Space Research at the SCF_LAB

SCF_LAB

Satellite/Lunar/GNSS laser ranging
Characterization Facility LABoratory

Simone Dell'Agnello for the SCF_LAB Team

Italian National Institute for Nuclear Physics, Laboratori Nazionali di Frascati (INFN-LNF),
Via Enrico Fermi 40, Frascati (Rome), 00044, Italy

44th Meeting of the LNF Scientific Committee

Frascati, June 4, 2012

SCF_LAB Team (**16.4** Full Time Equivalents)

SCF Group

S. Dell'Agnello, Resp.
G. Delle Monache, Vice
R. Vittori, G. Bianco
C. Cantone,
A. Boni
C. Lops,
M. Maiello
S. Berardi,
G. Patrizi,
Manuele Martini
G. Bellettini, R. Tauraso
R. March,
N. Intaglietta
M. Tibuzzi,
E. Ciocci,
L. Salvatori,
M. Lobello,
A. Stecchi

National Collaborations

ASI - Centro di Geodesia Spaziale - G. Bianco, SLR/LLR station and orbit sw, co-PI of ETRUSCO-2

Ministry of Defense, Aeronautica Militare Italiana (AMI) - R. Vittori, co-PI of ETRUSCO-2

International Collaborations

Univ. of Maryland at College Park - D. Currie, inventor of LLR
Harvard-Smithsonian Center for Astrophysics – J. Chandler, PEP lunar orbit sw, M. Pearlman.
Univ. of California at San Diego - T. Murphy, best LLR Station
NASA-GSFC, J. McGarry

Membership of International Scientific Communities

ILRS - Signal Processing WG
ILN - Core Instrument WG

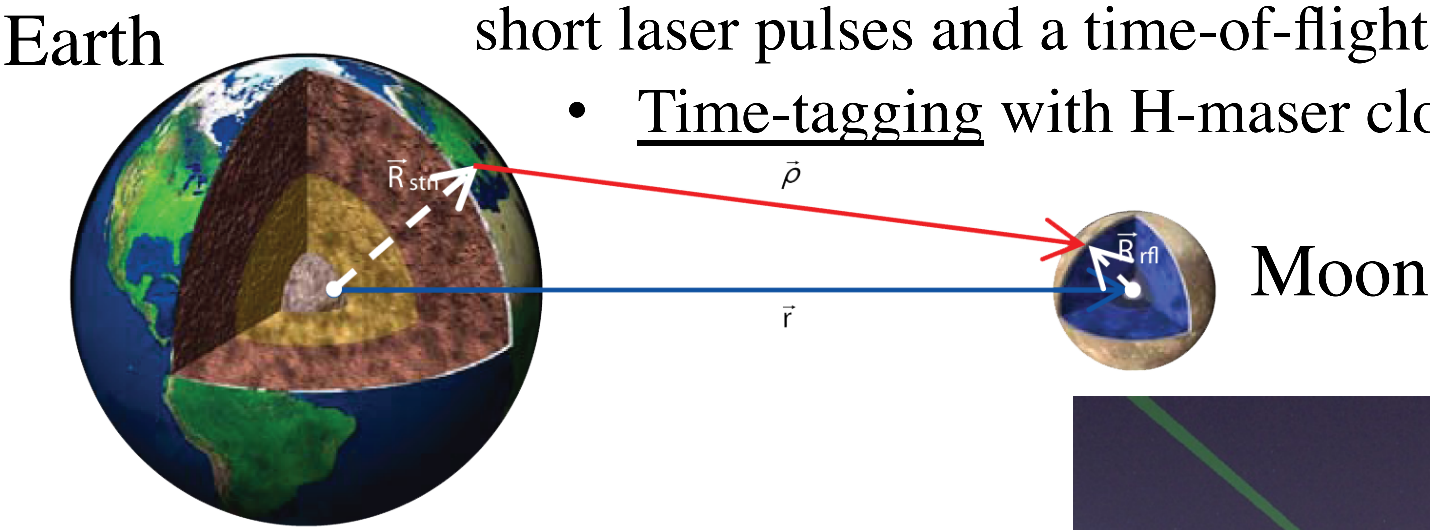
Students: L. Palandra, S. Contessa, S. Rinaldi, R. Heller (US DoE)

Outline

- Satellite/Lunar Laser Ranging (SLR/LLR)
  - **GeoMetroDynamics** (GMD) in space
- SCF_LAB @ LNF
  - SLR/LLR **Characterization** Facilities Laboratory
- Projects/contracts for fundamental GMD (gravity)
  - Moon: Test of **General Relativity,** Selenodesy and spacetime Torsion
- Projects/contracts for applied GMD (space geodesy)
  - **Galileo** and other Global Navigation Satellite System (**GNSS**)
- Mission opportunities, contracts, external funds, proposals

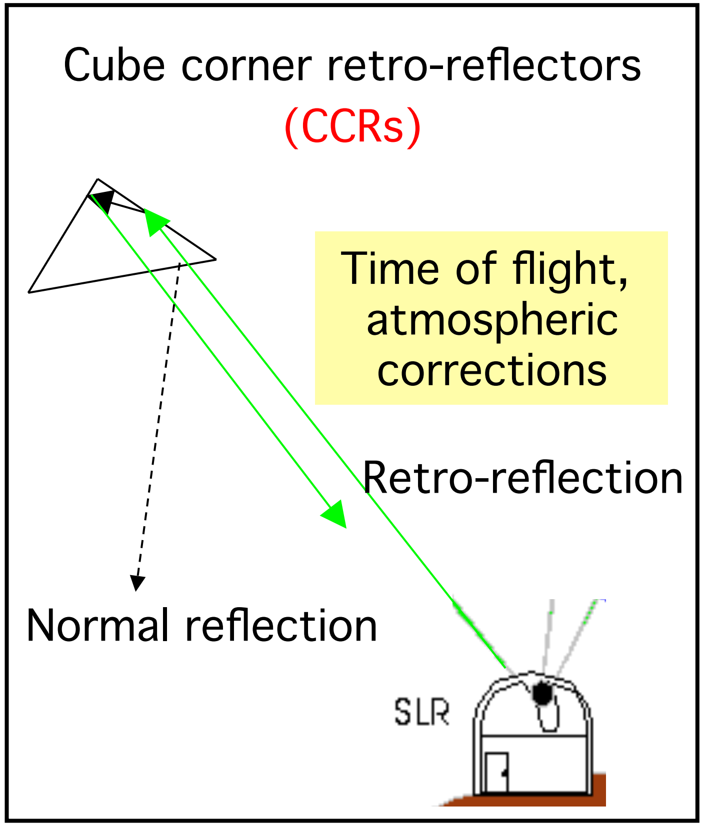
Satellite/Lunar Laser Ranging (SLR/LRR)

