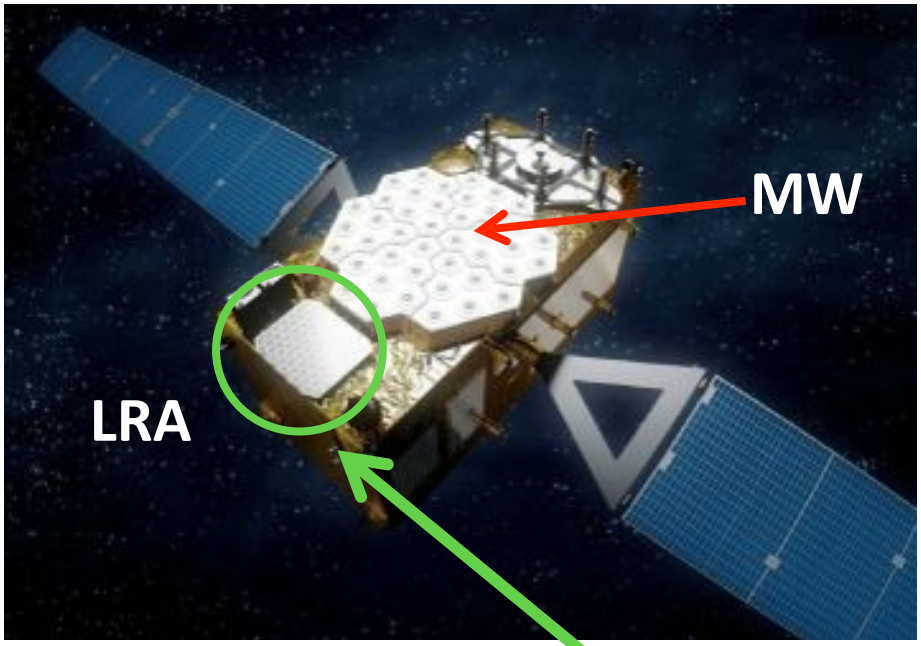


Galileo In-Orbit Validation satellite (IOV)



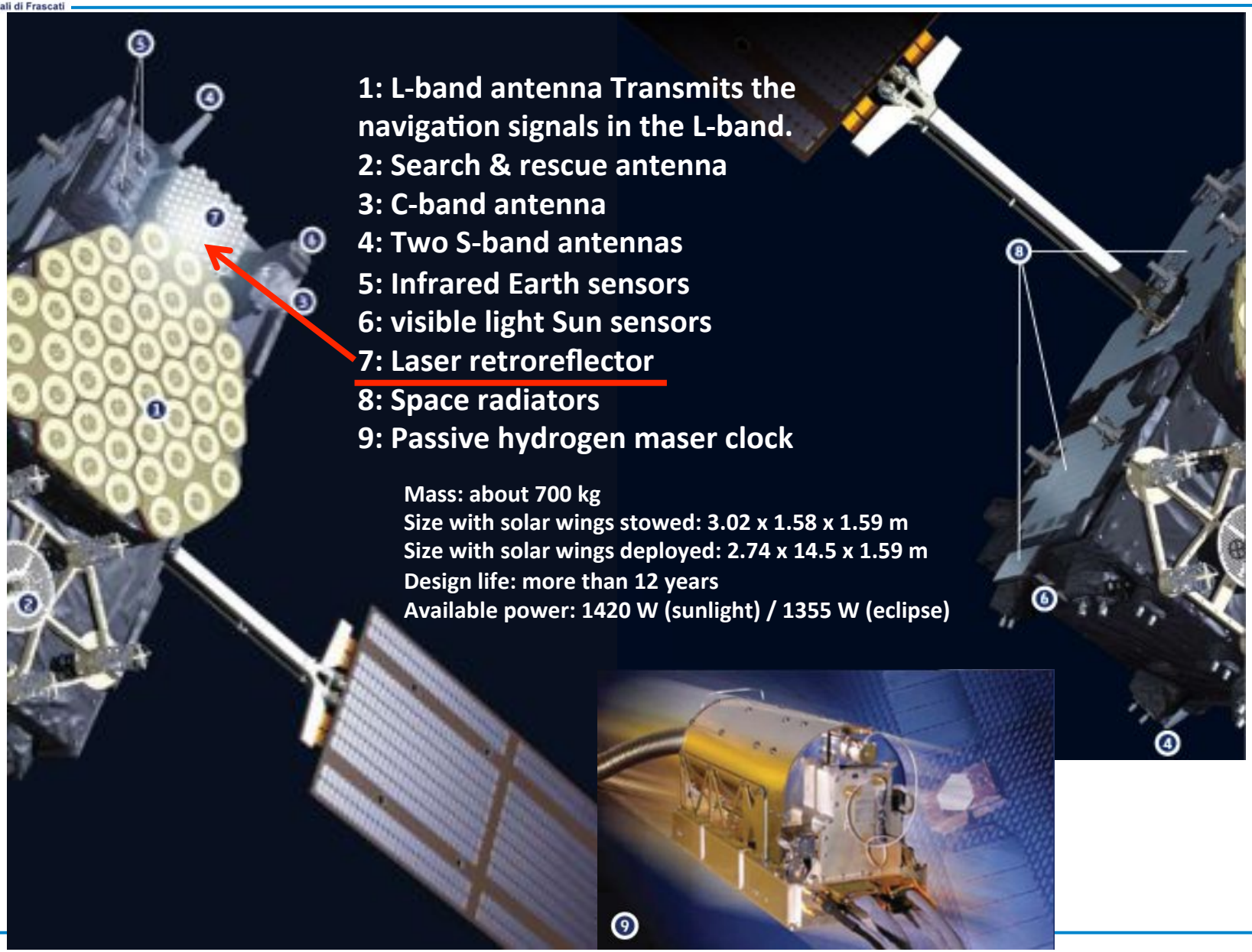
Satellite Laser Ranging to Galileo (or GPS …)

<u>Satellite Laser Ranging **(SLR)**:</u>
position/distance measurement to cube corner retroreflectors (**CCR**) with short laser pulses and a time-of-flight technique time-tagging with H-maser clocks



- **PRECISE POSITIONING** (normal points at mm level, orbits at cm level)
- **ABSOLUTE ACCURACY** (used to define Earth center of mass, geocenter, and scale of length)
- **PASSIVE, MAINTENANCE-FREE** Laser Retroreflector Array (**LRA)**

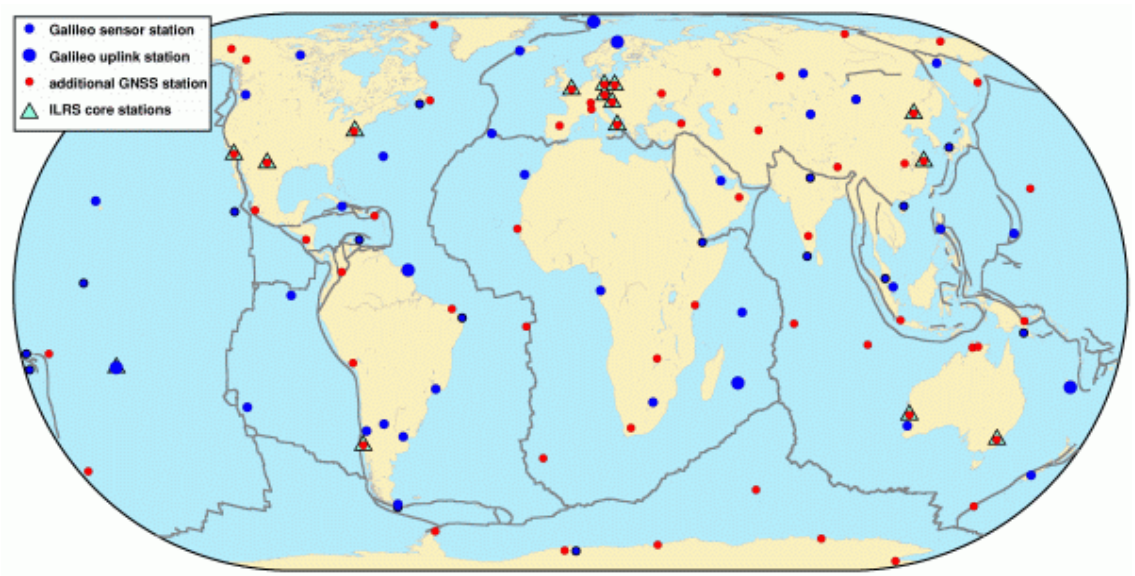
External anatomy of Galileo IOV satellite



Towards a 'Galileo' Terrestrial Reference System

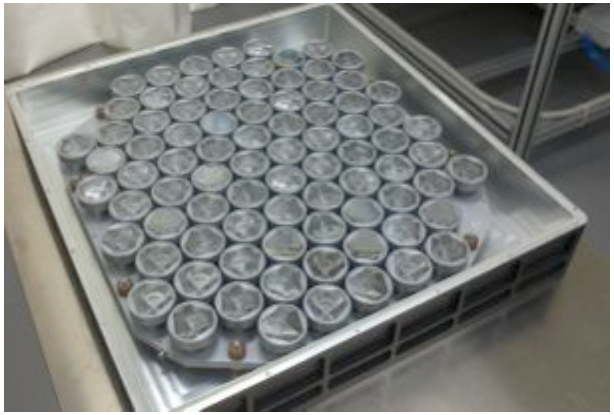
A **Terrestrial Reference System (TRS)** is a spatial reference system co-rotating with the Earth in its diurnal motion in space. In such a system, positions of points anchored on the Earth's solid surface have coordinates which undergo only small variations with time, due to geophysical effects (tectonic or tidal deformations). A **Terrestrial Reference Frame (TRF)** is a set of physical points with precisely determined coordinates in a specific coordinate system (Cartesian, geographic, mapping ...) attached to a TRS. Such a TRF is said to be a realization of the TRS. Next slide shows the current International TRS/TRF

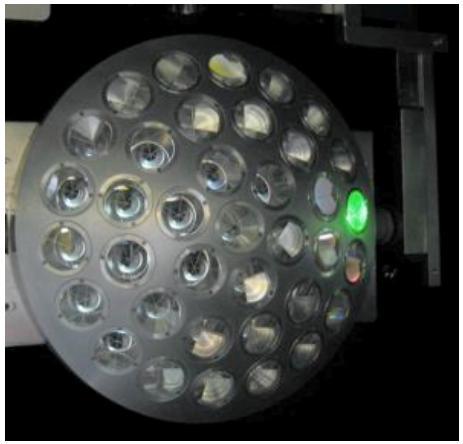
In the future: when the Galileo constellation will be complete and fully operational, a GTRF realization and long-term maintenance might be possible, also thanks to its retroreflectors

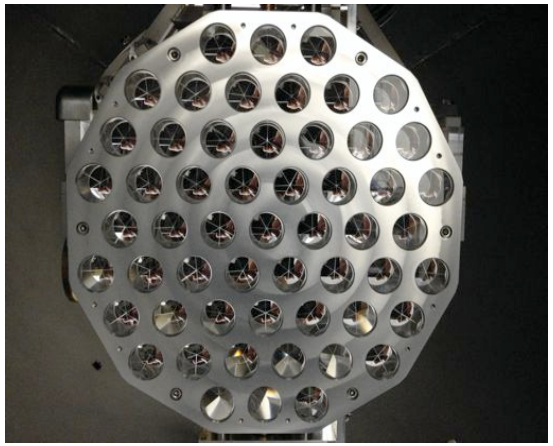


GNSS Retroreflector Arrays (and LAGEOS))

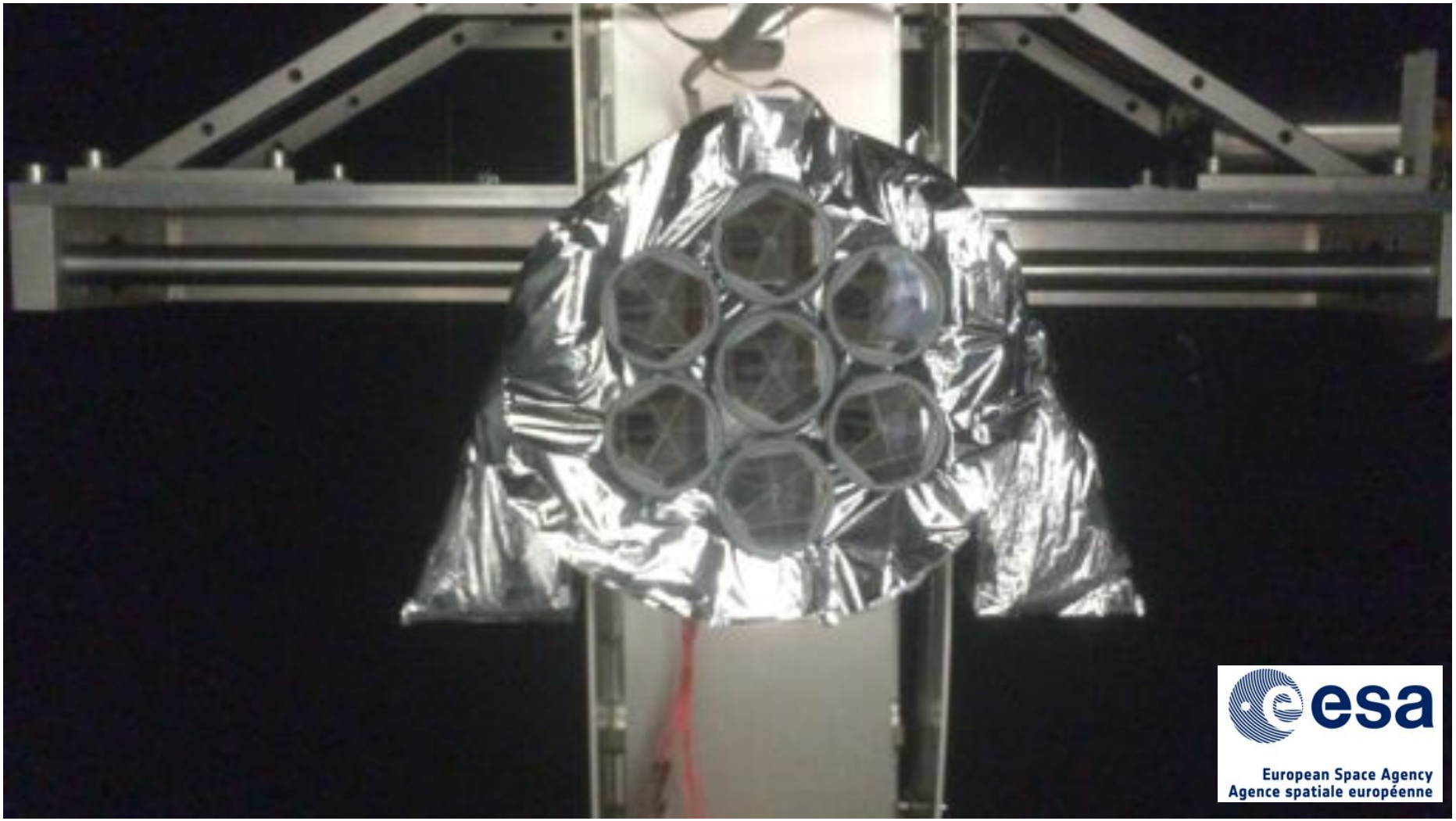
- Left: Galileo IOV reflector array
- Center: LAGEOS Sector, reference payload for Earth Orbits
- Right: ASI-INFN product for standard GNSS Retro Array (GRA)







Test of Galileo IOV reflectors for ESA

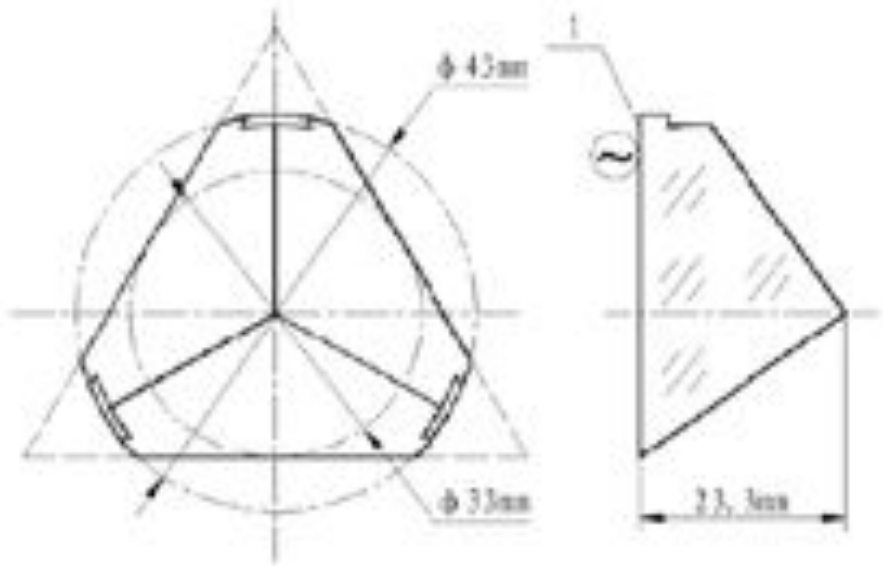


Assembly setup ready for testing.

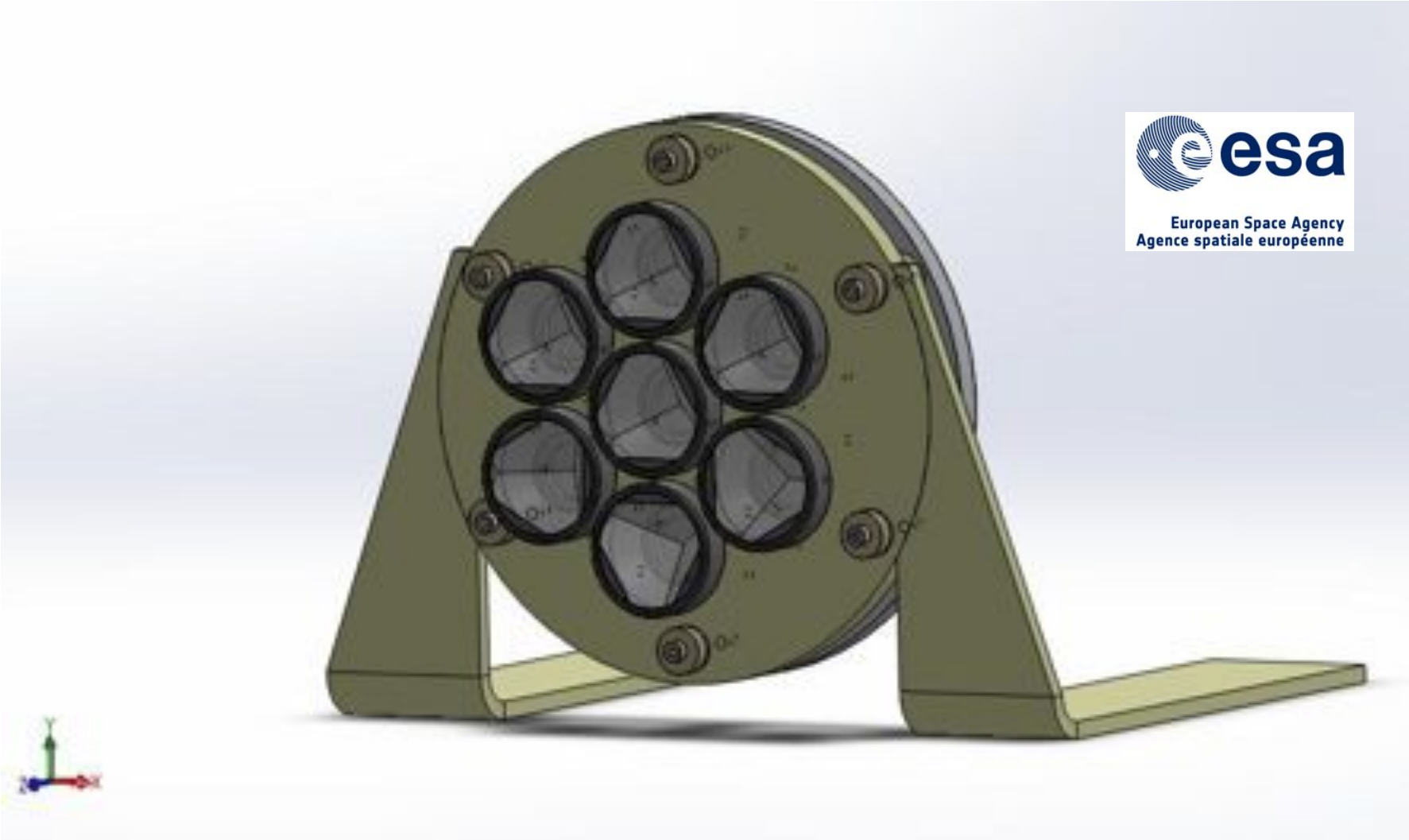
Galileo IOV Laser Retroreflectors

- 84 Corner Cube Retroreflectors (CCR)
  - doped fused silica (Suprasil 311) glass tetrahedron
  - no metallic coating on reflective surfaces
  - front surface coated with ITO
  - 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
  - N = 1.46, critical angle16.9 deg
    - which covers the entire LRR operating range (Earth radius of 12.44°)
    - no coating, total reflection is obtained without any loss
  - Velocity aberration compensation 24 µrad
  - CCR are randomly oriented
  - LRA Centre of Phase TBD after Qualification