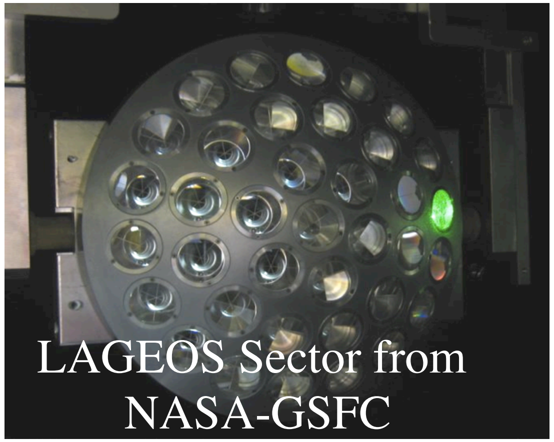
- **GeoMetroDynamics** (GMD) in space
- Unambiguous position/distance measurement (so-called 'laser range') to cube corner retroreflectors (CCRs) with short laser pulses and a time-of-flight technique
- Time-tagging with H-maser clocks

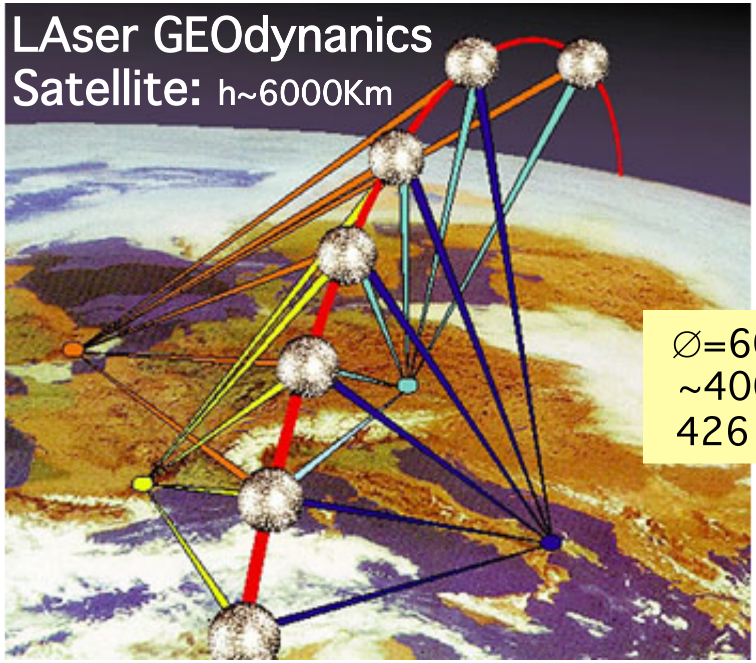


- **Precise** positioning (normal points at mm level, orbits at cm level)
- **Absolute** accuracy (used to define Earth center of mass, geocenter, and scale of length)
- **Passive**, maintenance-free Laser Retroreflector Arrays (**LRAs)**

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







∅=60 cm
~400 Kg
426 CCRs

(Precise). AND. (cost-effective) distance measurement in space
(few millimeters to 1-2 centimeters) .AND. (100K€ to M€)
Laser interferometry much more precise but much more expensive/difficult

Gravitation, Space geodesy, GNSS

LEO, GNSS, GEO, Moon

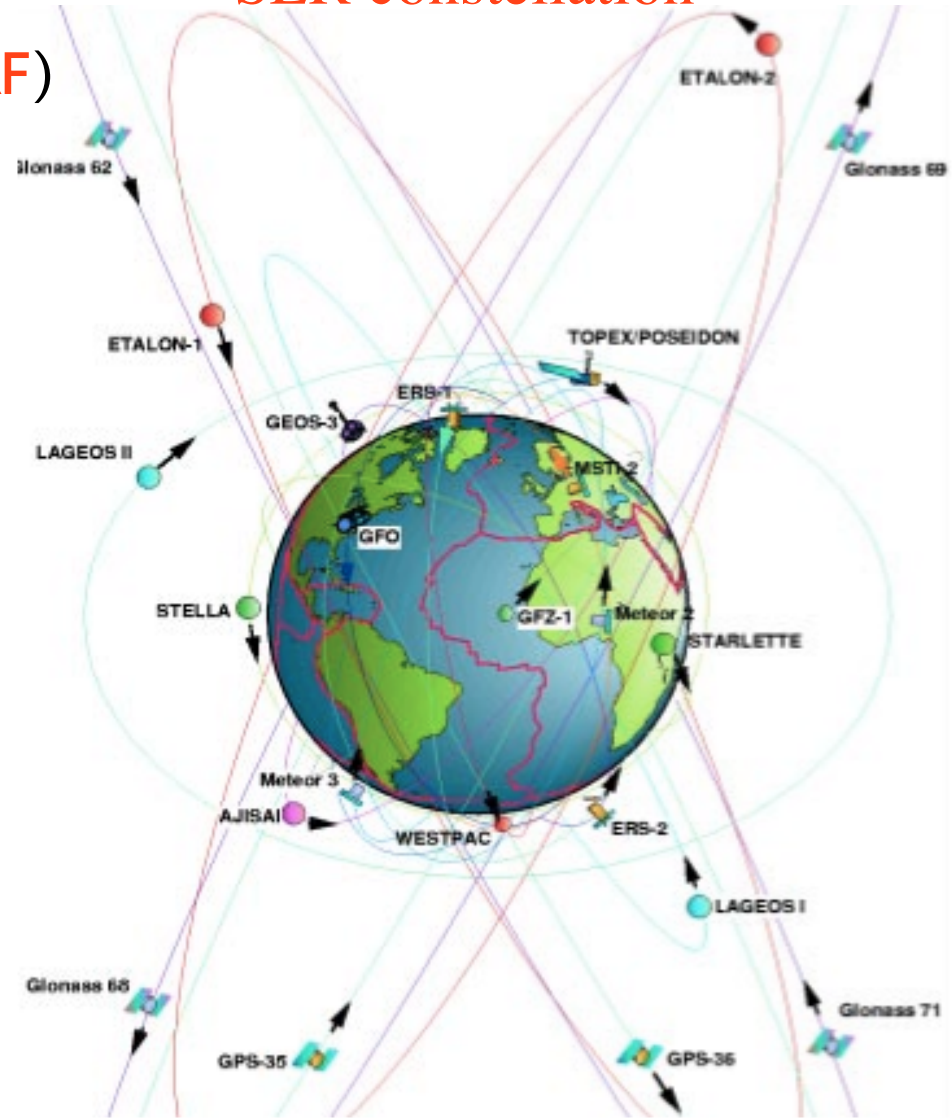
Int. Terrestrial Reference Frame (ITRF)

- Geocenter from SLR (LAGEOS)
- Scale from SLR (LAGEOS) and VLBI
- Orientation (wrt ICFR) from VLBI
- ITRF distribution w/GNSS
- DORIS, ...

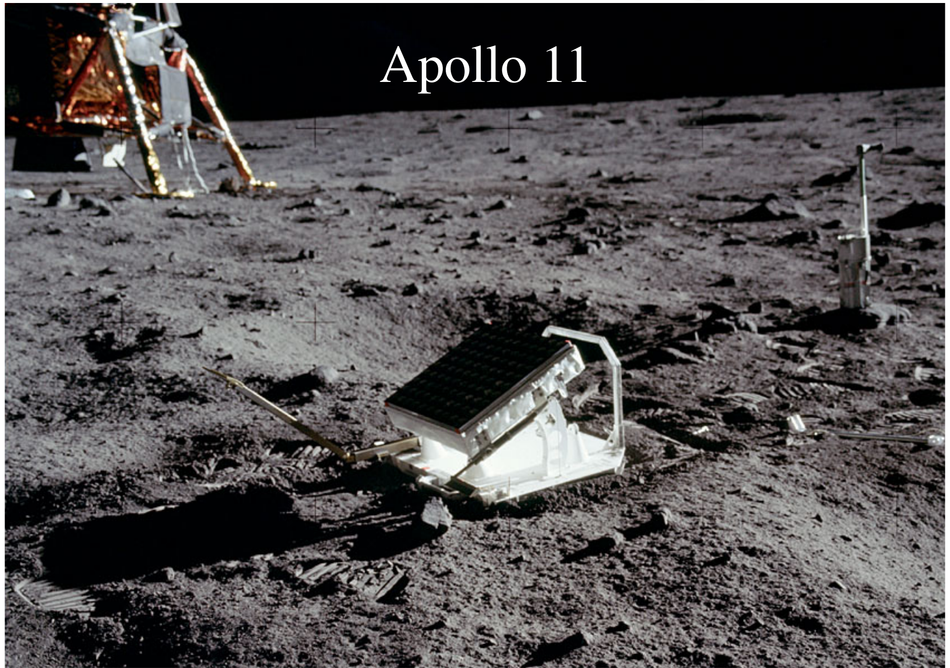
LAGEOS

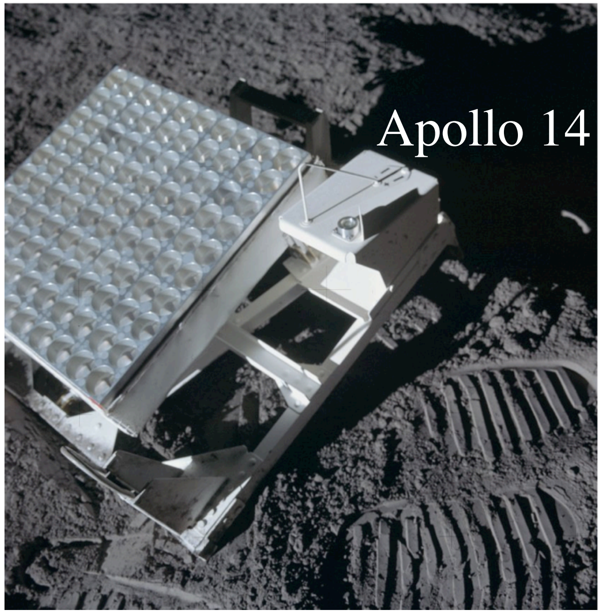
International Laser Ranging Service

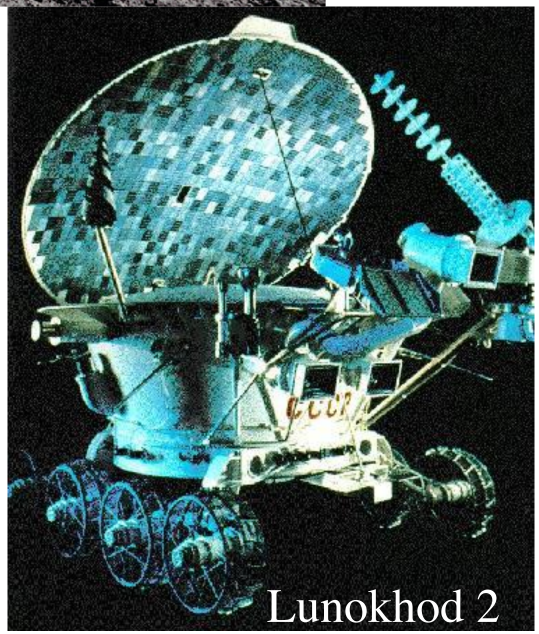
SLR constellation

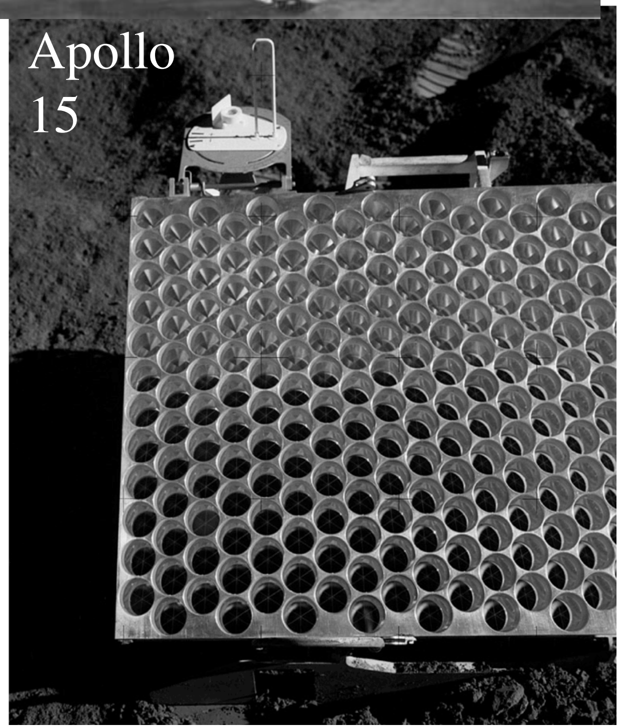


Current LLR arrays







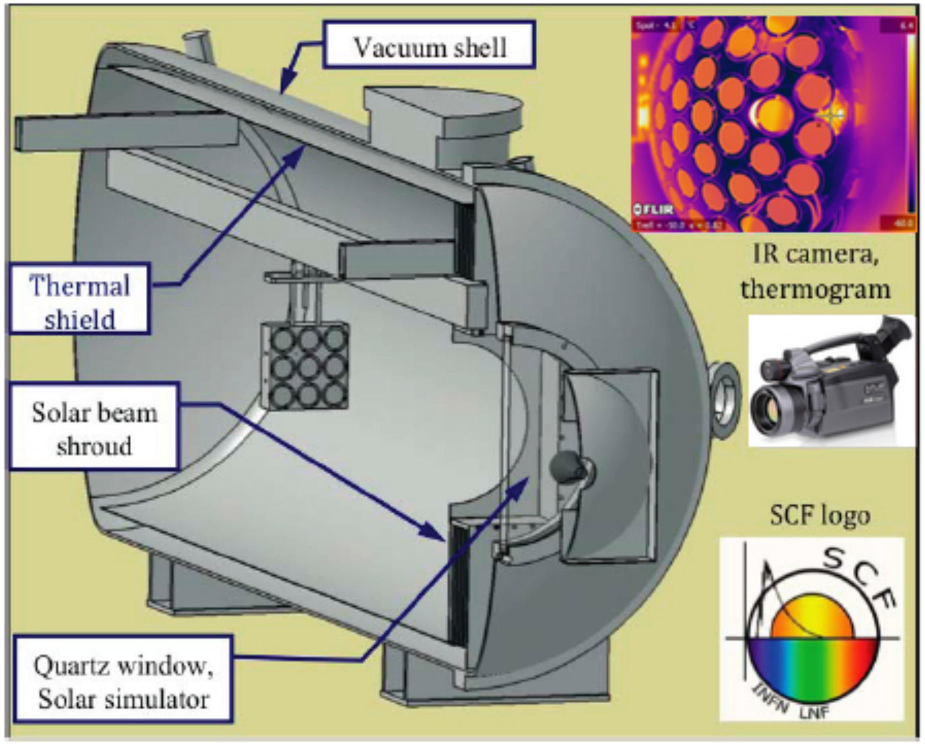


SCF_LAB

Satellite/Lunar/GNSS laser ranging Characterization Facility LABoratory

Two unique and unprecedented OGSEs (Optical Ground Support Equipments) facilities in a clean room to characterize the SLR/LLR/GNSS space segments

SCF for SLR/LLR (RD-1, RD-2)