- 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"

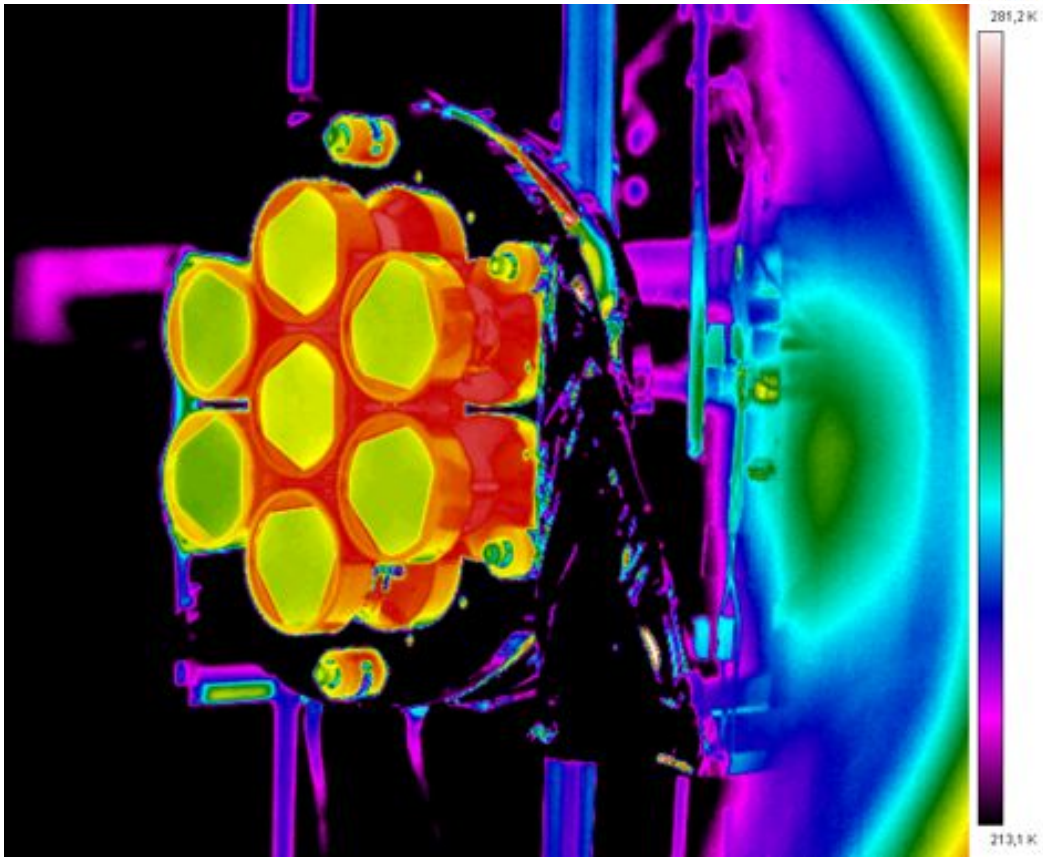


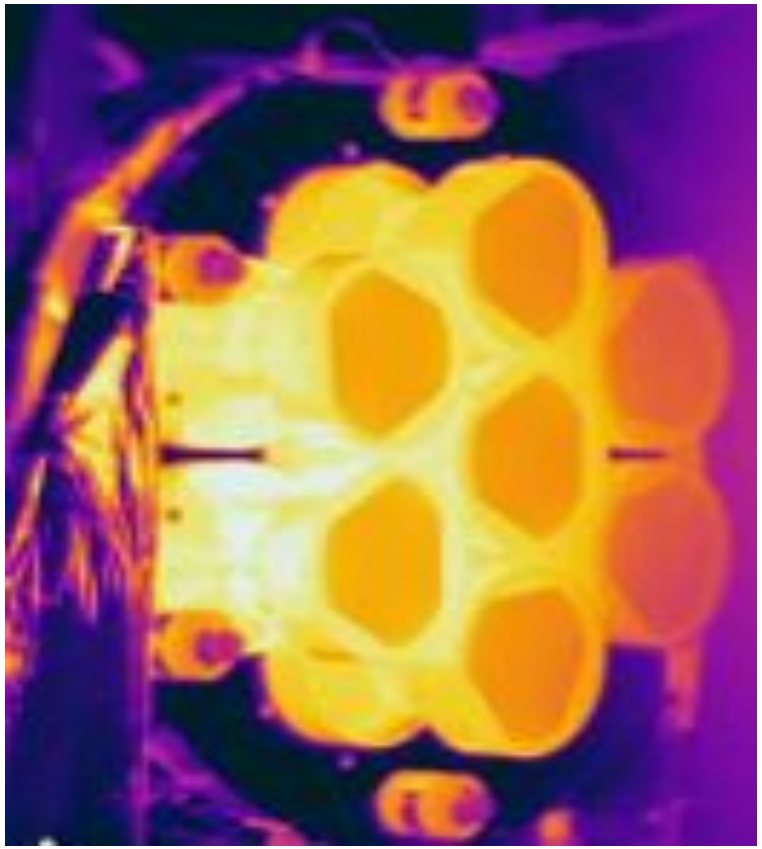
Test of Galileo IOV reflector model



Retroreflector Front Face Infrared Temperature

Infrared Image of GALILEO IOV retroreflectors during SCF-Test at 0°C, heating phase

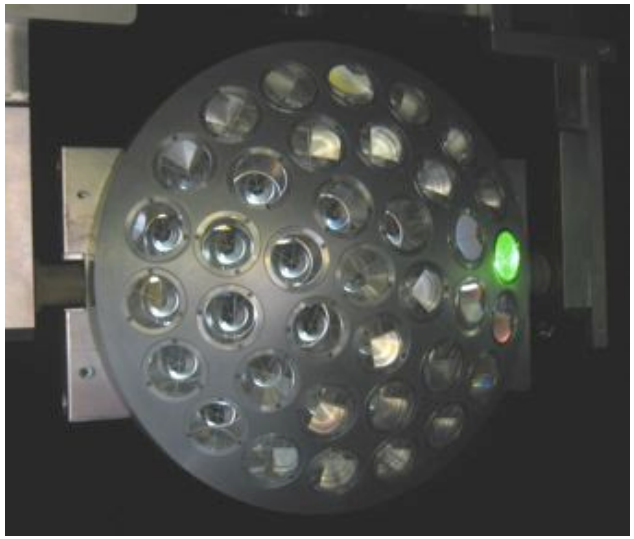




SCF-Test of LAGEOS GLO/GPS/Giove

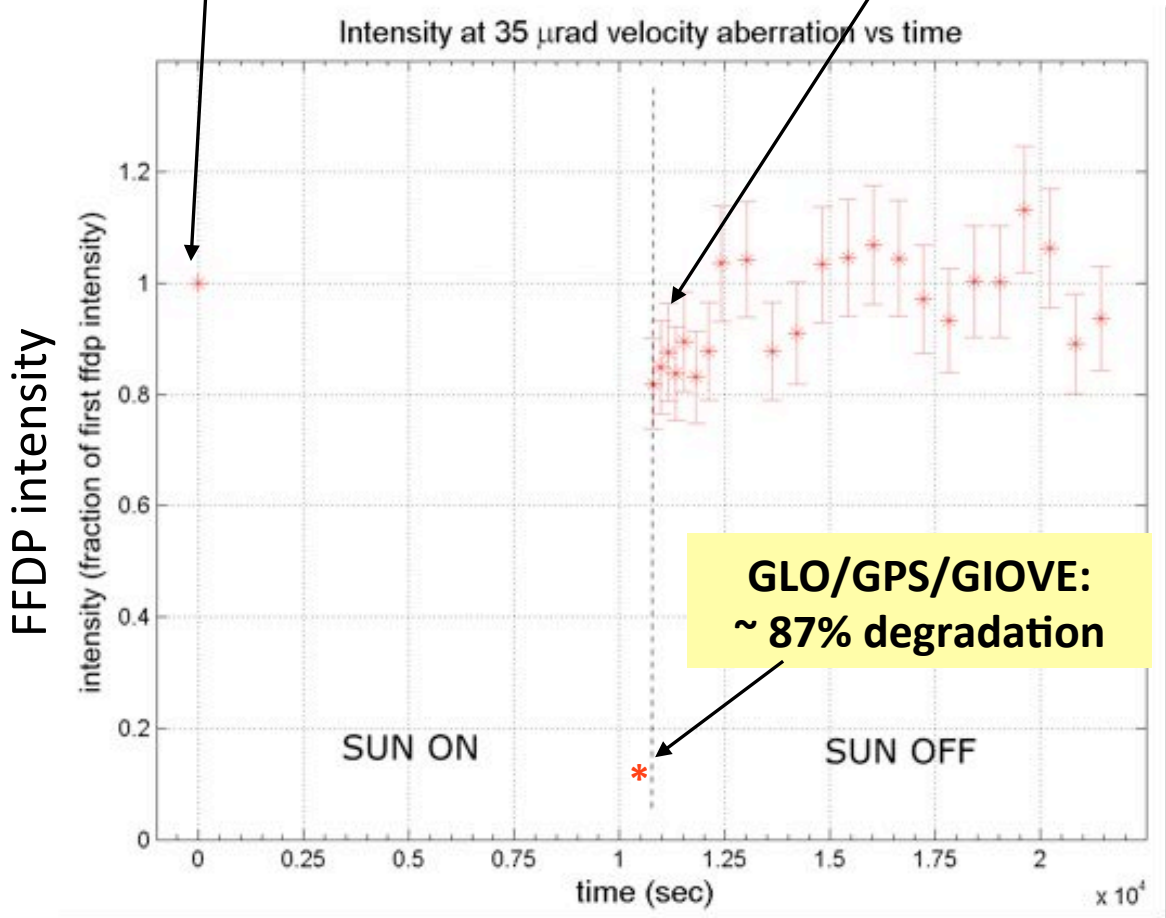
LAGEOS IS THE ILRS REFLECTOR STANDARD

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



LAGEOS: unperturbed laser return

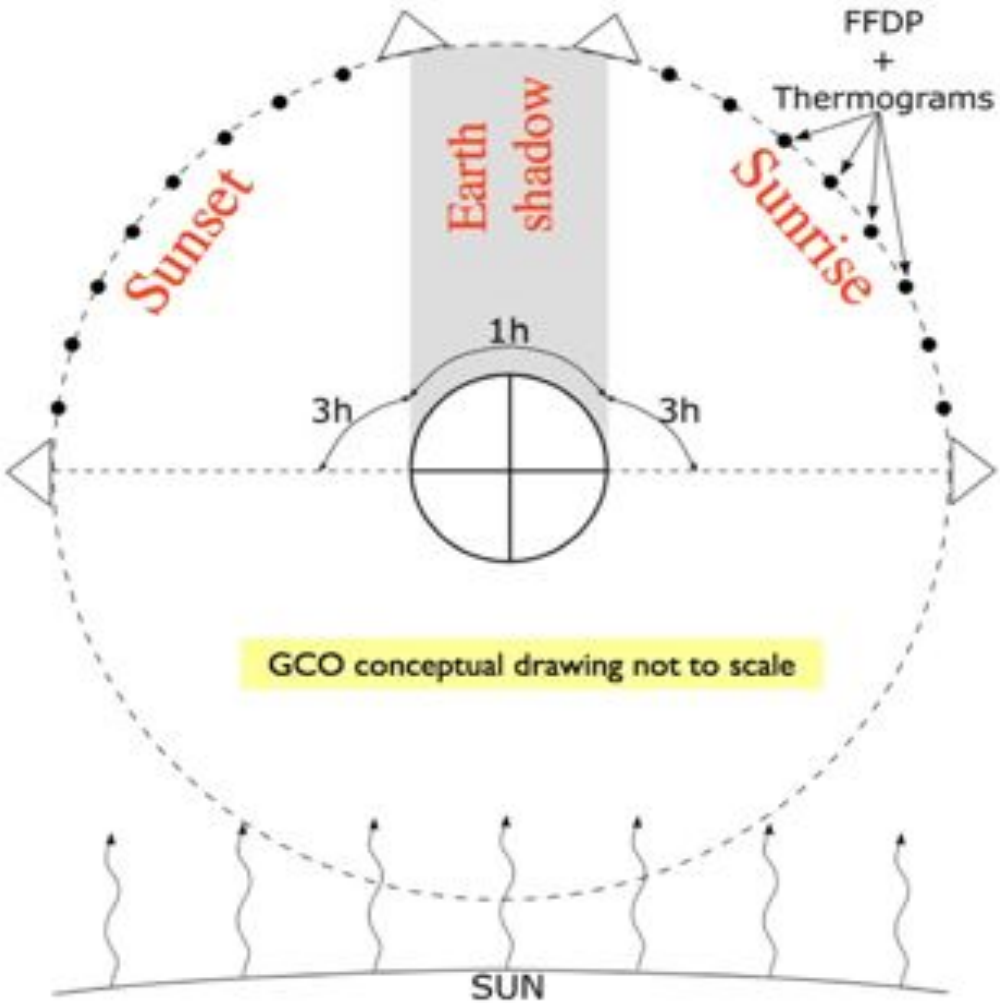
LAGEOS: 20% degradation of laser return after 3 hr exposure to Sun simulator



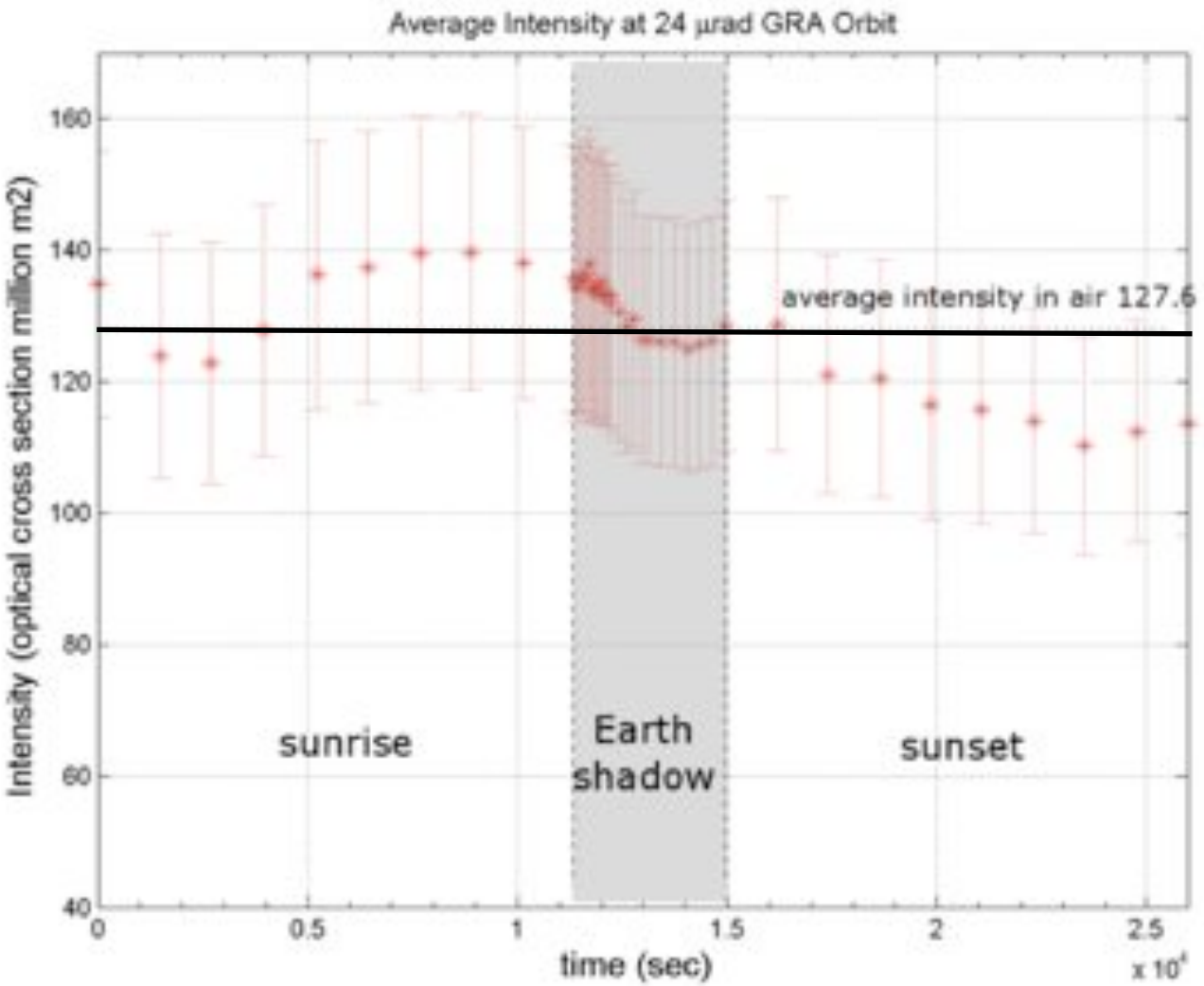
GLO/GPS/GIOVE: ~ 87% degradation

GRA performance in SCF_Lab simulated "critical" space conditions

- Thermal-optical-vacuum test, "**SCF-Test**", along the GNSS Critical Orbit, "**GCO**"
- Sunrise-Eclipse-Sunset probes critical features of the thermal and optical behavior of the CCR



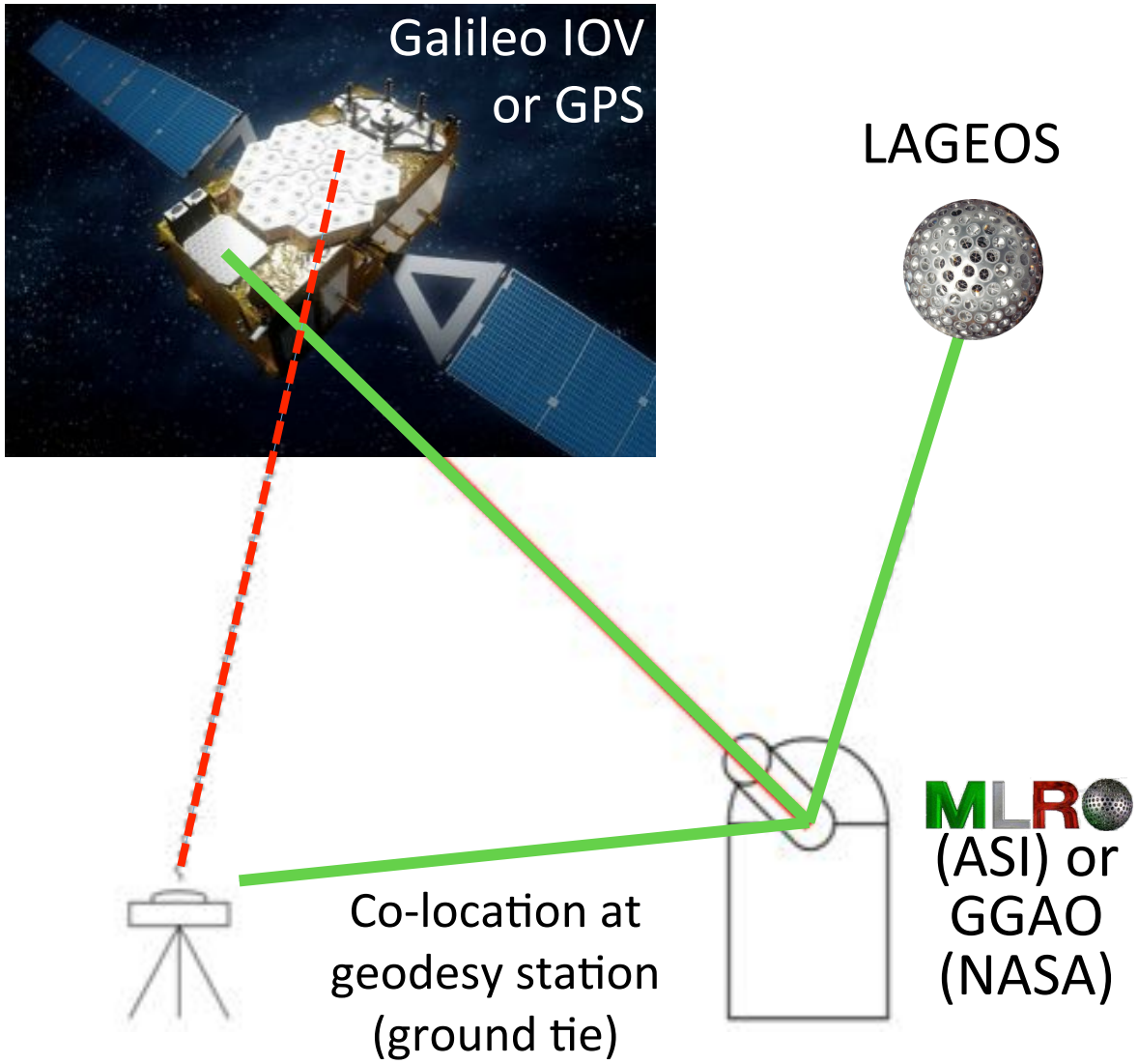
GRA optical performance: no degradation wrt nominal (in-air) within ±15% errors