SCF-G for GNSS (RD-10)

SCF_LAB

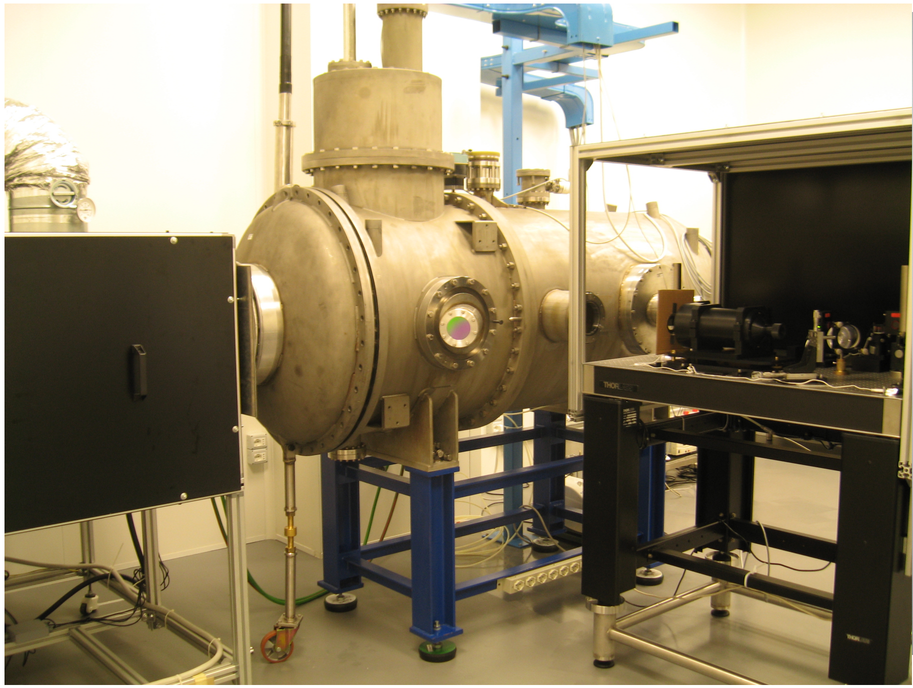
Satellite/Lunar/GNSS laser ranging Characterization Facility LABoratory

INFN Istituto Nazionale di Fisica Nucleare

SCF INFN LNF

Two unique and unprecedented OGSEs (Optical Ground Support Equipments) facilities in a clean room to characterize the SLR/LLR/GNSS space segments

SCF for SLR/LLR (RD-1, RD-2)



SCF-G for GNSS (RD-10)

SCF repainted for clean room compatibility

SCF-Test

- 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)**
    - **Wavefront Fizeau Interferogram (WFI)**