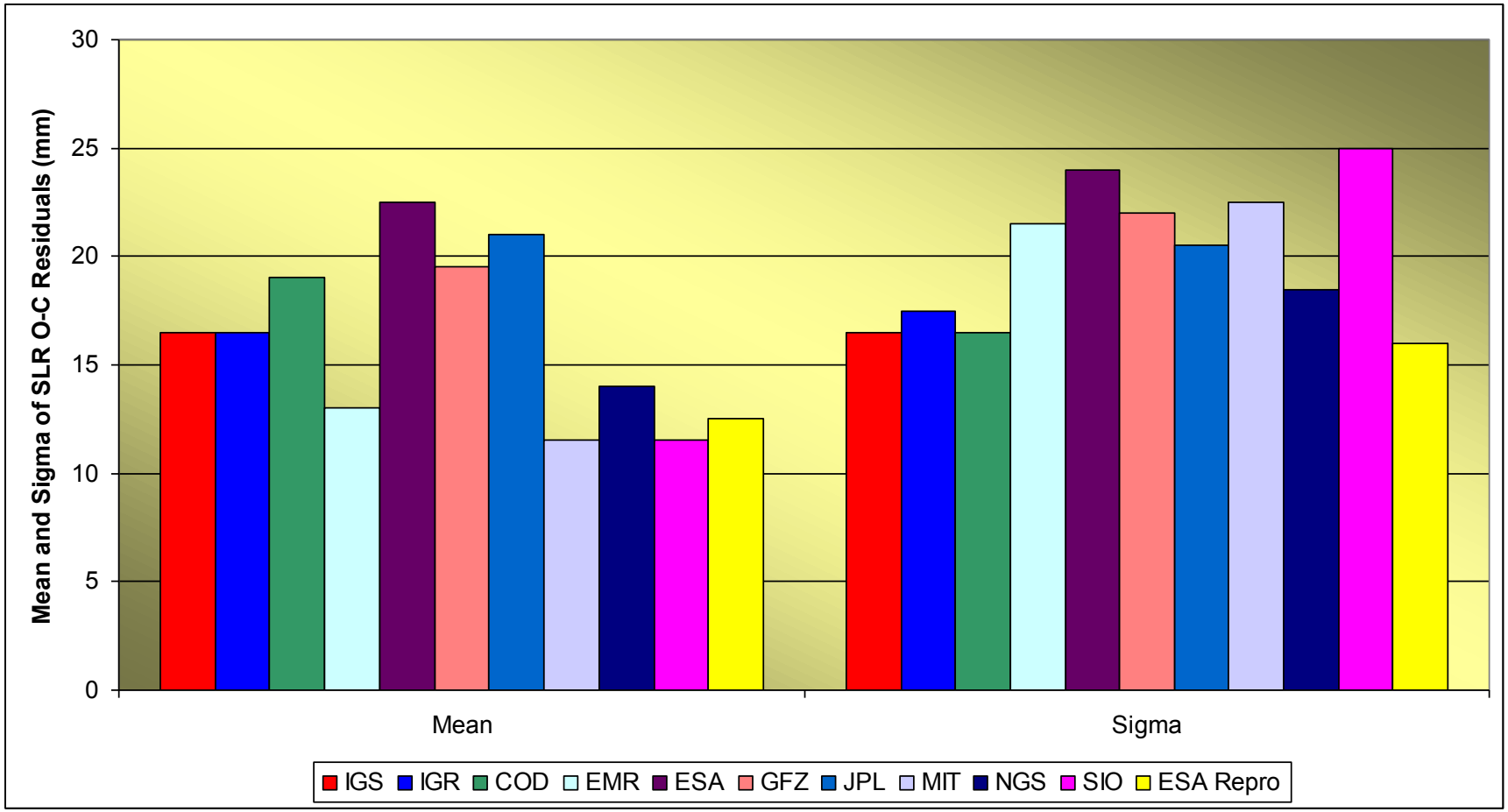
Co-location of SLR & GNSS positioning

Co-location at GNSS satellite (space-tie)

Laser positioning of GNSS referenced to *geocenter* thanks to laser ranging to LAGEOS, whose orbit defines *geocenter*

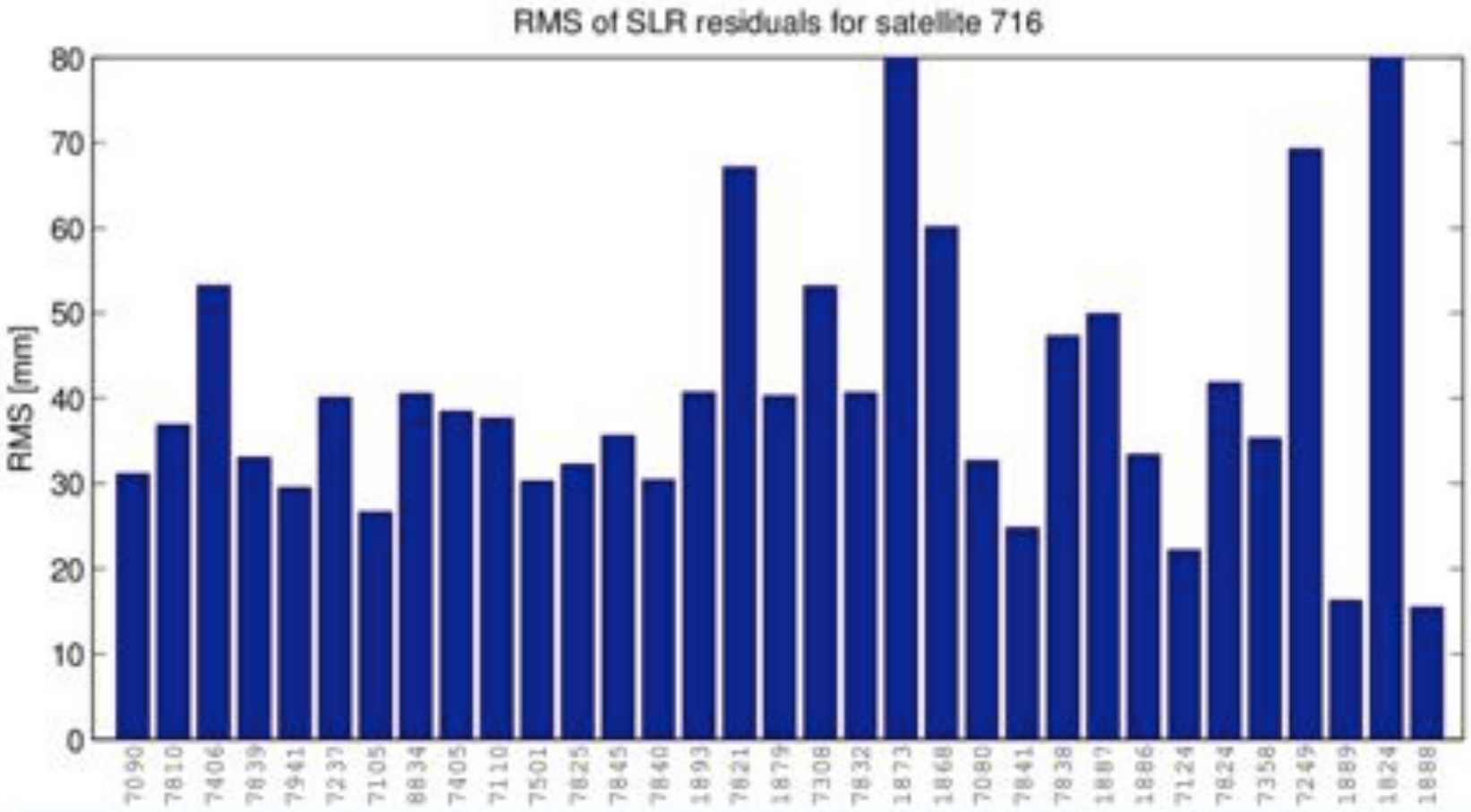


Laser Ranging validation of GNSS orbits



“Residual” between GPS orbit and Satellite Laser Ranging (SLR) measurement

R-716 for 2007 - 2014



Federal Agency for Cartography and Geodesy

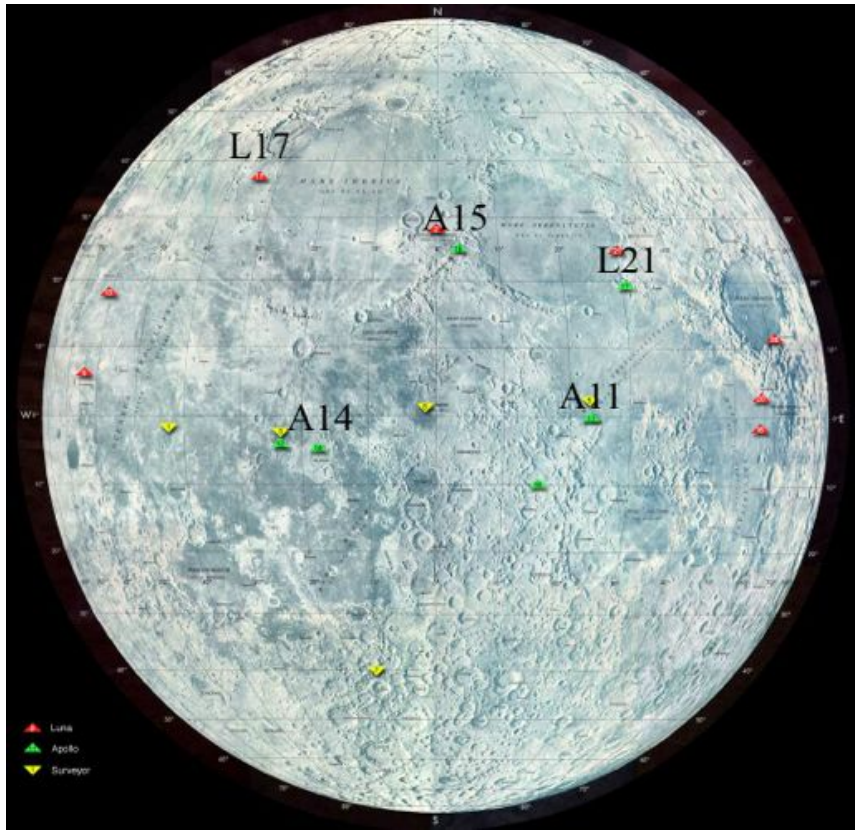
D. Thaller et al. | Pre-combined GNSS-SLR solutions | 28.10.2014 | Page 24

Conclusions: benefits of SLR for GNSS

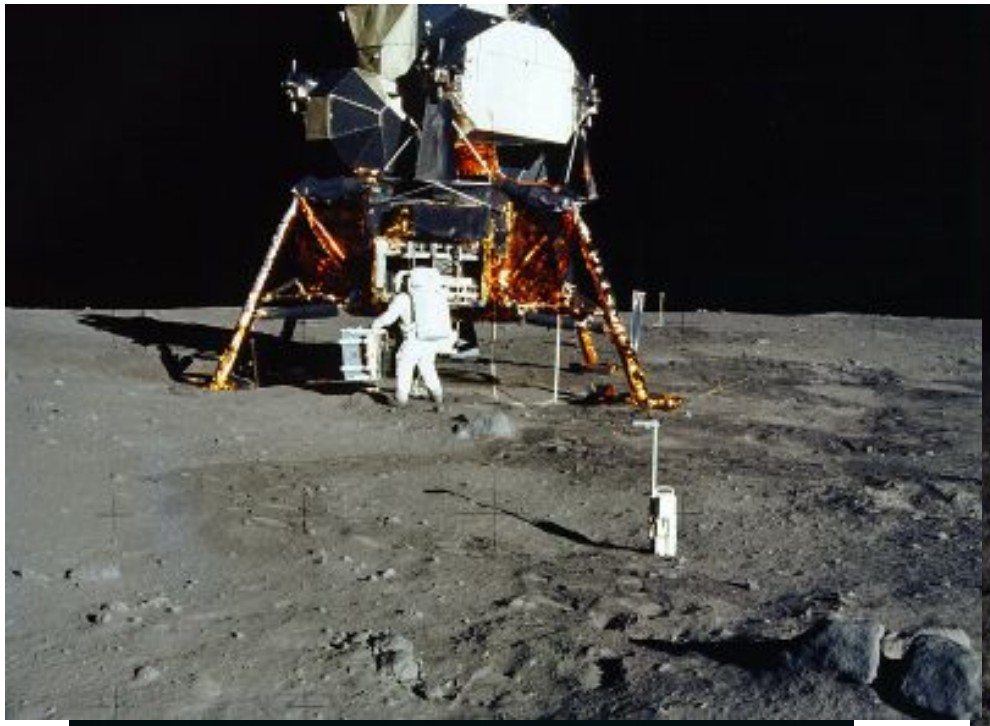
- SLR by ILRS provides independent validation of GNSS orbits
- Combining GNSS and SLR measurements is NOT easy, but provide the most accurate and stable GNSS orbits, with absolute reference to the geocenter and scale of the ITRS
- To achieve this improvement we need
  - Best possible LRAs on GNSS satellites: GLONASS, Galileo, GPS, Beidou, IRNSS, QZSS, and their future generations …
  - ILRS Stations keep optimizing laser ranging procedures & instrumentation

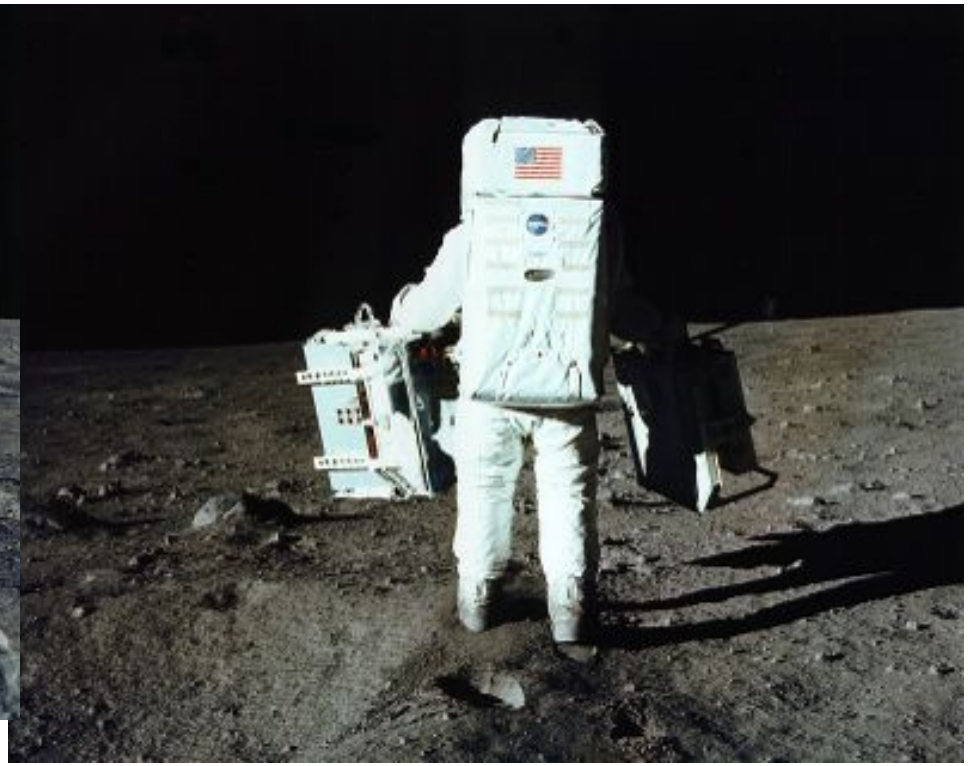
Lunar Laser Ranging

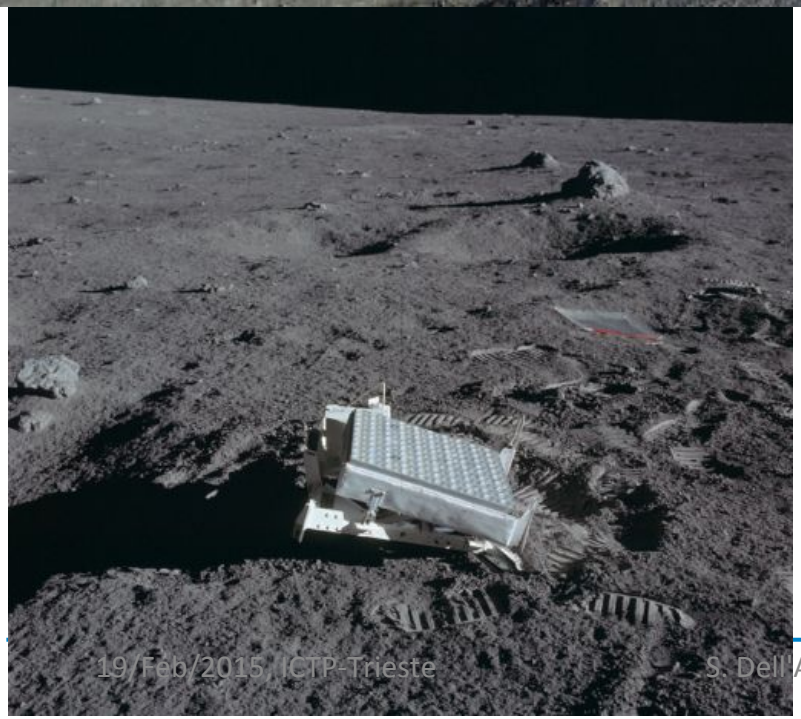
- Laser invented ~1960
- MIT and URSS shoot lasers to lunar surface in the '60
- Laser Retroreflectors deployed by 3 Apollo missions and 2 Luna/ Lunokhod missions



- Apollo: arrays of fused silica Suprail 1 with circular aperture of 3.8 cm
- Apollo 11 e 14: used 100 CCR
- Apollo 15: 300 CCR

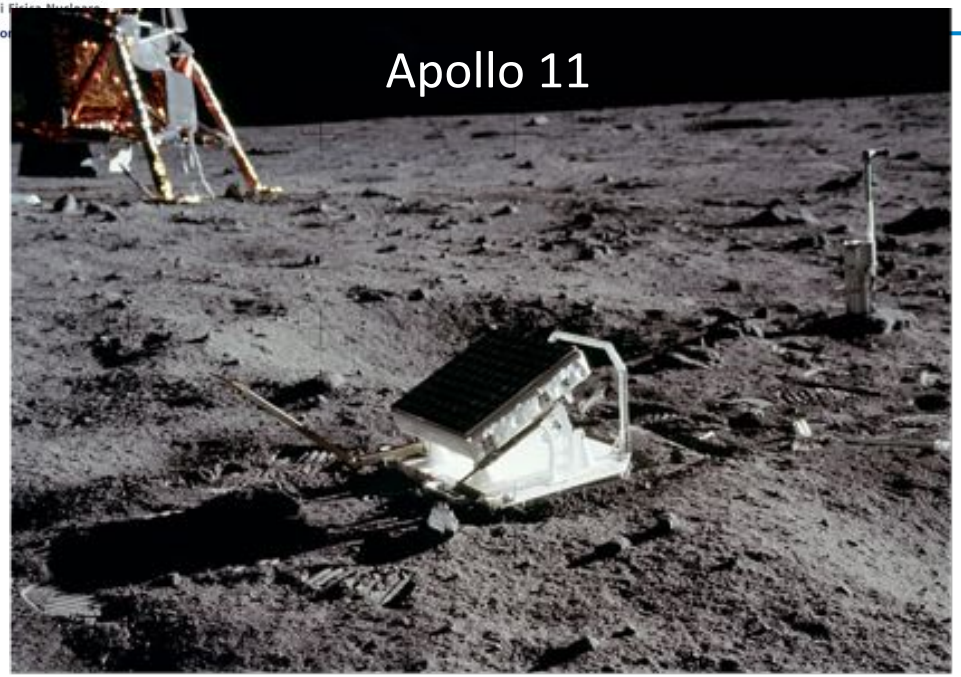


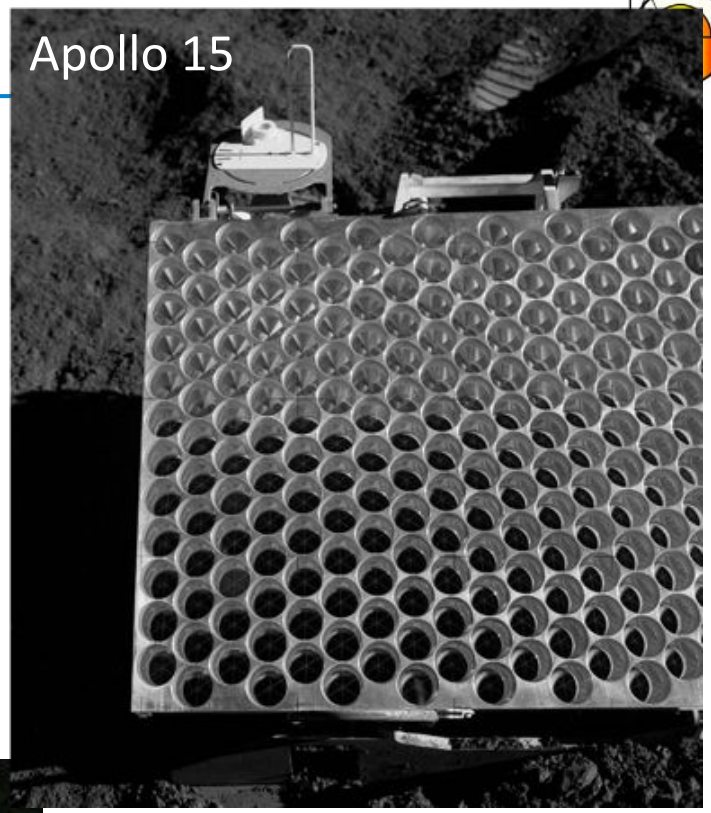


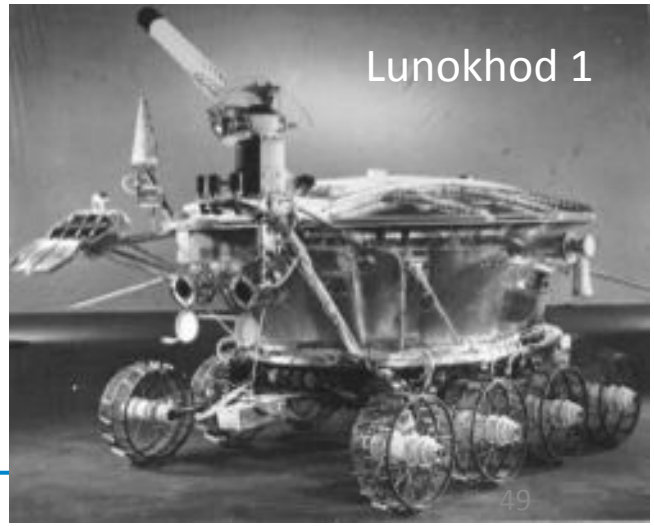


LLR: only Apollo experiment still providing data since 1969 (2009 NASA patch)