SCF: product for VQR 2004-2010, the evaluation of INFN research

Proposed product: SCF = Satellite/lunar laser ranging Characterization Facility

Version 3, May 14, 2012

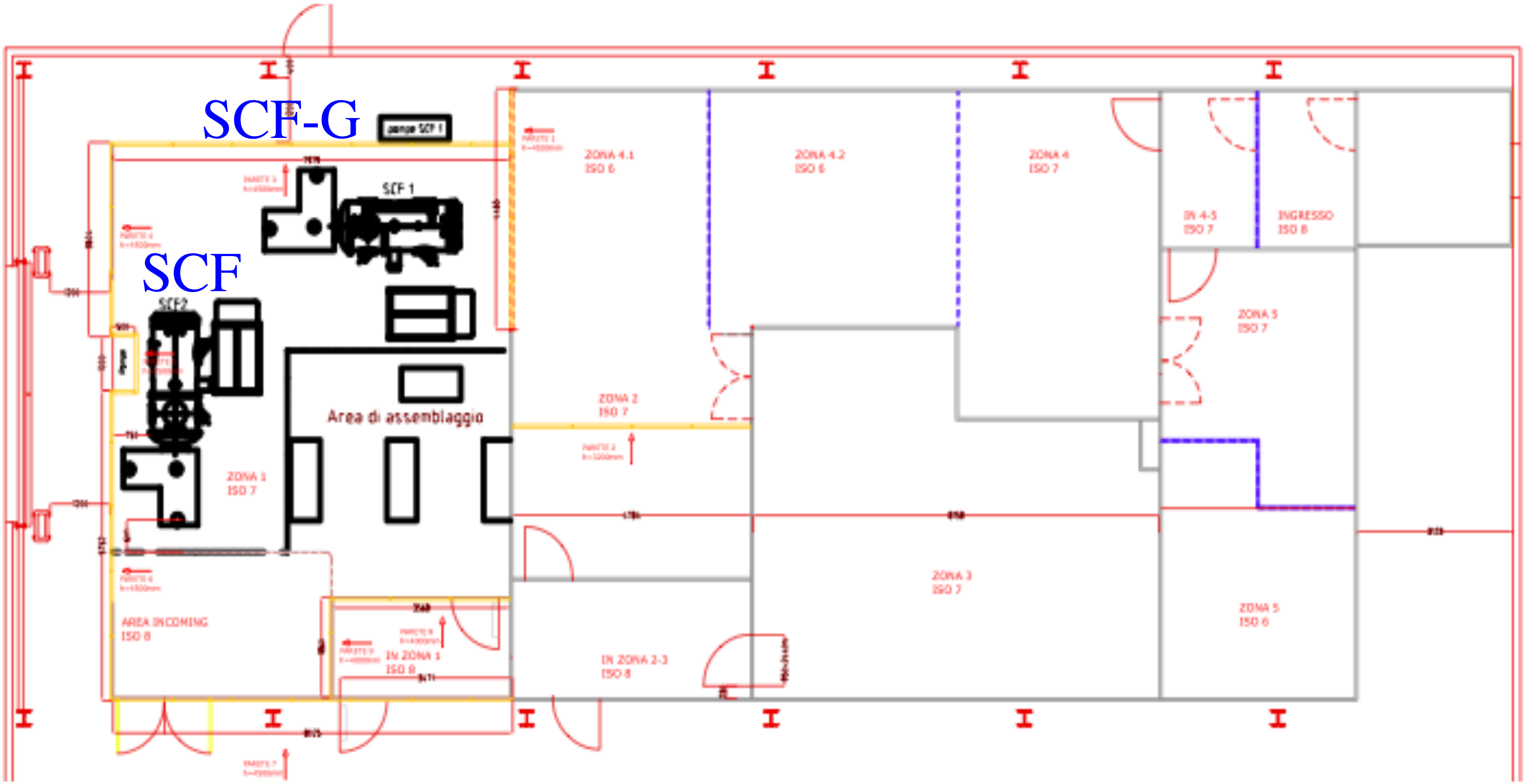
- **Author List**: S. Dell'Agnello, G.O. Delle Monache, R. Vittori, C. Cantone, A. Boni, M. Martini, C. Lops, M. Garattini, M. Maiello, S. Berardi, G. Patrizi, M. Tibuzzi, E. Ciocci, L. Porcelli, N. Intaglietta, R. Tauraso
- **INFN Experiments (sigle):** ETRUSCO[1], MoonLIGHT[2] of CSNV.
- **Product (Manufatto):** SCF = Satellite/lunar laser ranging Characterization Facility.
- **INFN Laboratory/Sections Involved:** INFN-LNF.
- **Industries Involved:** none.
- **Description**: The SCF (Satellite/lunar laser ranging Characterization Facility) is a unique and unprecedented Ground Segment Product to characterize the performance and behaviour of the Space segment of laser ranging (laser positioning in space), laser retroreflectors. The SCF is identified as "Optical Ground Support Equipment (OGSE)". The SCF-Test is set of OGSE procedures, adapted to specific laser reretroreflector payloads for specific space missions. The SCF and SCF-Test are Background Intellectual Property Rights_(BIPR) of INFN, created in 2006, accepted and funded as such by its users (ASI, NASA, ESA, ISRO space agencies). The manpower used for its development was about Full Time Equivalent (FTE) persons for about 3 years. The cost for development (including manpower) was about 500 k€. The external funding attracted by the developed SCF/SCF-Test product has been about 2.5 M€.
- **Authors**: S. Dell'Agnello, G.O. Delle Monache, R. Vittori, C. Cantone, A. Boni, M. Martini, C. Lops, M. Garattini, M. Maiello, S. Berardi, G. Patrizi, M. Tibuzzi, E. Ciocci, L. Porcelli, N. Intaglietta, R. Tauraso
- **Reference Paper:** *Creation of the new industry-standard space test of laser retroreflectors for GNSS and LAGEOS,* S. Dell'Agnello, G.O. Delle Monache, D.G. Currie, R. Vittori, C. Cantone, M. Garattini, A. Boni, M. Martini, C. Lops, N. Intaglietta, R. Tauraso, D.A. Arnold, M.R. Pearlman, G. Bianco, S. Zerbini, M. Maiello, S. Berardi, L. Porcelli, C.O. Alley, J.F. McGarry, C. Sciarretta, V. Luceri, T.W. Zagwodzki, J. Adv. Space Res. 47 (2011) 822–842.
- **Year**: 2006.
- **PDF doc description of product: file** SCF_PDF-doc-description.pdf
- **Image 1:** Image of SCF: file Image1_SCF.png
- **Image 2:** Poster of ETRUSCO: file Image2_ETRUSCO.jpg

[1] Extra Terrestrial Ranging to Unified Satellite COnstellations.
[2] Moon Laser Instrumentation for General relativity High-accuracy Tests.

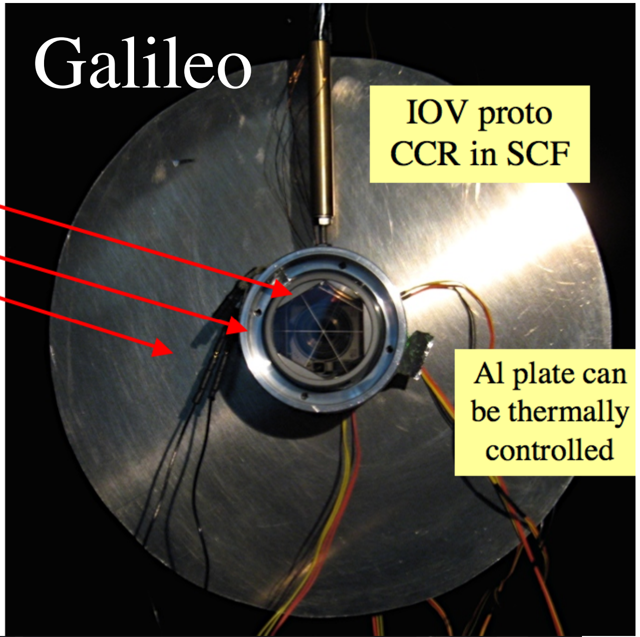
G. Sasso Clean Room Complex:

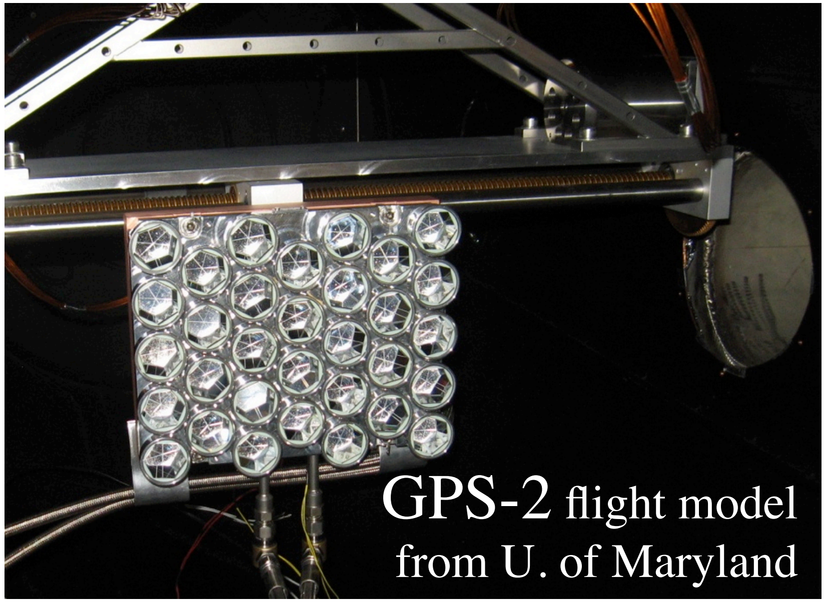
1/3 left part is the **SCF_LAB**

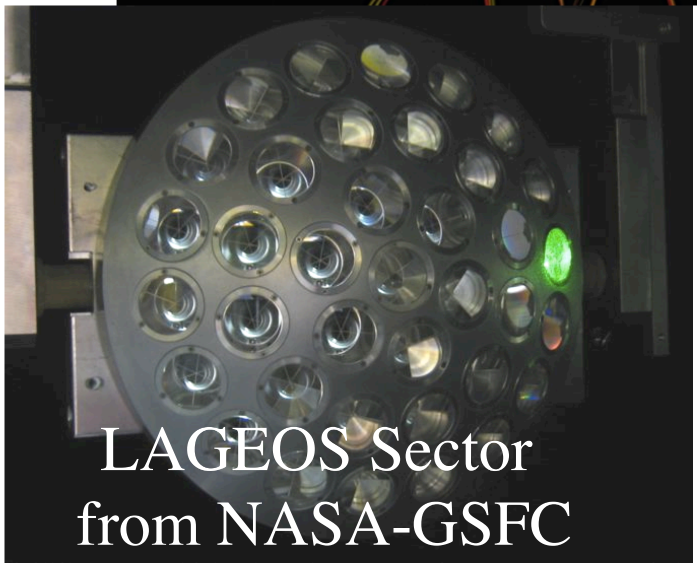
(85 m^2, Class < 10000)

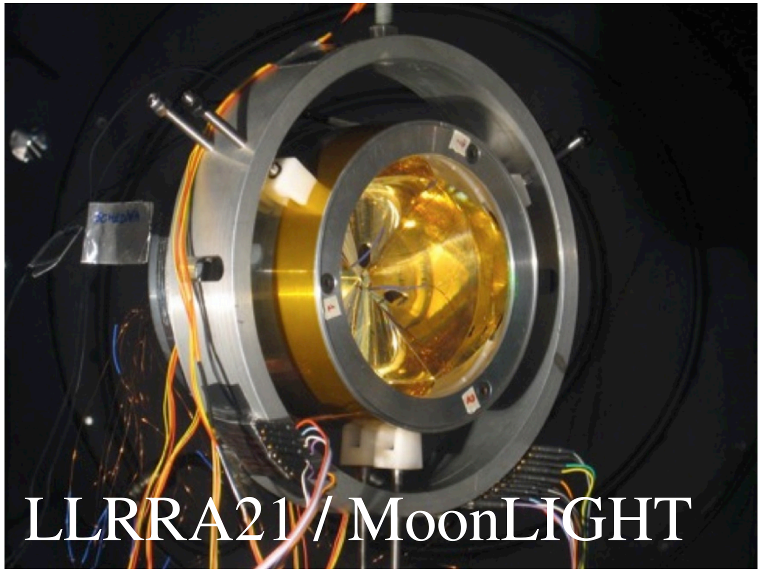


World-first SCF-Tests









Lunar Physics/Geophysics Network (LGN)

http://iln.arc.nasa.gov/ Nine Countries

Multi-site simultaneously operating instruments:

- Seismometer
- **Lunar Laser Ranging payload**
- Thermal heat flow probe
- E&M Sounder

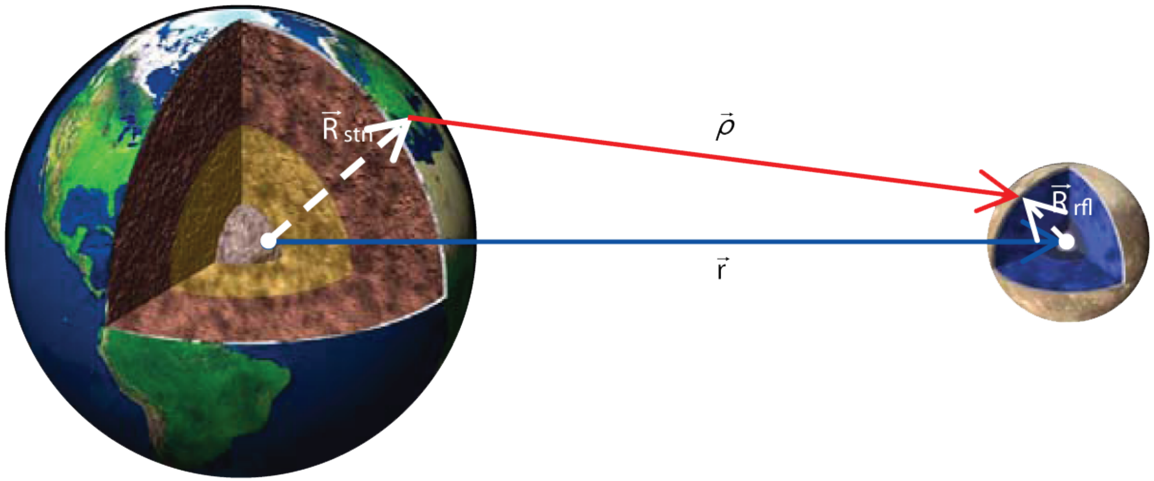
40 years of 'LLR' test of General Relativity

(Logo by NASA)