Riflettori lunari di 1ª generazione







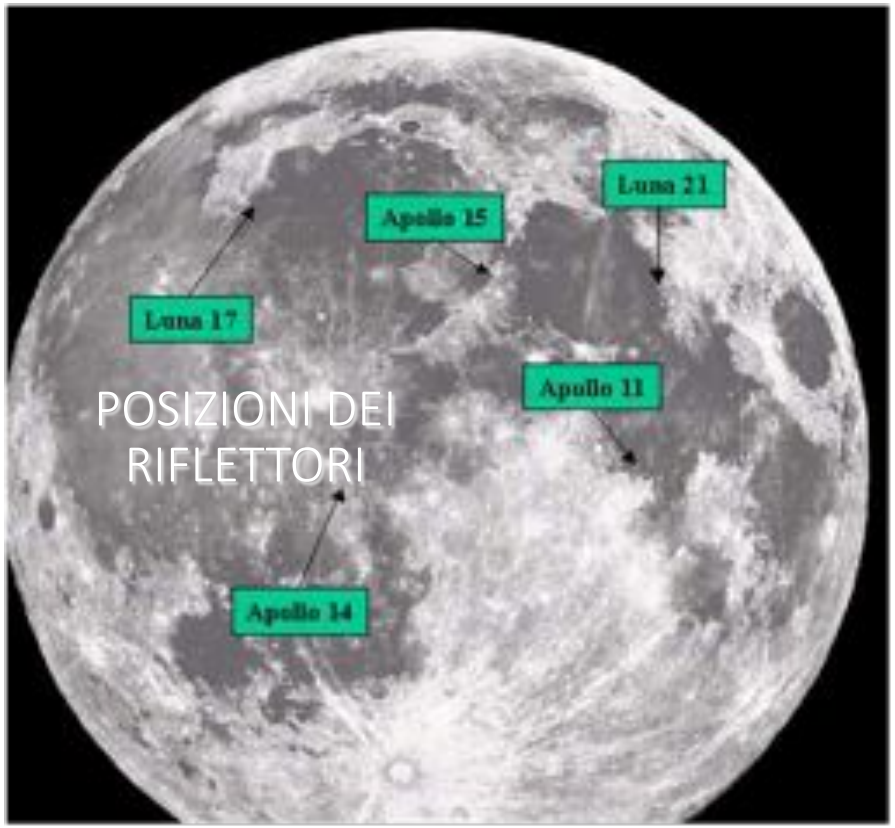
Precision: ~2 cm ~ 5×10^{-11} of Earth-Moon distance

Distance and size approximately to scale

(animated GIF from Wikipedia)

Round-trip time of flight ~ 2.5 sec

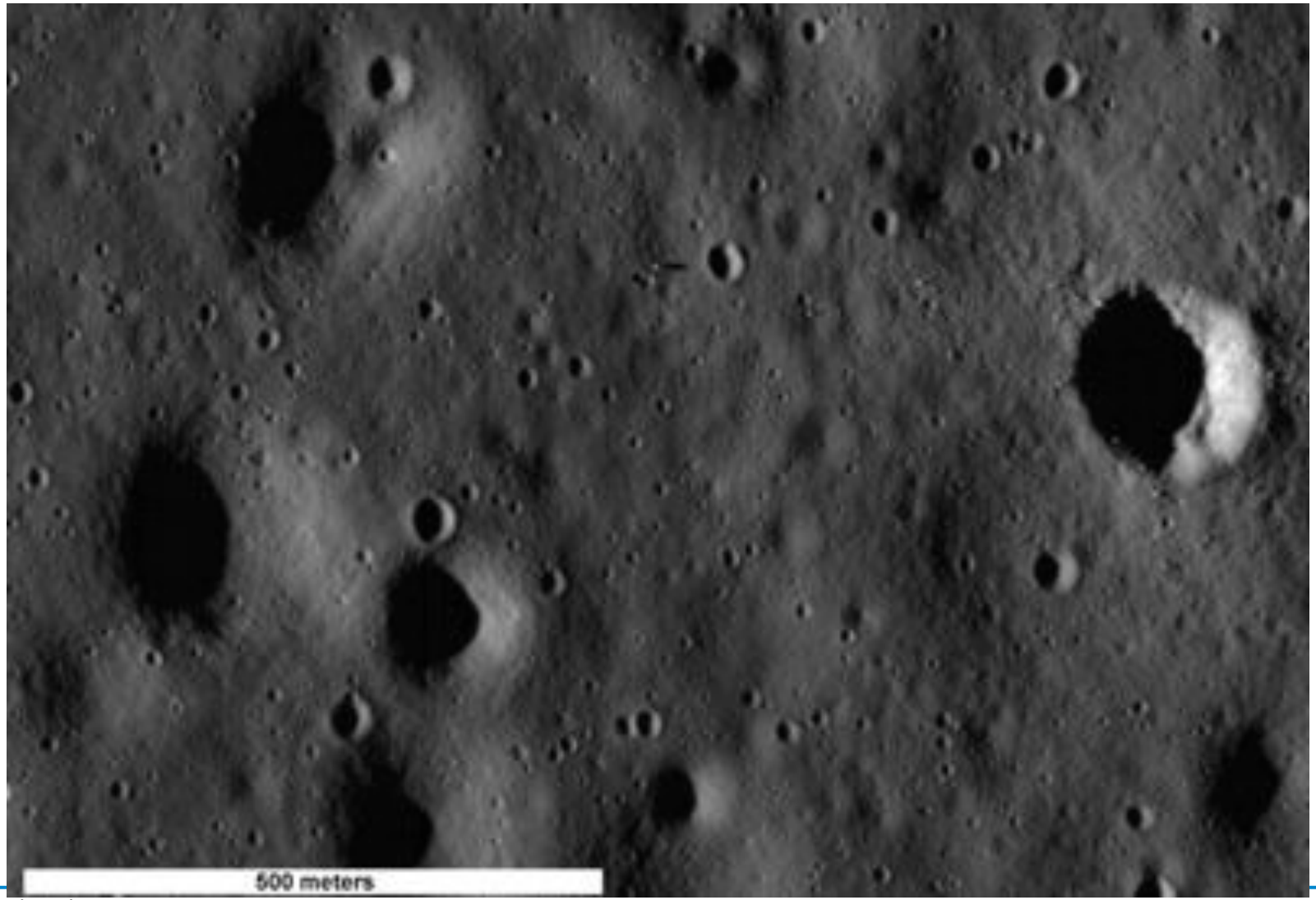
Distance ~ 384,000 km



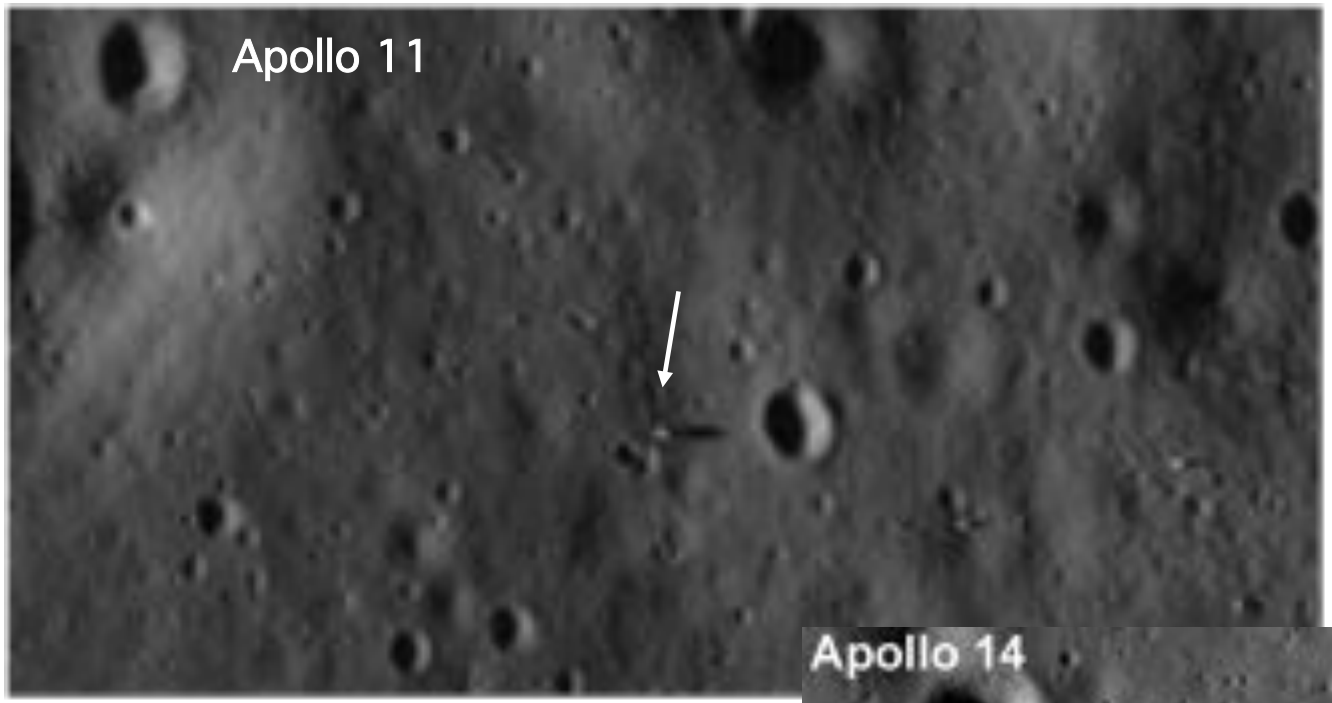
L'uomo è atterrato davvero sulla Luna?

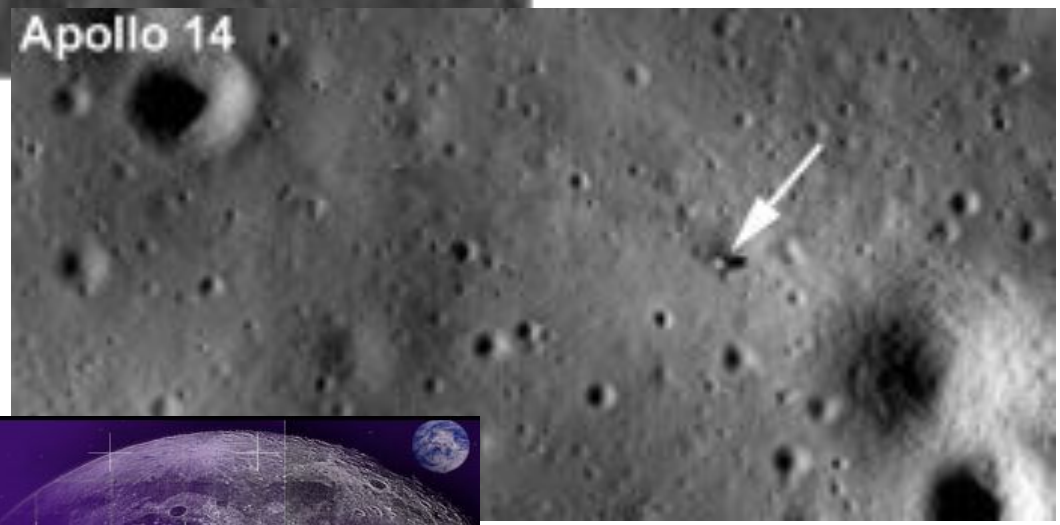
Lo testimoniano da 40 anni i retroriflettori delle missioni Apollo. Non basta?

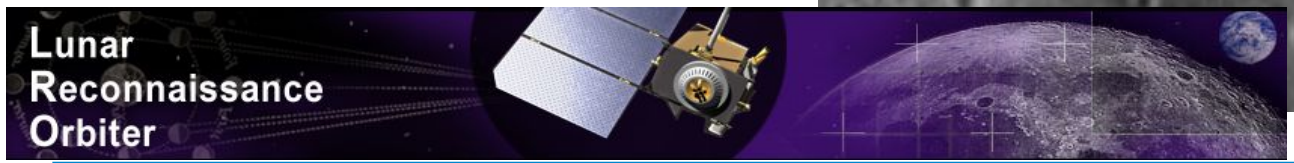
Immagini di Apollo 11 da LROC, la camera digitale del Lunar Reconnaissance Orbiter (NASA)



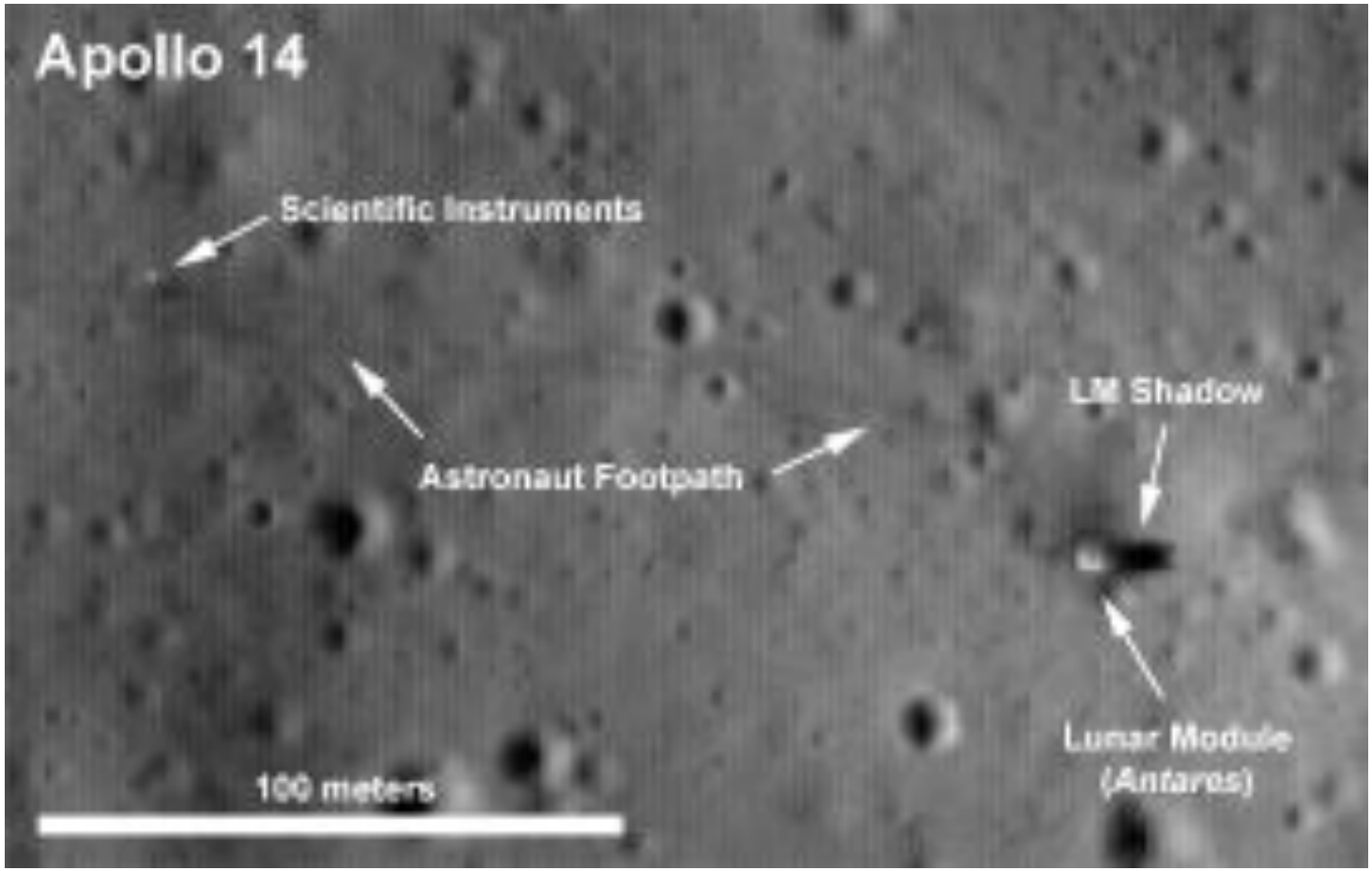
Apollo 11 & 14 seen by LROC on LRO







Apollo 14 seen by LROC on LRO

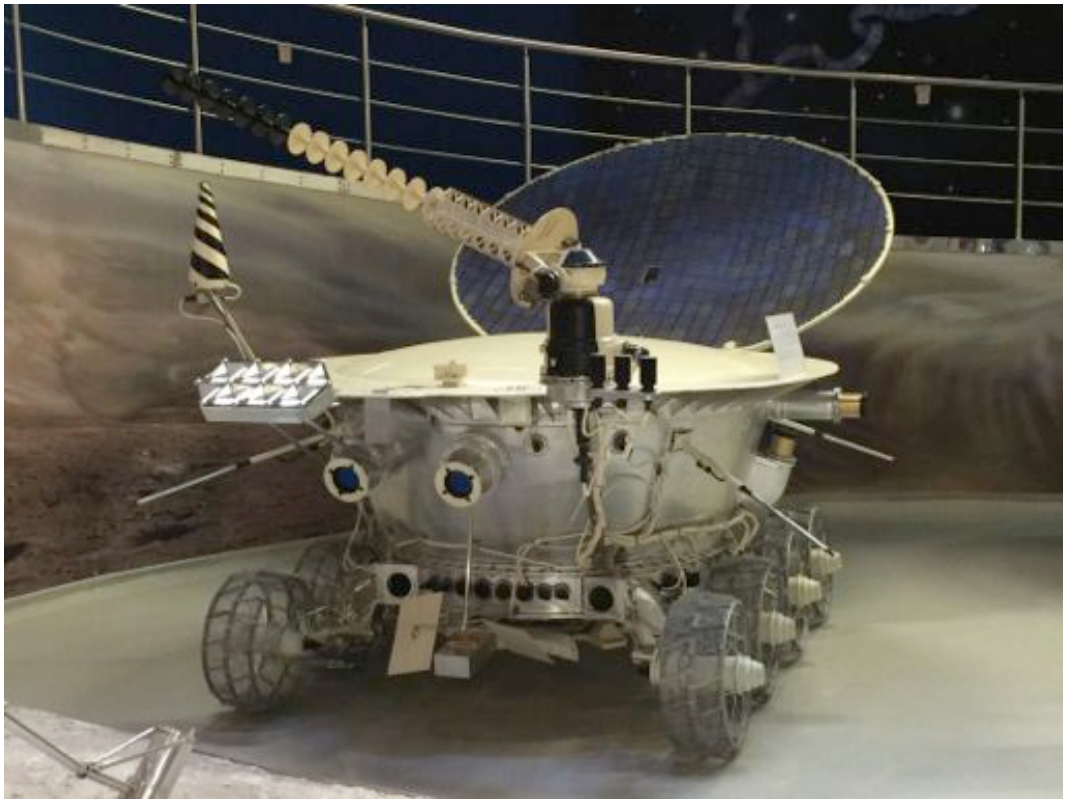


Lunokhod 1, re-discovered by LRO

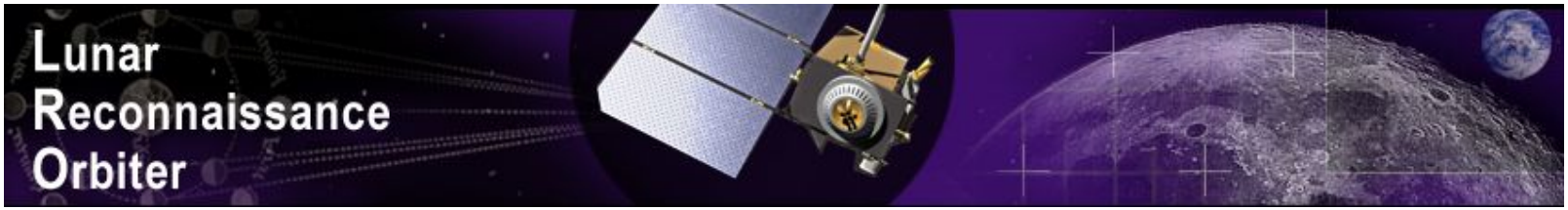
Retroriflettori Francesi sul rover Russo