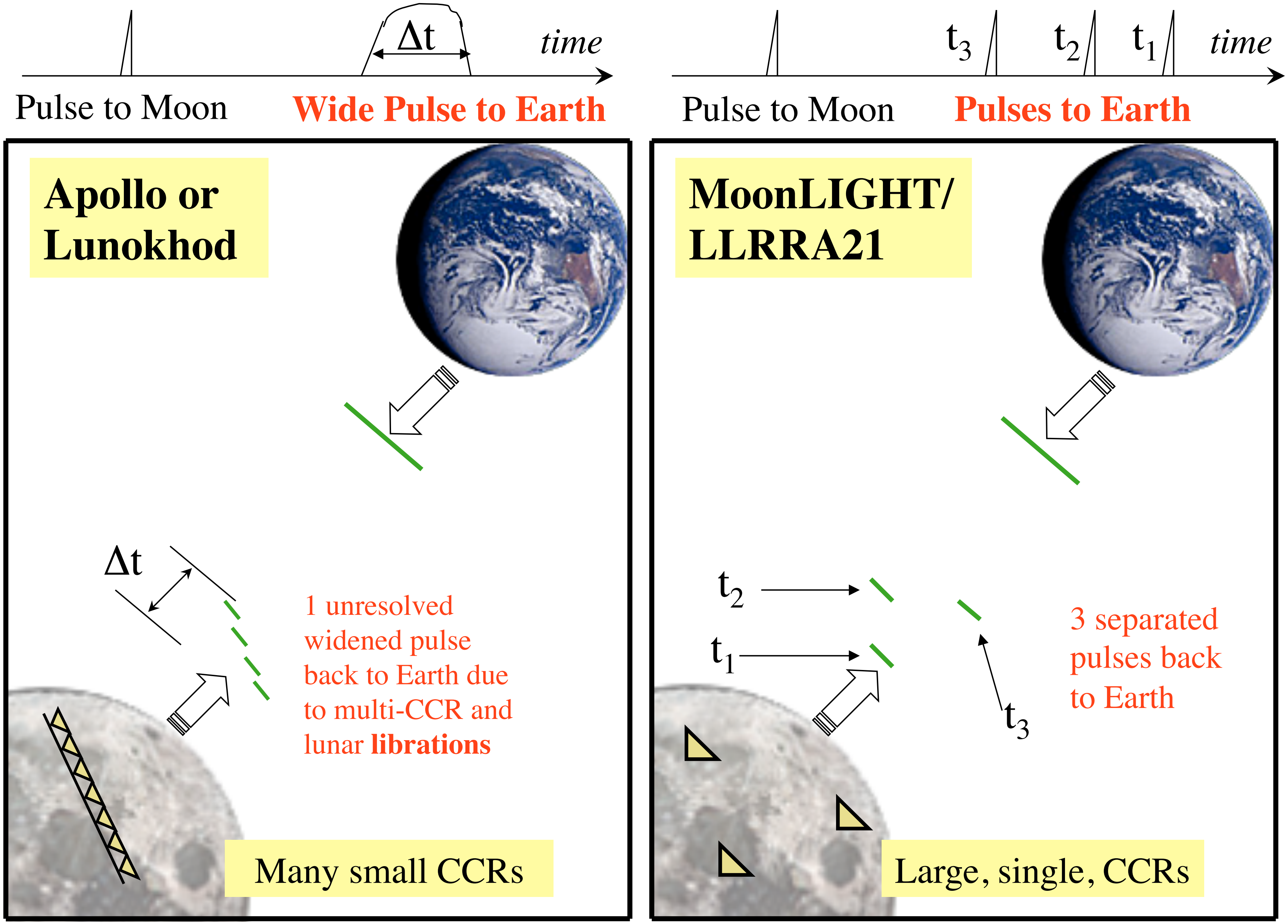
Fundamental GMD science with LLR

- Best test of General Relativity (GR) with single experiment
  - Sun-Earth-Moon, 3-body physics → see Geodetic Precession!!
- Lunar geophysics (Selenodesy)
  - Librations, Core interior parameters, complementary to GRAIL!!
- IMRF (International Moon Reference Frame) referenced to ITRF with laser and/or radio
  - Apollo/Lunokhod + landers, rovers, with laser reflector or radio-beacon
  - For lunar surface exploration/colonization

ITRF



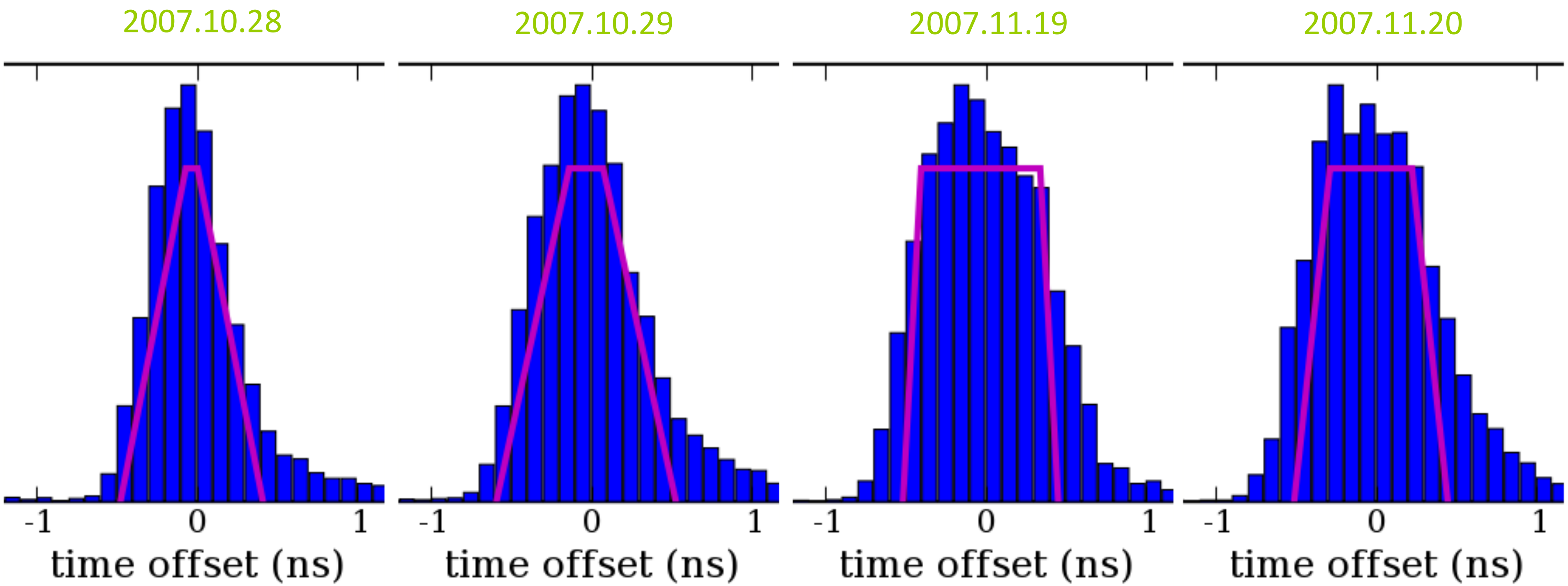
IMRF, proposed in RD-4, RD-5


Δt
time
Pulse to Moon
Wide Pulse to Earth
t3
t2
t1
time
Pulse to Moon
Pulses to Earth
Apollo or Lunokhod
Δt
1 unresolved widened pulse back to Earth due to multi-CCR and lunar **librations**
Many small CCRs
MoonLIGHT/ LLRRA21
t2
t1
t3
3 separated pulses back to Earth
Large, single, CCRs