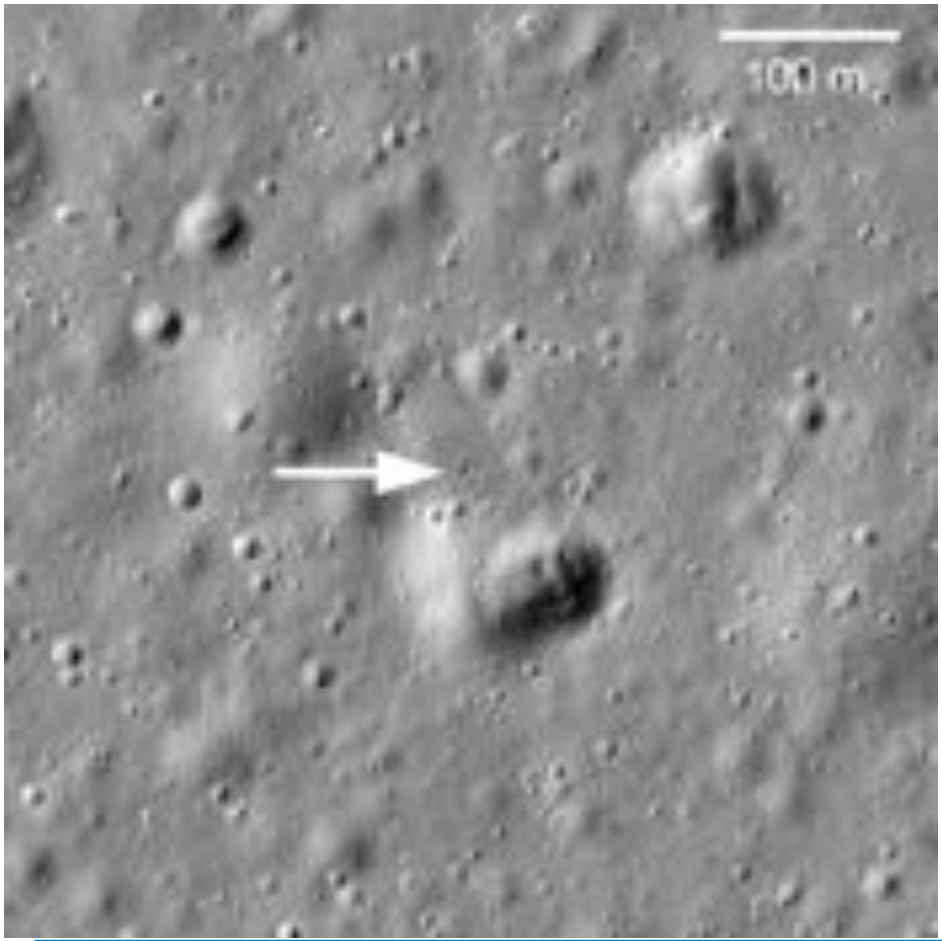
Lunokhod 3 at NPO-Lavochkin, Moscow

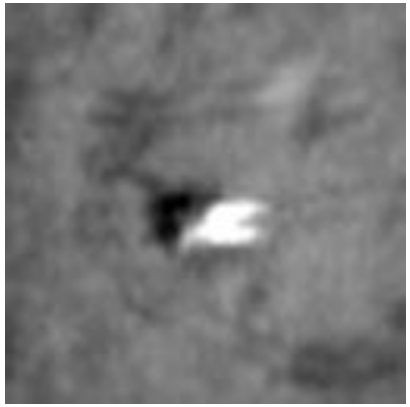
Lunokhod 3 at Space Museum, Moscow



Lander Luna 17/Rover Lunakhod 1, ritrovati da LRO



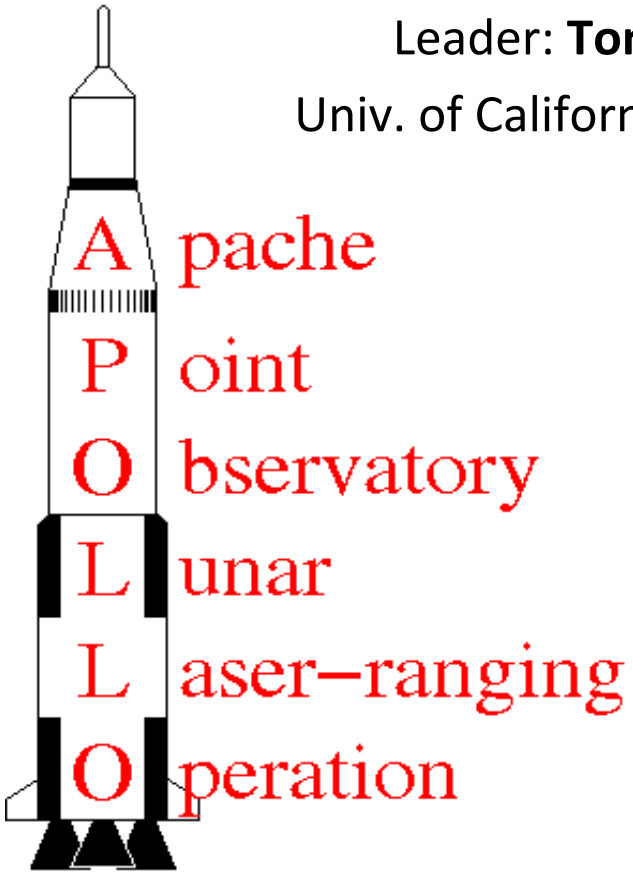




Enlargement of Luna 17 lander,
note the rover Lunokhod 1 tracks starting at the ramp and circling the lander
[NASA/GSFC/Arizona State University].

Lunokhod 1 re-discovered by Laser Ranging

Nuova stazione 'APOLLO' (dal 2007)



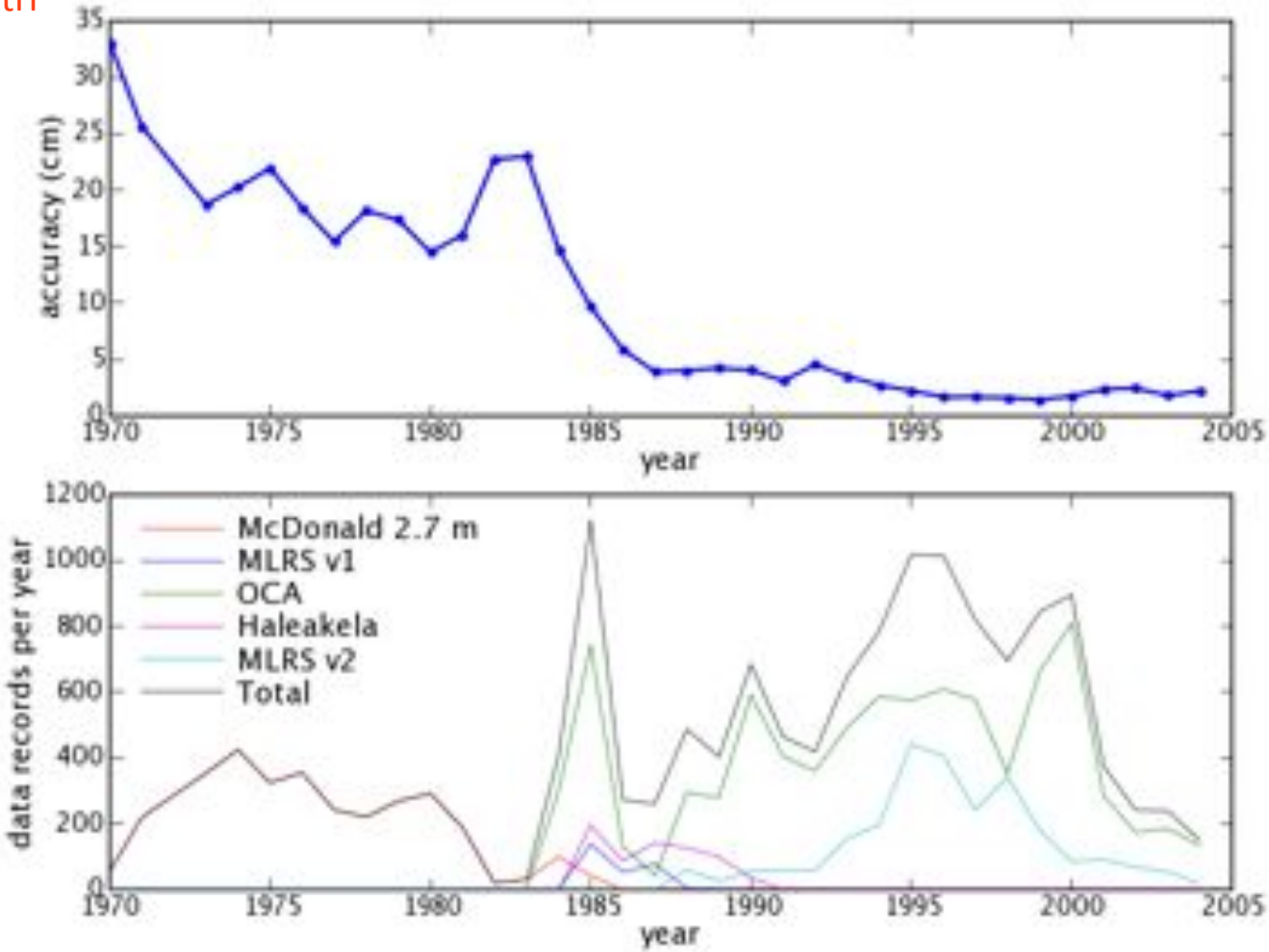
Leader: **Tom Murphy**,

Univ. of California at San Diego

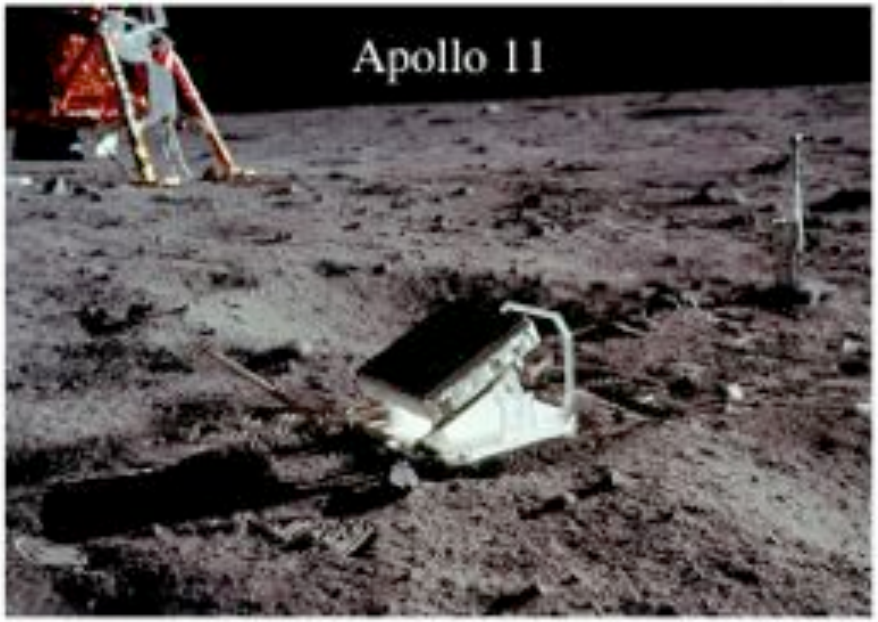
(Apollo) Laser beams are sent to reflectors on the moon from a telescope in New Mexico. Credit: Dan Long, Apache Point Observatory

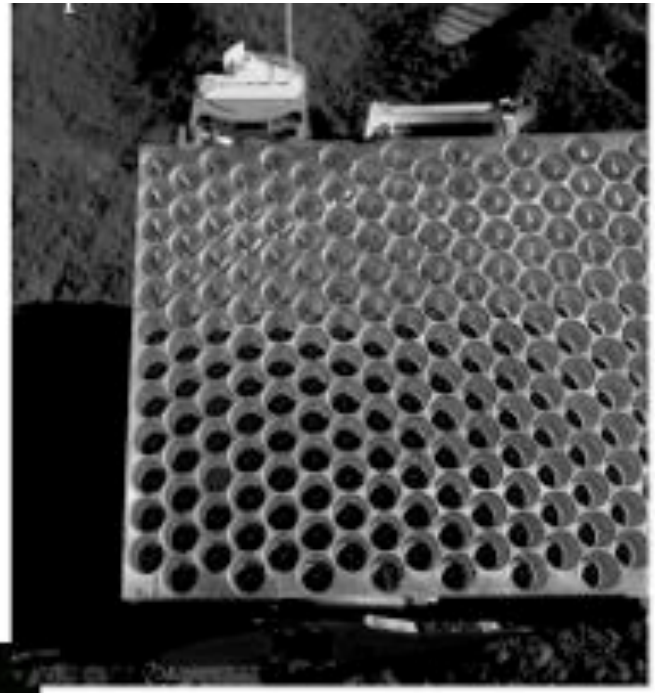
LLR distance precision from 1970 to 2000s

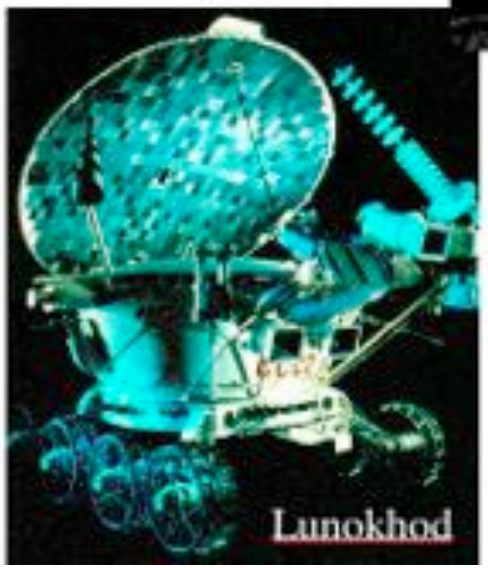
Prima:
centinaia di metri



Lunar retroreflectors: Apollo & Lunokhod







ANALYSIS OF GCO Orbit

- Initial condition: payload to cold shield (-90°) and plate at steady state at -45°C.
- Sunrise (3h): 1FFDP+1IR every 20m.
- Earth Shadow (1h): 1IR every 30s, 1FFDP/min for first 15m, 1FFDP/2m for next 15m, 1FFDP/30m for last 30m.
- Sunset(3h): 1FFDP+1IR every 20m.

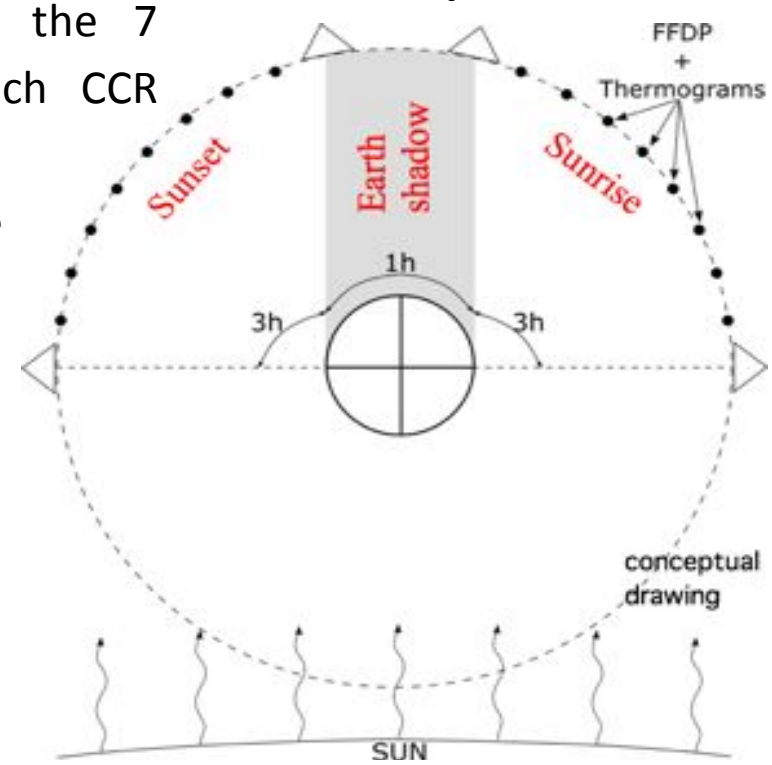
2 orbit:

- **Optical Test CCR1**
- **Optical Test CCR7**

- **Thermal data analysis:** IR pictures analyzed them with a dedicated software and temperature variation of the 7 temperature probes positioned on the rear of each CCR mounting of the array.

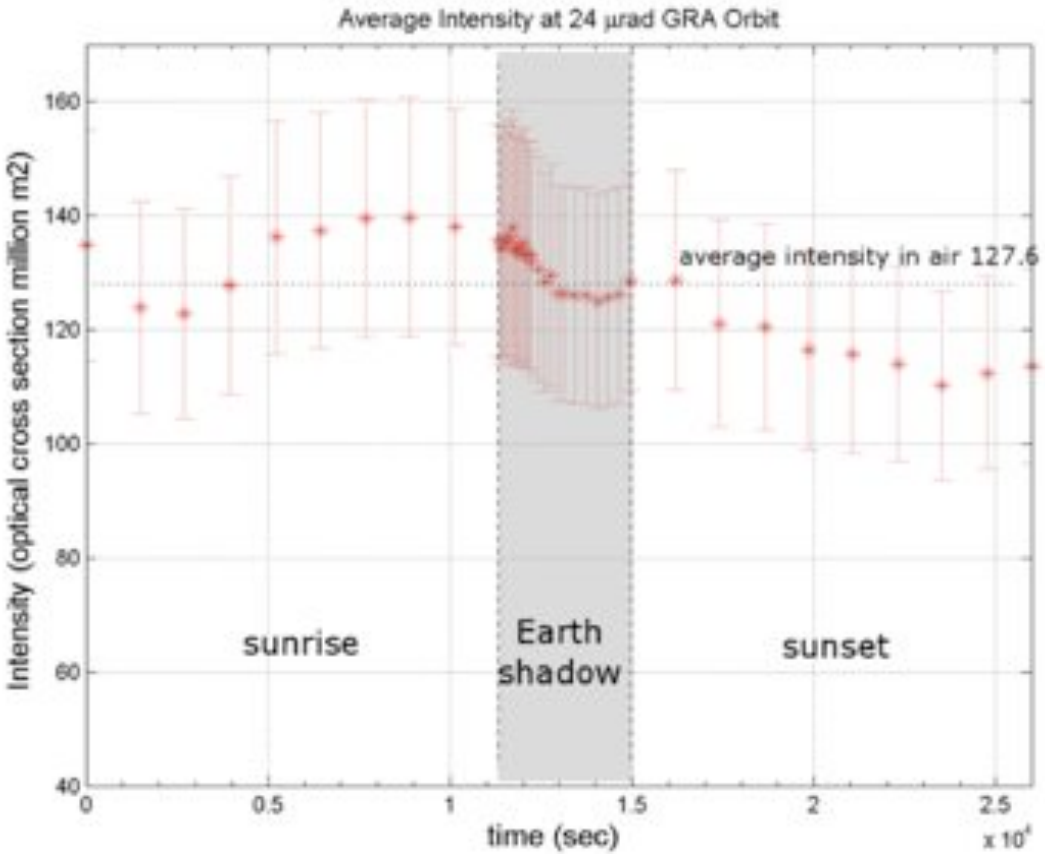
- **Optical data analysis:** MATLAB program to process the raw optical data of the two polarization components. For each tested CCR, the program computes:

- FFDP
- OCS intensity distribution vs va.
- OCS intensity distribution in annulus at 24 µrad va.
- Average OCS intensity at 24 µrad velocity aberration at total CCR FFDP.



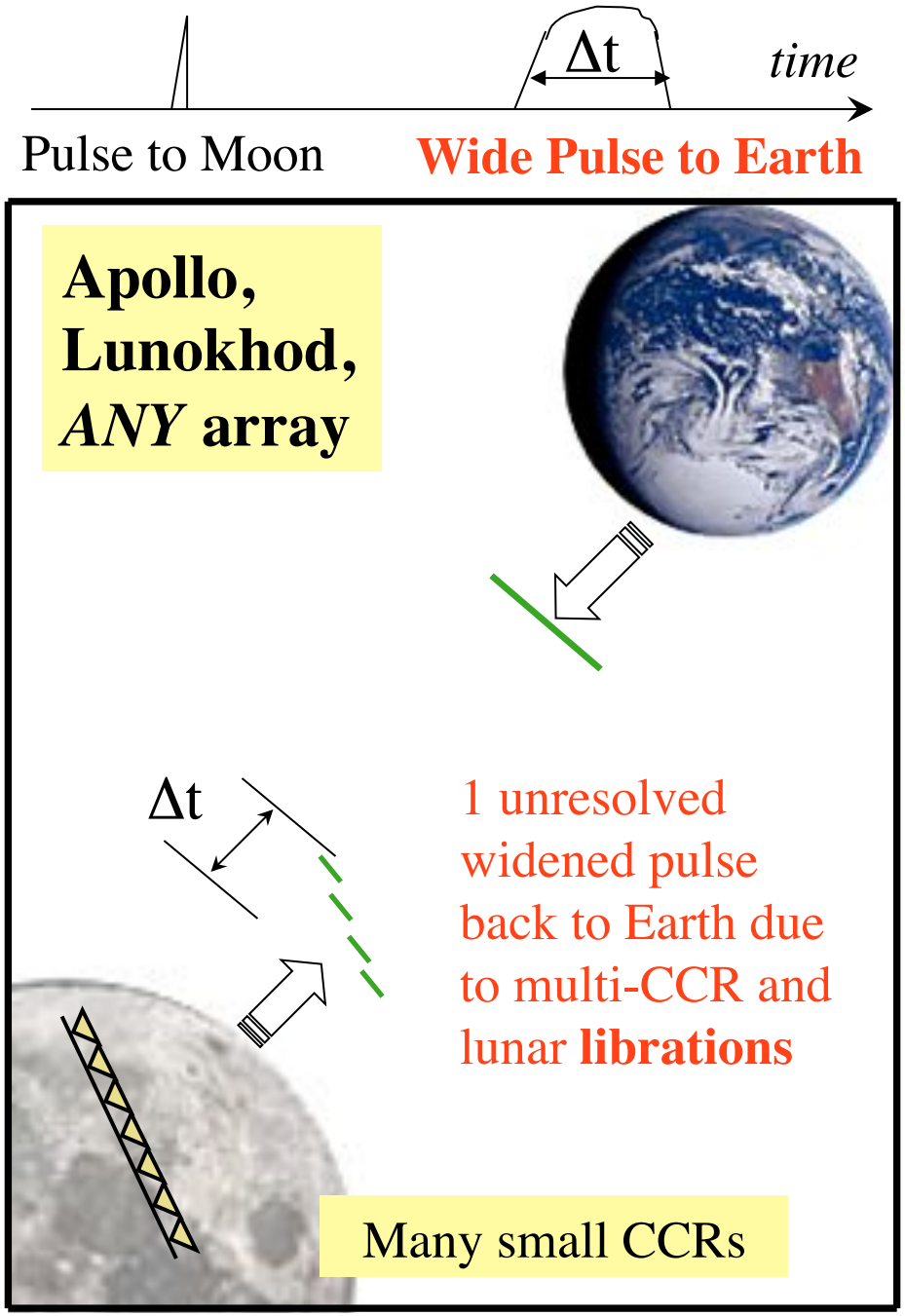
GRA and Galileo IOV reflector performance

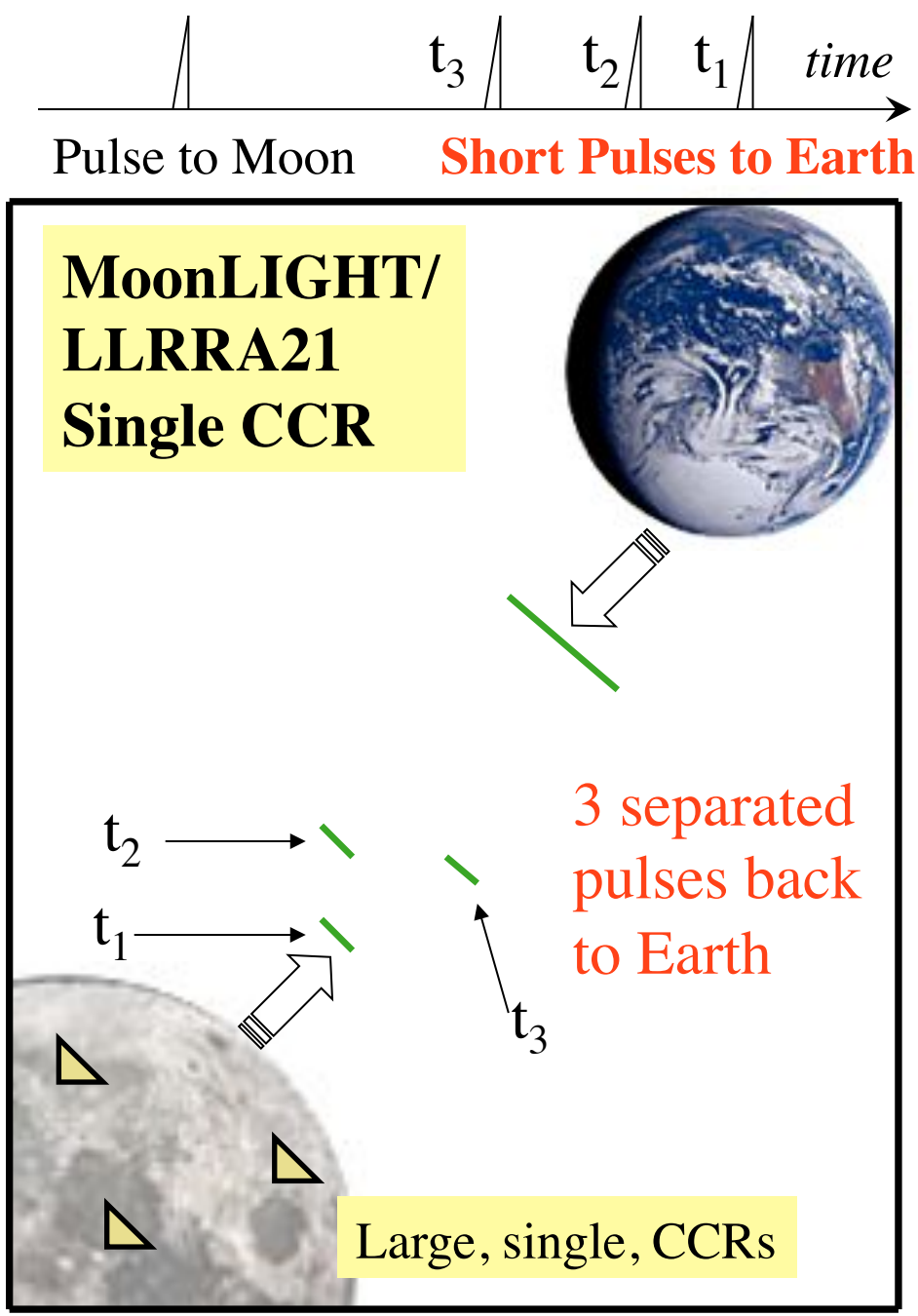
- GRA (GNSS Retroreflector Array) by INFN-ASI: 3.5 kg, 400 mm diameter; lighter/smaller than Galileo IOV
- No degradations within ±15% errors (note scale of plot)



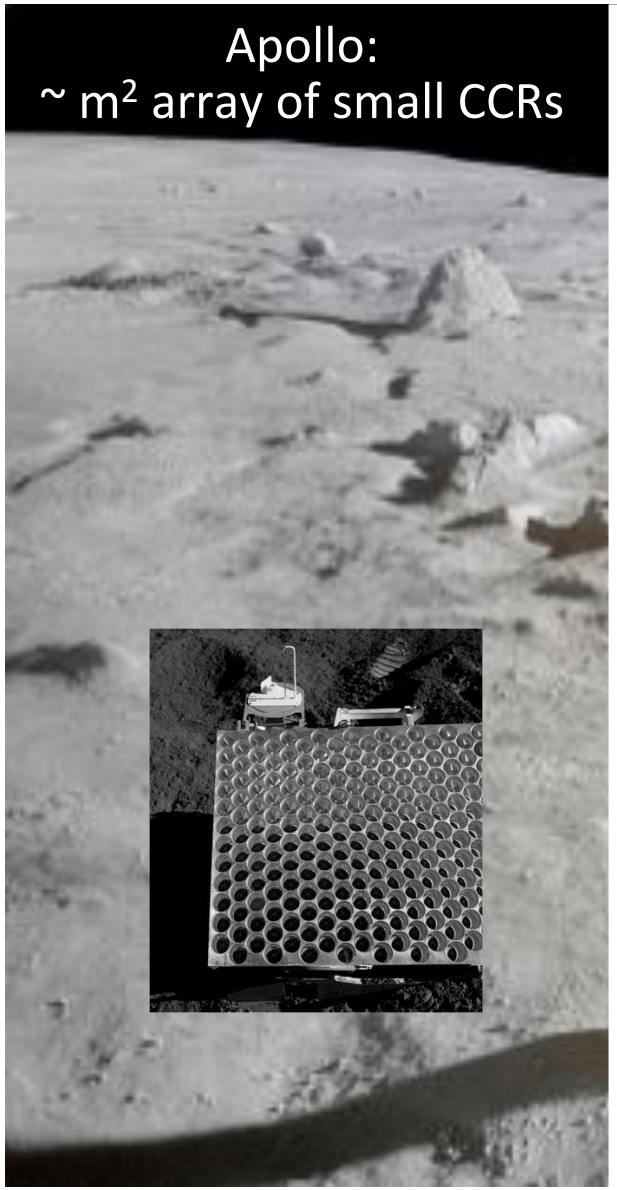
Advanced laser reflectors for the Moon

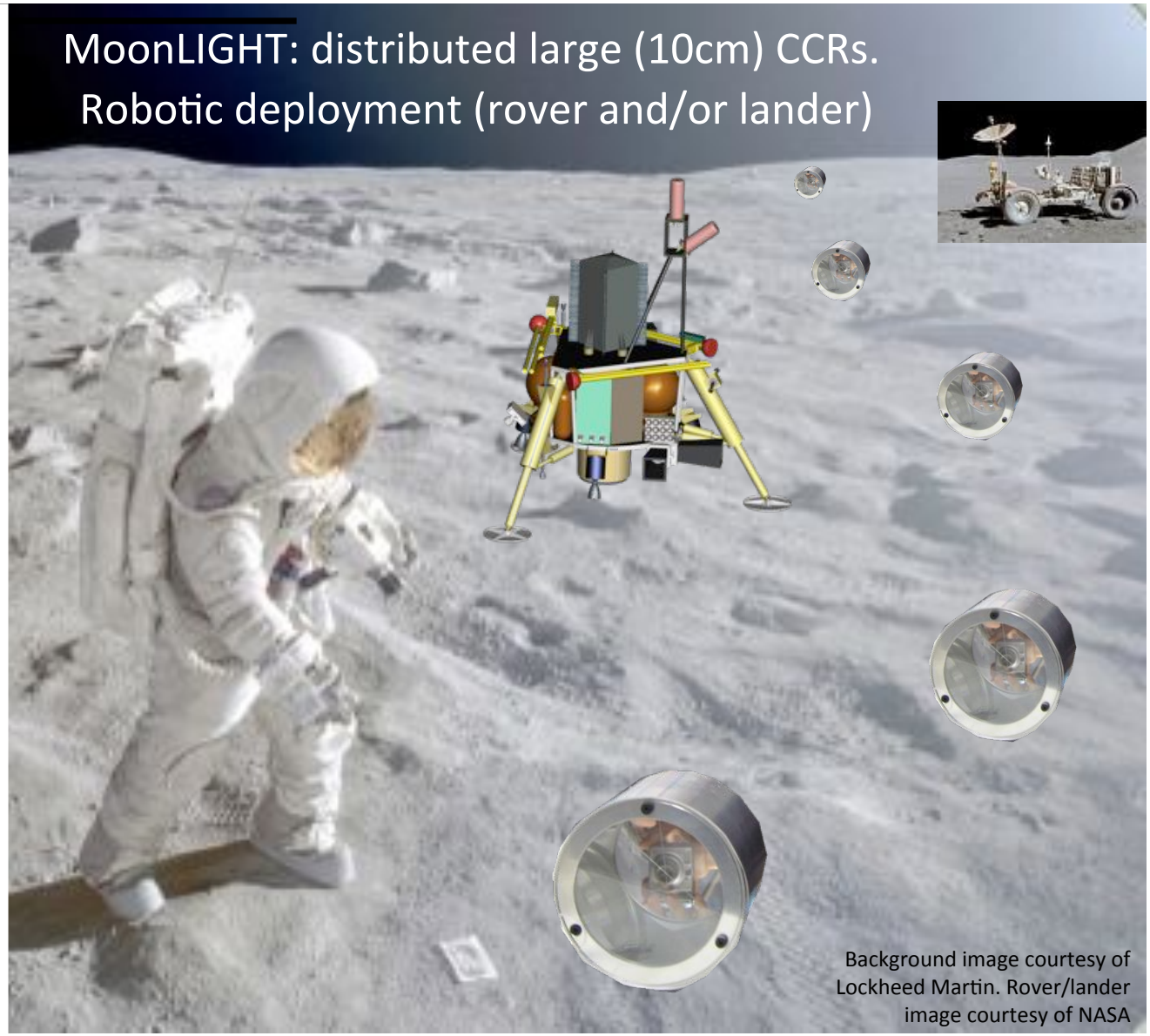
- The Moon: a laser-ranged test body for General Relativity
- Precision of old reflector array limited by librations and
- New **single, large reflector** "MoonLIGHT"
    - D. Currie, Univ. of Maryland
        - Apollo Veteran
    - Italian Teams: INFN (PI), ASI-Matera, University of Padua


Δt
time
Pulse to Moon
Wide Pulse to Earth
Apollo, Lunokhod, *ANY* array
Δt
1 unresolved widened pulse back to Earth due to multi-CCR and lunar **librations**
Many small CCRs


t_3
t_2
t_1
time
Pulse to Moon
Short Pulses to Earth
MoonLIGHT/ LLRRA21 Single CCR
t_2
t_1
t_3
3 separated pulses back to Earth
Large, single, CCRs

MoonLIGHT: single, large sparse reflectors

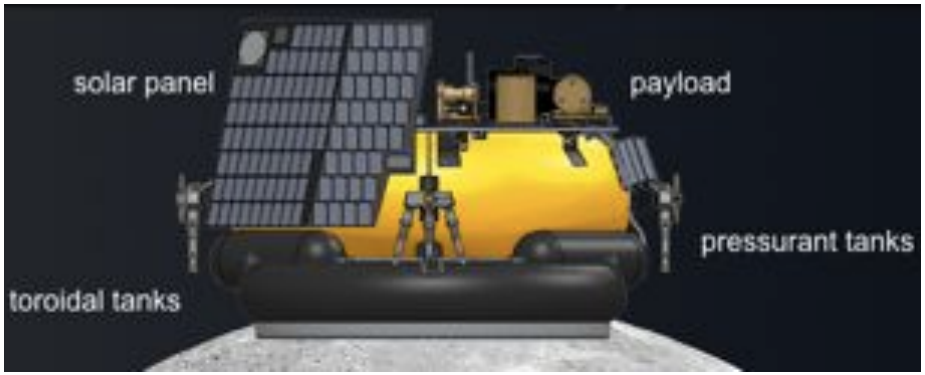




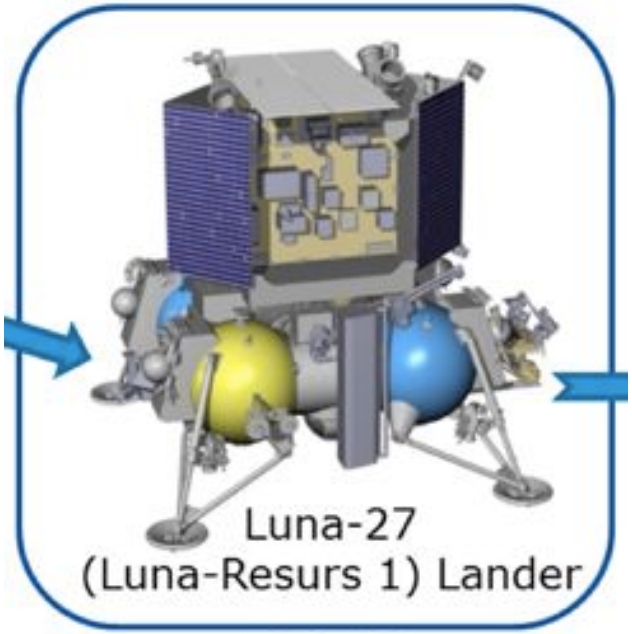
Background image courtesy of Lockheed Martin. Rover/lander image courtesy of NASA

Lunar mission opportunities

- **Moon Express**, lander for Google Lunar X Prize, 2015

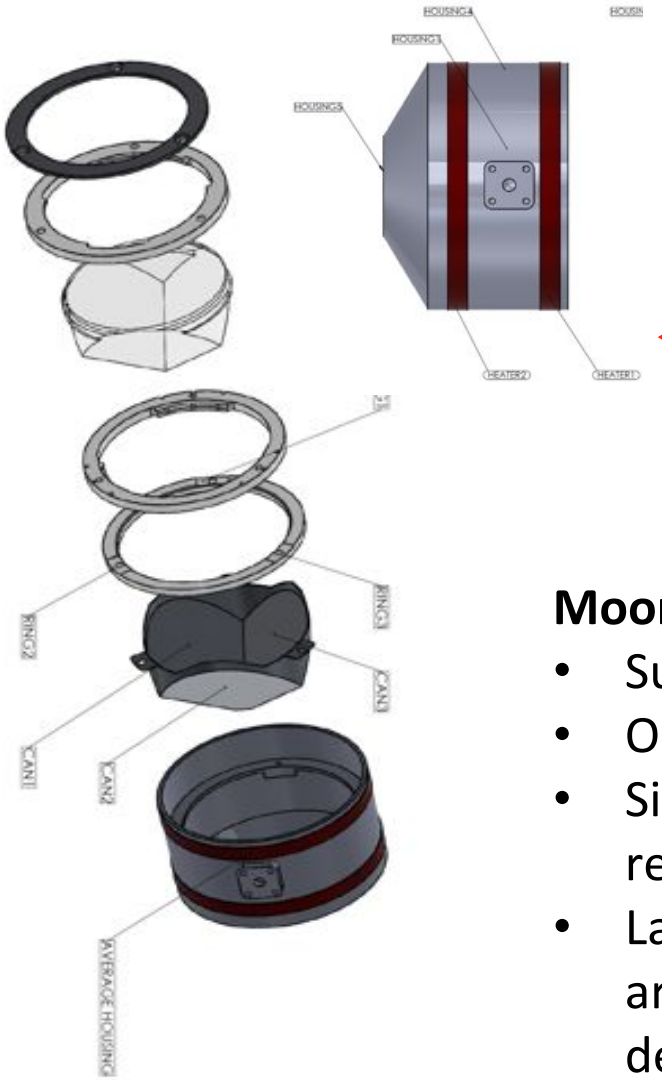


- Proposal to IKI-RAS/Roscosmos for the Lander **Luna-27**



MoonLIGHT laser retroreflector

(Moon Laser Instrumentation for General relativity High accuracy Tests)



MoonLIGHT single reflector vs. Apollo reflector arrays:

- Suprasil 311 vs. Suprasil 1
- Optical specs wave/10 RMS vs. wave/4
- Single reflector 100 mm vs. array of 100-300 reflectors of 38 mm
- Laser return better than Apollo 15 (brightest reflector array) due to A15 degradation, likely due to dust deposit

Science with Lunar Laser Ranging

- **General Relativity**: precisions tests, improvement potentially up to ×100, in the long term
- **Selenodesy**: measurement of deep interior; first evidence of molten lunar core; complementary to GRAIL
- **Exploration**: precise positioning of landing site, hopping and roving. GLXP

Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod few cm accuracy*	MoonLIGHTs 1 mm	MoonLIGHTs 0.1 mm
Parameterized Post-Newtonian (PPN) β	$\lvert\beta-1\rvert<1.1\times10^{-4}$	10^{-5}	10^{-6}
Weak Equivalence Principle (WEP)	$\lvert\Delta a/a\rvert<1.4\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	$\lvert\eta\rvert<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of the Gravitational Constant	$\lvert\dot{G}/G\rvert<9\times10^{-13}\mathrm{yr}^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	$\lvert\alpha\rvert<3\times10^{-11}$	10^{-12}	10^{-13}
Geodetic Precession	$\lvert K_{gp}\rvert<6.4\times10^{-3}$	6.4×10^{-4}	6.4×10^{-5}

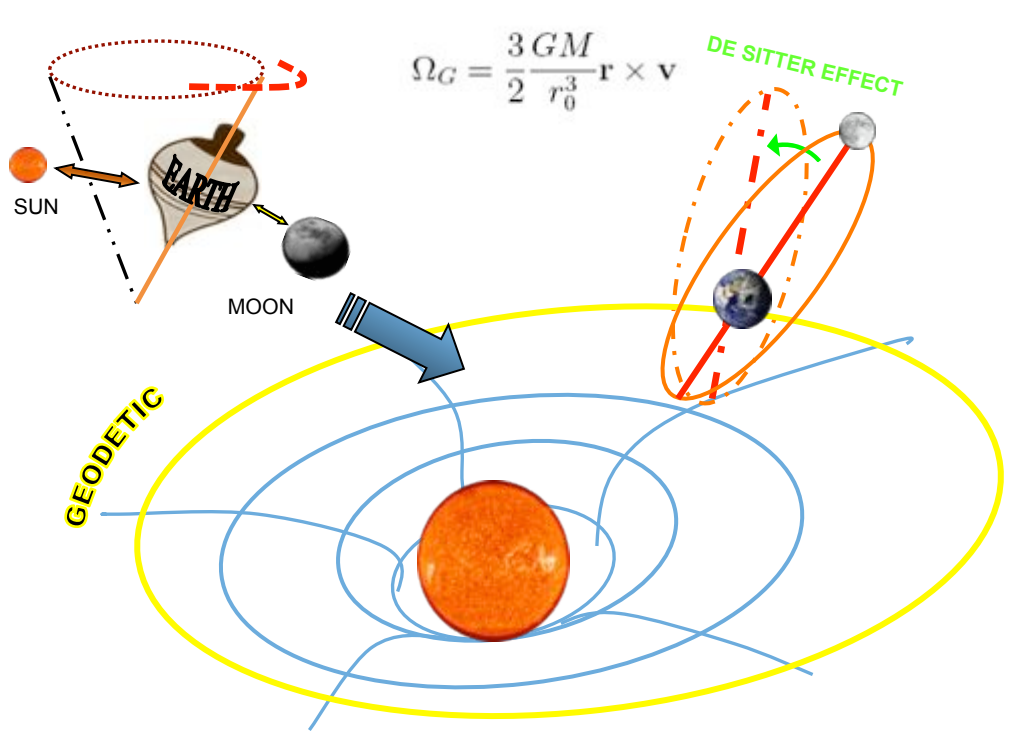
* J. G. Williams, S. G. Turyshev, and D. H. Boggs, PRL 93, 261101 (2004)

Geodetic precession in GR

3-body effect (Sun, Earth, Moon) predicted by GR:

Precession of a moving gyroscope (the Moon orbiting the Earth) in the field of the Sun. The precession due simply to the presence of a central mass is

~ 3.00 m/orbit (28 Earth days) ~ 2"/century

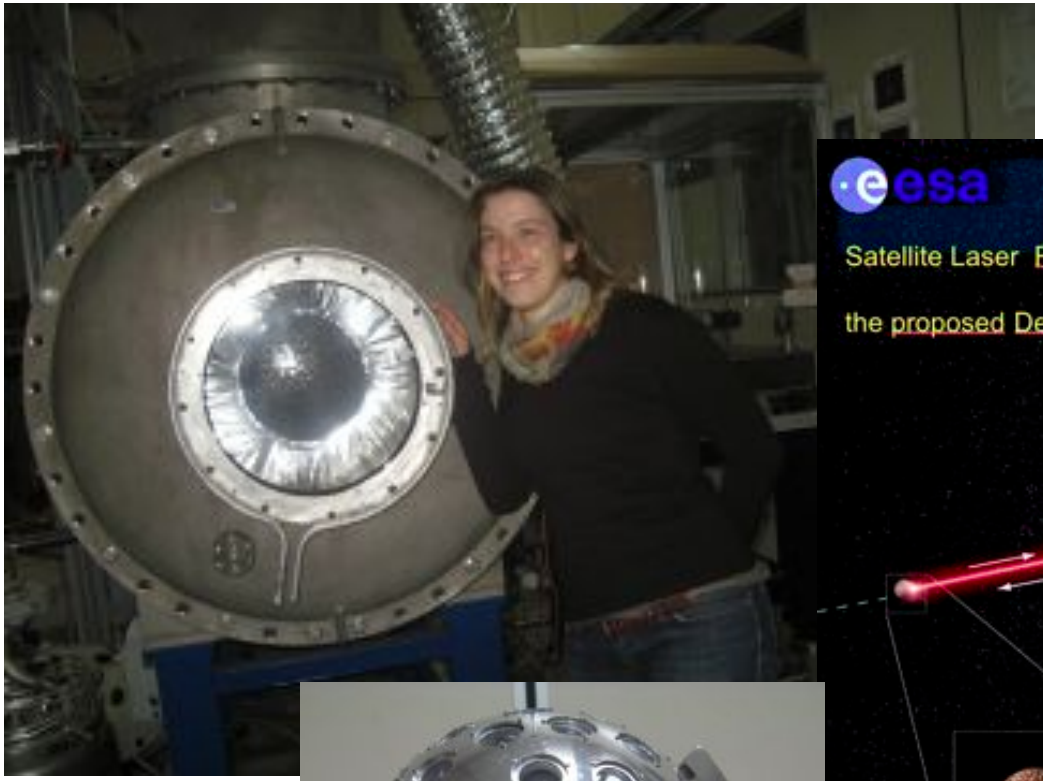


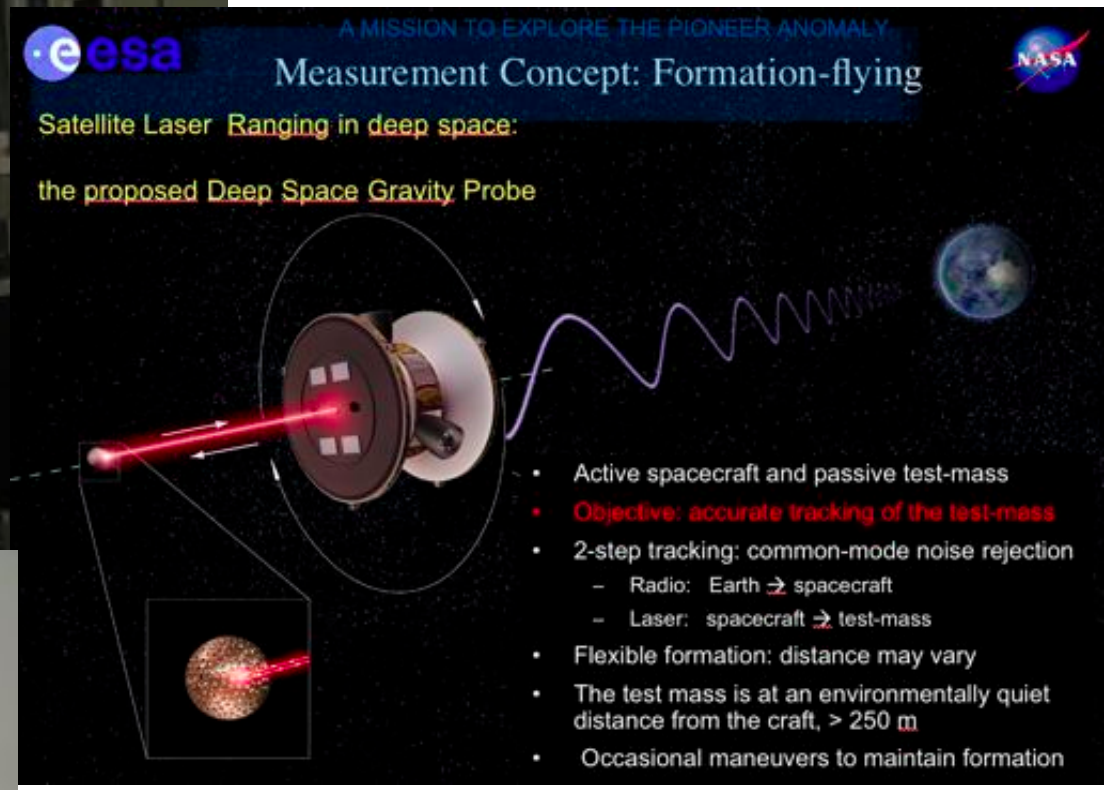
Relative deviation of geodetic precession from GR value:

$$K_{GP} = (\Omega_G - \Omega_G)/\Omega_G$$

Ω_G = geodetic precession
r_0 = circular orbit radius
v = gyroscope velocity
r = position vector
G = gravitational constant
M = central body mass

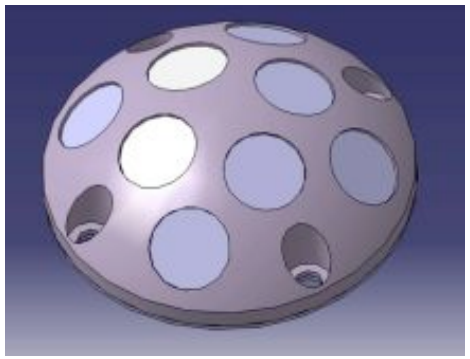
‘Small LAGEOS’ to test $1/r^2$ in deep space

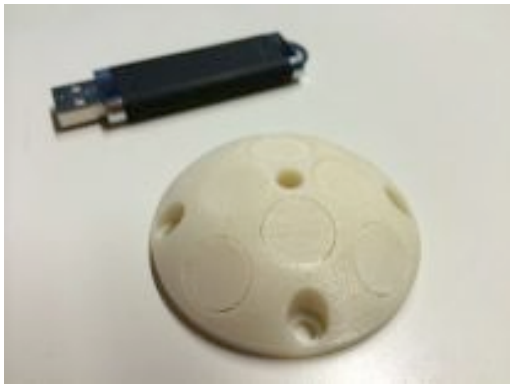




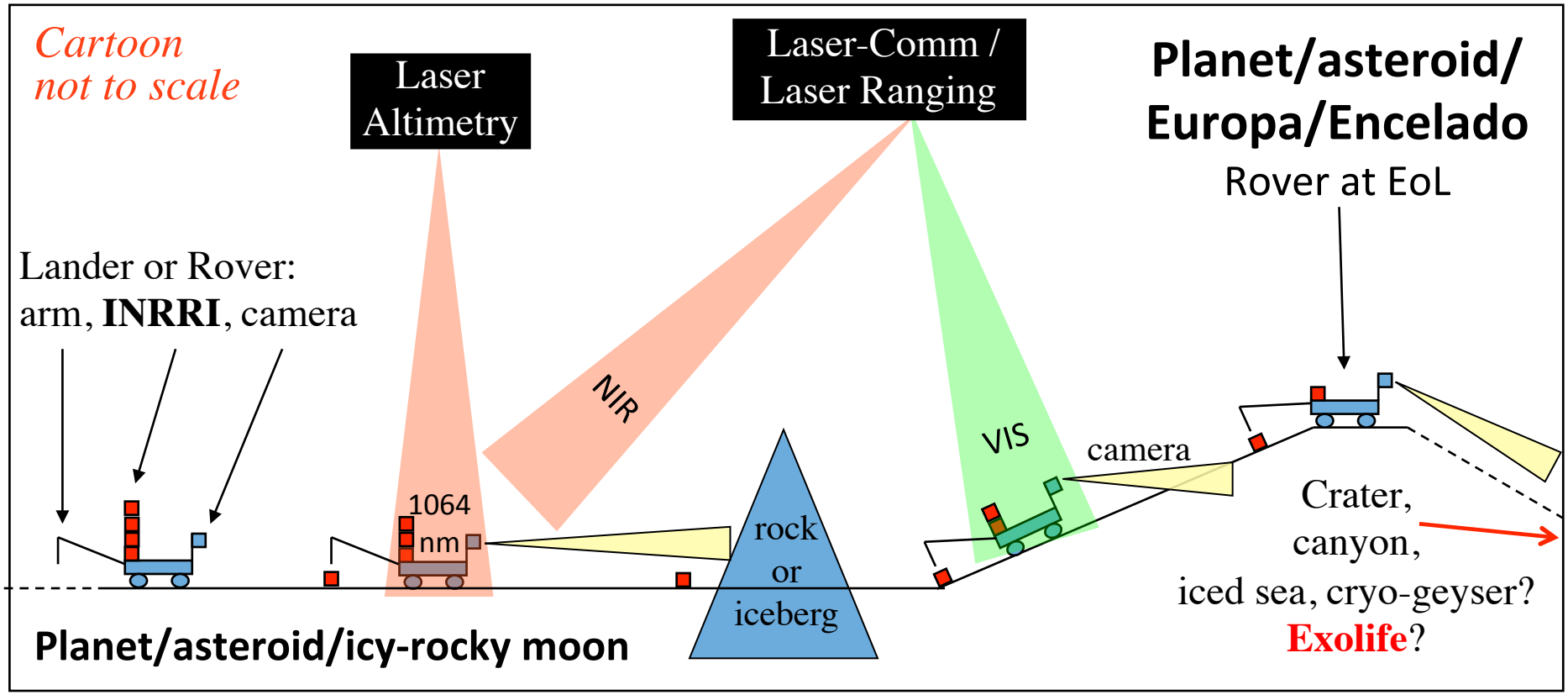
INRRI: INstrument for landing-Roving laser Retroreflector Investigations

- Laser-located by orbiters like NASA mission LADEE
  - **LLCD demonstrated laser time-of-flight with ~100 picosec accuracy**
  - **Accurate positioning of landing site and roving exploration activity**
  - **Multiple INRRIs: establish MGN (Mars Geophysical Network)**
- Motivated by effort on lasercomm by NASA, ESA, etc.:
  - Mars Lasercomm terminals by JPL (Mars 2020), GRC (iROC)
  - ESA: OGS @Tenerife, Alphasat-Sentinel 1A; OPALS @ISS by JPL
- Passive, maintenance-free, lifetime of decades
  - Several geometries/n. CCRs: 5, 7, 8, …
  - Lightweight: ~25 gr
  - Compact (~5 cm x 2 cm)
  - No pointing required





INRRIs on Moon, Mars, Jupiter/Saturn moons



- Selenolocate Rover/Lander with laser retroreflector:
  - Laser Ranging/Comm to reflectors anywhere (LLCD/iROC/OPALS-like)
- **Deploy INRRI networks**. Also on far side of Earth's Moon

Some NASA slides by D. Cornwell

- Shown at workshop IPM-2014, Instrumentation for Planetary Mission
  - November 2014 at NASA-GSFC
- Approved for public release
- Shown to justify how deployment for laser retroreflectors for Solar System exploration can exploit lasercomm payloads capable or time-of-flight (laser ranging) measurements

National Aeronautics and Space Administration

NASA's Optical Communications Program

Don Cornwell, Director

Optical Communications Division

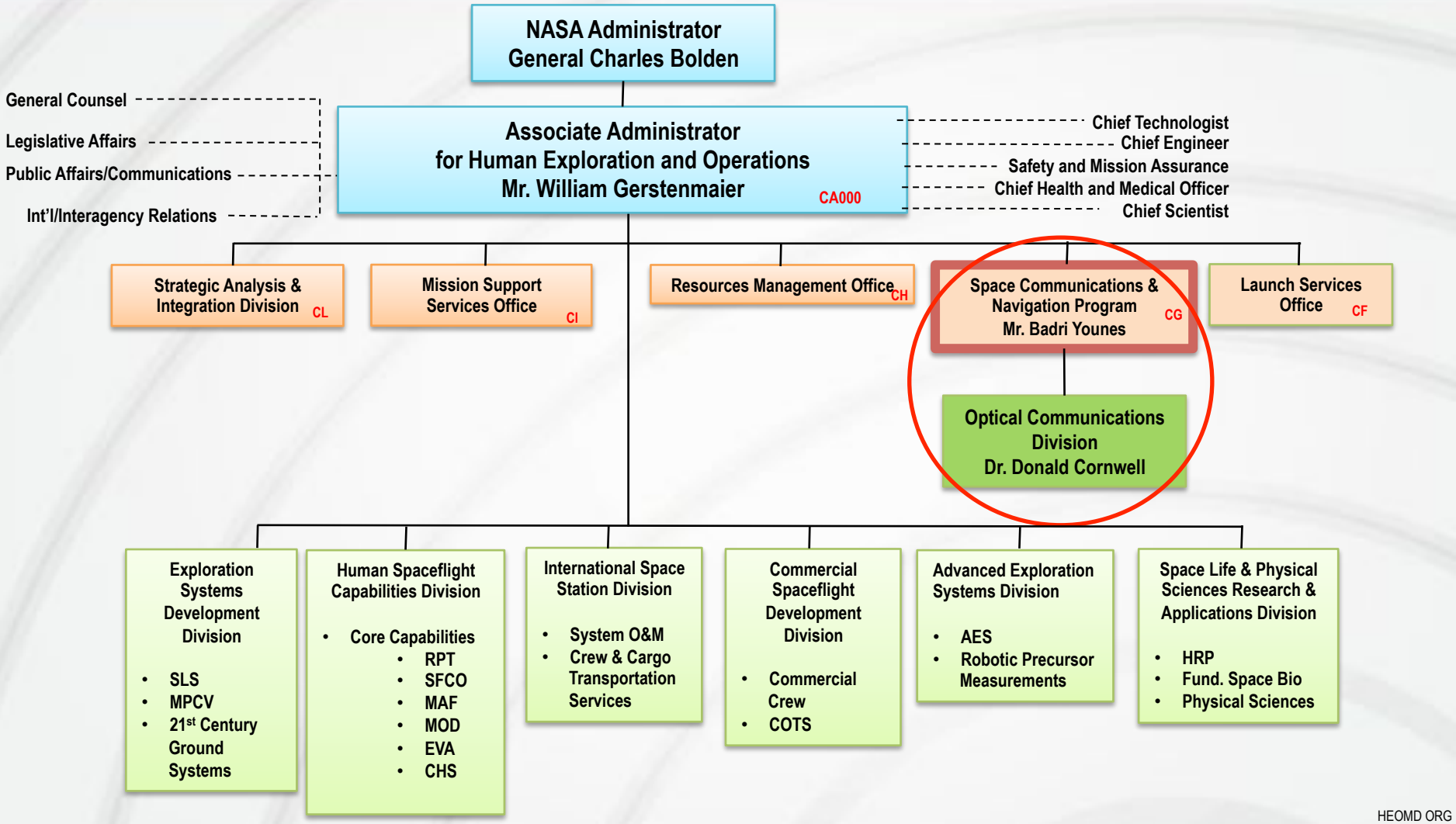
Space Communications and Navigation (SCaN) Program

NASA Headquarters, Washington, DC

Keeping the universe connected.

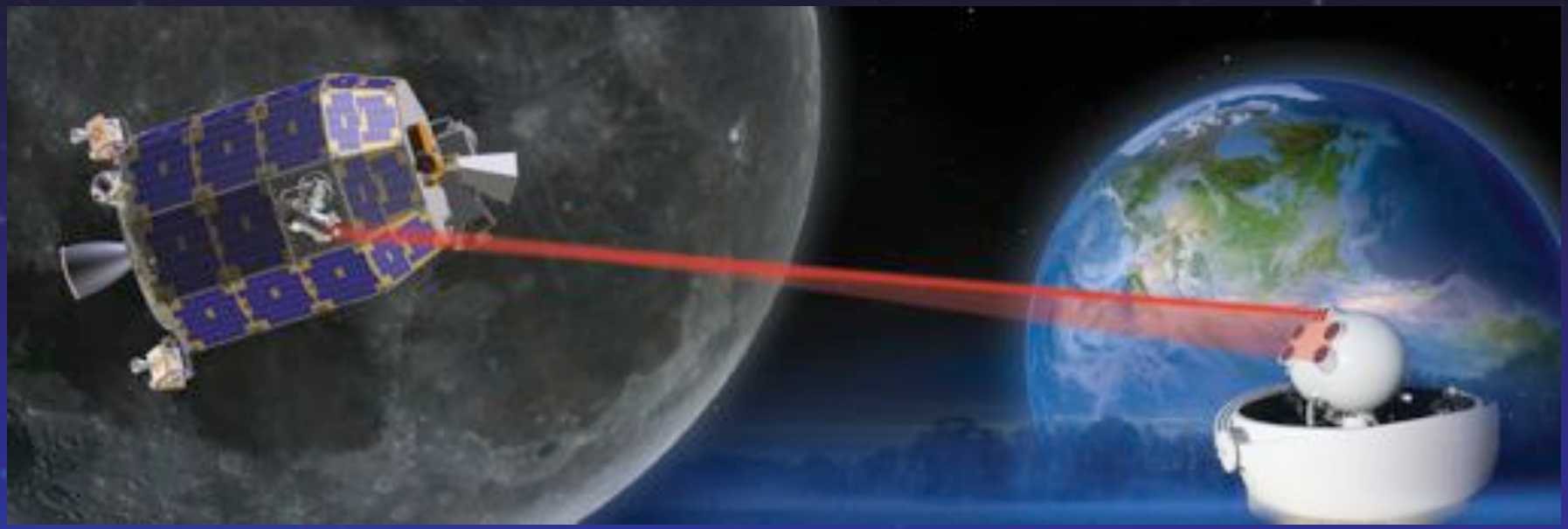
www.nasa.gov

Where is SCaN within NASA?



HEOMD ORG
4.9.12

NASA's First, Historic Lasercom Mission



The Lunar Laser Communication Demonstration (LLCD), Flown to the Moon in September 2013

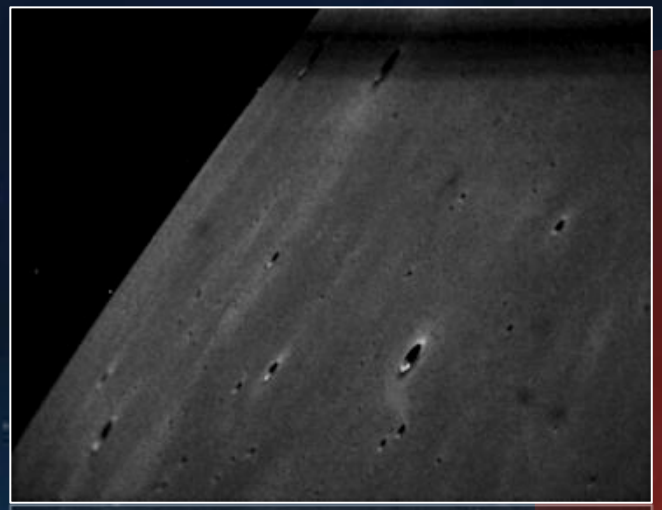
NASA GSFC, MIT Lincoln Laboratory, NASA JPL, ESA

LLCD: NASA's First High-Data-Rate, Two-Way Space Lasercomm Demonstration

- LLCD was flown to the Moon on the Lunar Atmosphere and Dust Environment Explorer (LADEE)
- Launched on September 6, 2013
- IMMEDIATE LASER CONTACT on October 17, 2013
- Set records for download and upload speeds to the Moon
- Planned operations ended November 22nd

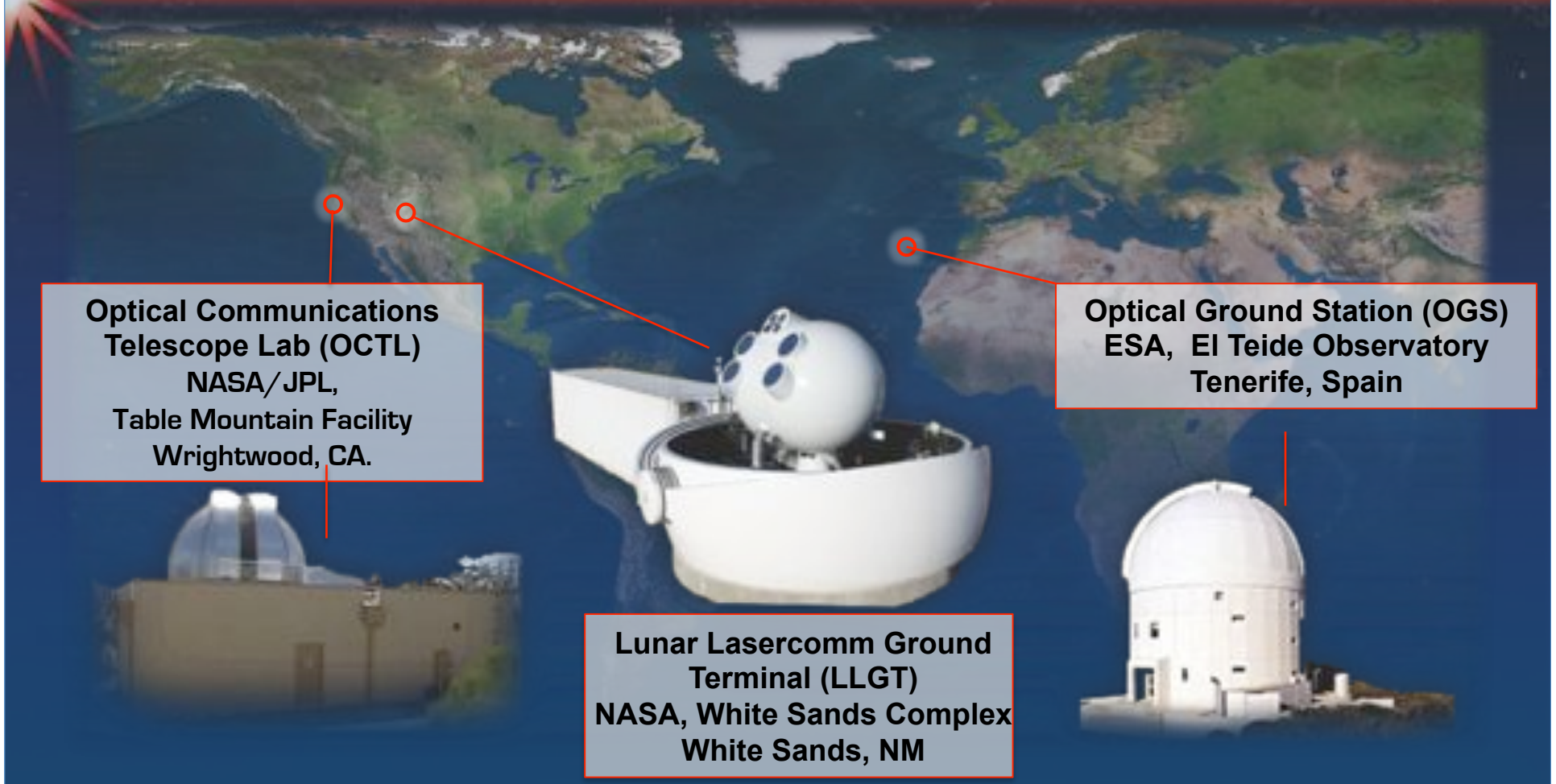
LLCD returned data by laser to Earth at a record 622 Megabits per second (Mbps)
= streaming 30+ HDTV channels simultaneously!

LLCD Accomplishments – Streaming HD Video and Delivering Useful Scientific Data from LADEE to Earth



Real LADEE Science Data and Telemetry Transmitted via LLCD

LLCD's Multiple Ground Terminals:
An International Collaboration

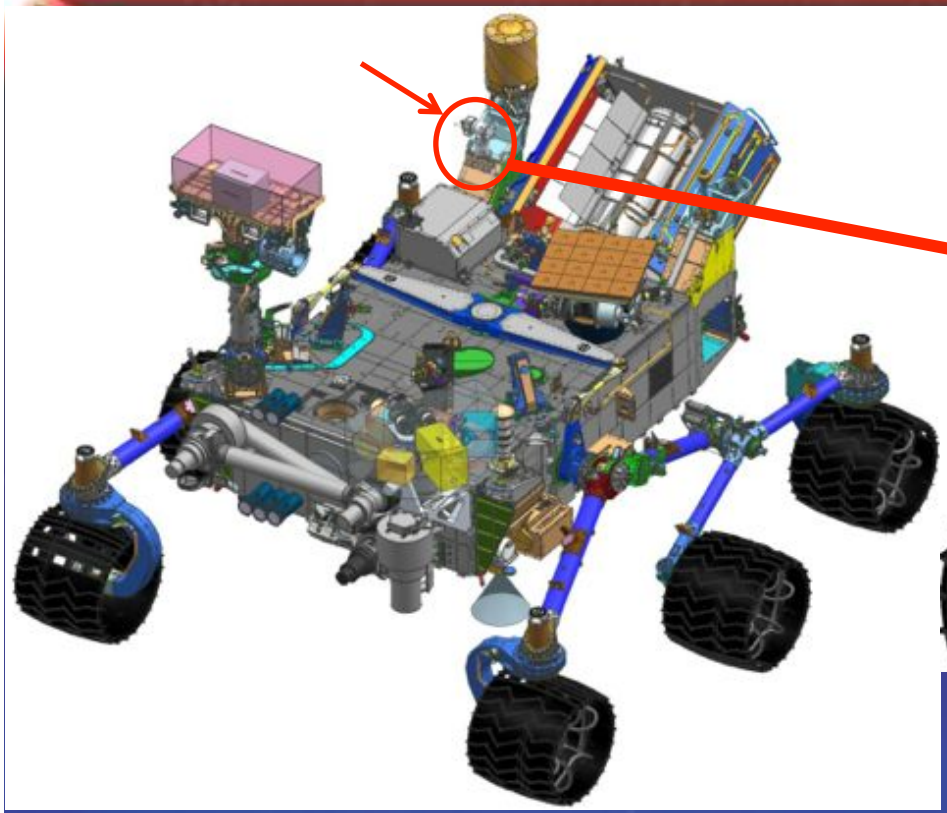


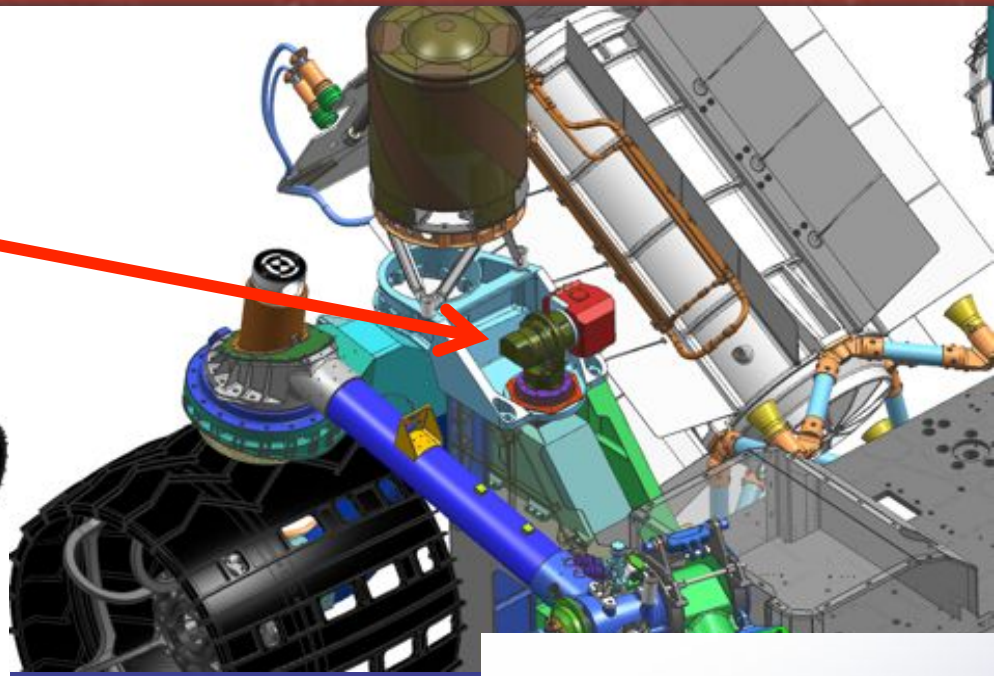
Geographic site diversity is required to reduce the likelihood that clouds will interrupt the link; it also allowed the opportunity to demonstrate international interoperability while sharing the costs of the system of LLCD

NASA-OPALS@ISS, ESA-OGS @Tenerife

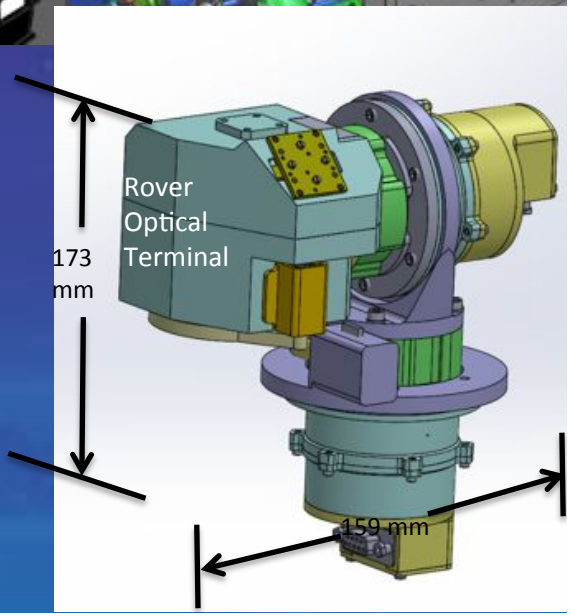
Optical PAyload for Lasercomm Science (OPALS)

LaserComm for the Mars 2020 Rover



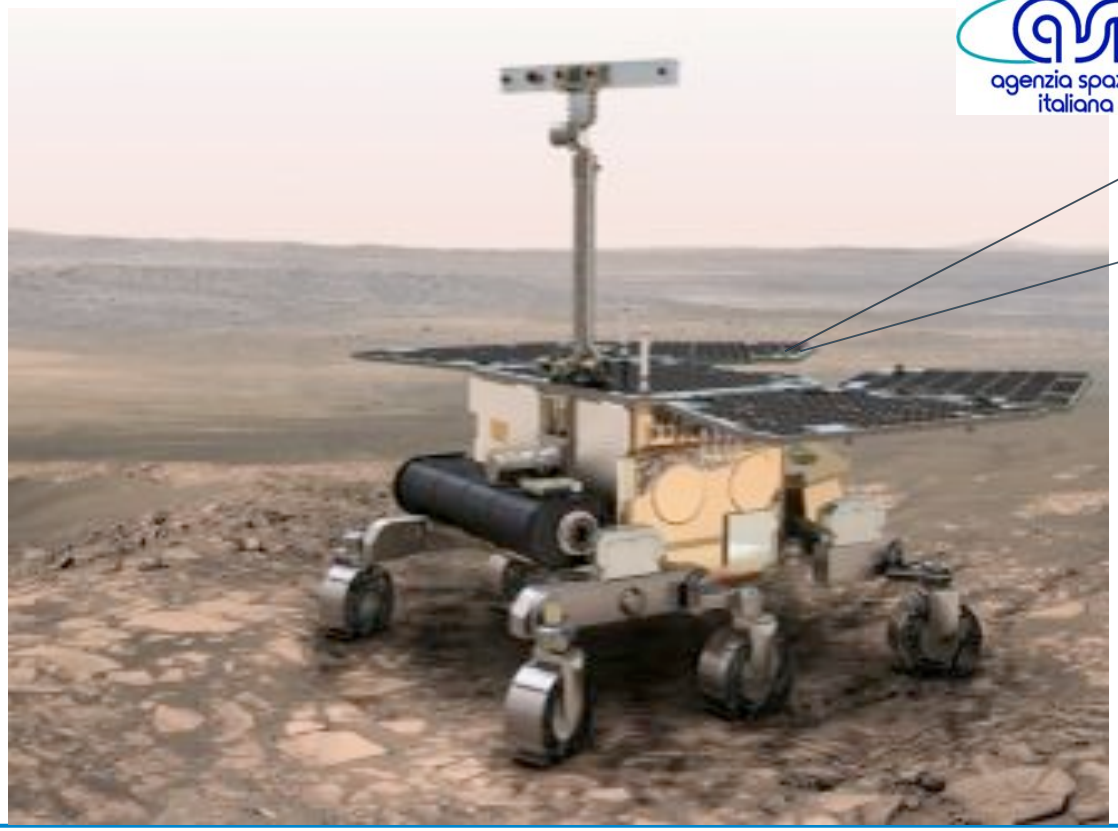


- Optical Terminal will support dual links:
  - "Proximity" link, to optical terminal on orbiter (20 Mb/s max)
  - Direct-To-Earth link (200 kb/s max, from 0.5 AU)
- Optical Aperture Diameter: 5 cm
- Average Laser Power: 1 W
- DC Power Consumption: 50 W
- Mass: 5.7 kg
- Volume: 4.6 liters



INRRI for Mars Rovers (and Landers)

- Geodesy/Geophysics: Mars Geophysical Network, Definition of Meridian 0
- Georeference exploration (Also light/laser flash + optical camera)
- Precision Lidar-based landing (return to astrobiologically relevant site)
- Lidar atmosphere trace species detection
- Lasercomm test & diagnostics



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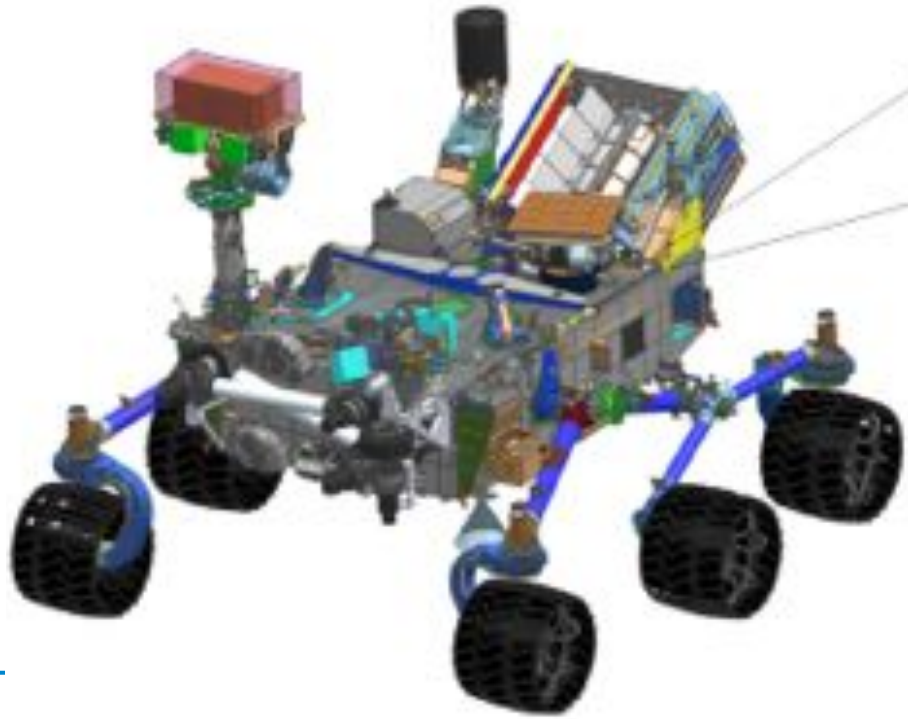
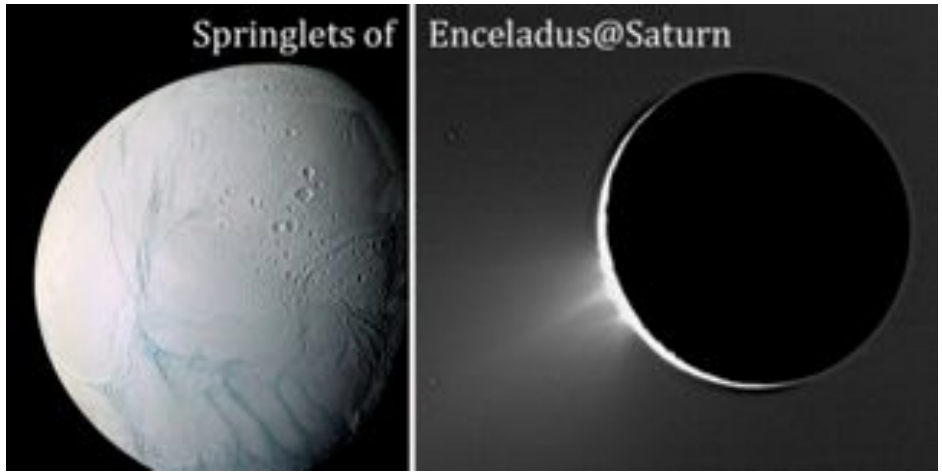
INRRI-2020:
INstrument for landing-**R**oving laser **R**etroreflector **I**nvestigations
on
Mars 2020



Europa/Encelado, “the” icy/rocky moons

- Europa/Enceladus Cube Corners retroreflectors for Exploration/Exolife
  - Recent NASA AO on Europa did not include landing/roving
  - But JPL has study for Europa Lander
  - Ultimate destination: Enceladus, and its “springlets”
- Terrestrial and Celestial Reference Frames
  - Link Earth-Moon, Mars/Phobos/Deimos and Europa/Encelado laser retroreflector networks
- Depending on mission/body
  - Different geometries
  - Varying sizes & n. of reflectors
  - Depending especially on s/c orbit (velocity aberration)



The Martian system

- Goals for the **Mars surface**
  - Georeferencing of lander or rover exploration activity
  - Define Mars Prime Meridian
    - Now: Airy-0 crater, accurate at 50 m level
  - Multiple INRRIs on landers/rovers can establish MGN
  - Lasercomm test/diagnostics (wavelength independent)
  - Atmospheric trace species detection by space-borne lidar
    - Full column sampling, at varying angles
  - Lidar-based/aided landing
- Phobos /Deimos
  - PANDORA: Phobos AND DeimOs laser Retroreflector Array

Conclusions

- Satellite and Lunar Laser Ranging started in 1964 about 50 years ago (~same time of ICTP)
  - Laser: T. Maiman, C. Townes, ~1960
  - Now: ILRS network of 40+ ground laser stations world-wide
    - SCF_Lab @INFN, Italy to design, build, validate, characterize, diagnose Laser Retroreflectors in Space
- Applications:
  - International Terrestrial Reference System (geocenter, scale)
  - Global Navigation Satellite System (Galileo etc)
  - Lunar Laser Ranging (Test of General Relativity)
  - Exploration of Mars System and rest of solar system, exploiting lasercomm

Acronyms and definitions

1. AM0: Air Mass Zero
2. ASI: Agenzia Spaziale Italiana
3. CCR: Cube Corner Retroreflector
4. EO = Earth Observation
5. ESA: European Space Agency
6. ETRUSCO: Extra Terrestrial Ranging to Unified Satellite Constellation
7. DEM = Digital Elevation Model
8. FFDP: Far Field Diffraction Pattern
9. FOC: Full Orbit Capability
10. GCO: GNSS Critical half Orbit
11. GMES = Global Monitoring for Environment and Security
12. GNSS : Global Navigation Satellite System
13. GPS: Global Positioning System
14. GRA: GNSS Retroreflector Arrays
13. GTRF: Galileo Terrestrial Reference Frame
14. ILRS: International Laser Ranging Service
15. IOV: In Orbit Validation
16. IPR: Intellectual Property Rights
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/GNSS laser ranging and altimetry Characterization Facility
23. SCF-G: Satellite laser ranging Characterization Facility optimized for GNSS
24. SLR: Satellite Laser Ranging
25. WI: Wavefront Interferogram

Some Reference Documents

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- [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).
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