Sensing Array Size/Orientation of Apollo reflectors

Effect of multi-CCR array orientation due to lunar librations

Apollo 11 Apollo 15



Apollo arrays: to get 2 cm range out of +/- 1 nsec ToF distribution, thousands of laser returns are needed. With MoonLIGHT: with just 1 return we get a mm/sub-mm range

LLR tests of General Relativity

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

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

Our measurement of the Geodetic Precession with Apollo/Lunokohd, including new APOLLO station, with Planetary Ephemeris Program (PEP) by CfA: **~1% accuracy**

Number of laser returns to make a “standard” ~2-cm LLR range:

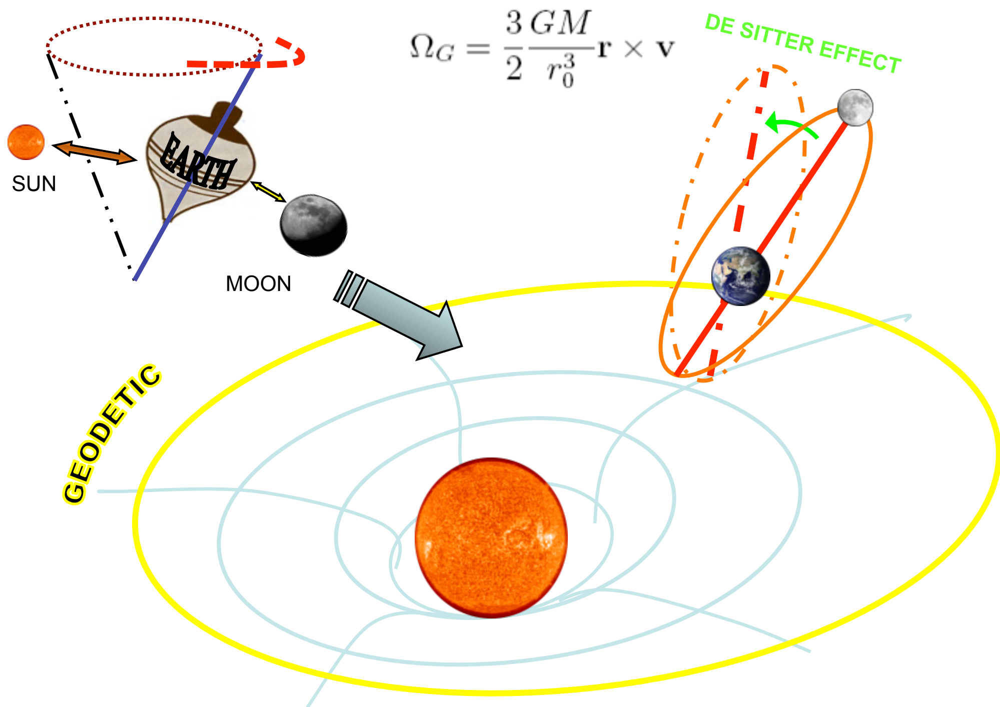
- **MoonLIGHT single, large reflector**: ~1
- Apollo/Lunokhod/Luna-Glob multi-reflector array: few thousands

LLR measurement of geodetic precession

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± 0.02)m/M_{orbit} ~ 2"/cy**



Relative deviation of geodetic precession from GR value:
JPL: J. G. Williams et al 2004 PRL. 93, 261101
K_{GP} = (-1.9 ± 6.4) x10^{-3}
Our measurement: ~ 1% accuracy

LLR data give unique science products both in relativistic gravity AND in lunar geophysics.

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

LLR test of the Strong Equivalence Principle

Williams et al, arXiv: gr-qc/0507083v2, 2 Jan 2009

- LLR test of EP sensitive to *both* composition-dependent (CD) and self-energy violations

UW: Baessler et al, PRL **83**, 3585 (1999);
Adelberger et al Cl. Q. Gravity **12**, 2397 (2001)

- University of Washington (UW) laboratory EP experiment with "miniature" Earth and Moon, measures *only* CD contribution:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,UW} = (1.0 \pm 1.4) \times 10^{-13}$$

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,LLR} = (-1.0 \pm 1.4) \times 10^{-13}$$

- Subtracting UW from LLR results one gets the SEP test:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{SEP} = (-2.0 \pm 2.0) \times 10^{-13}$$

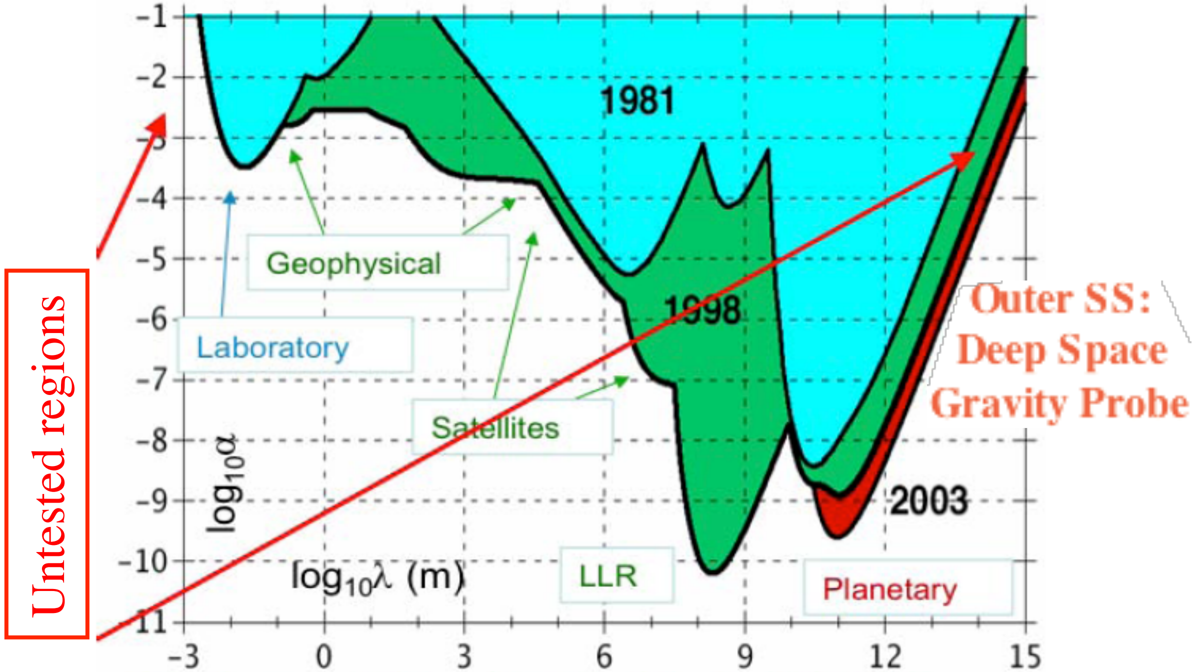
SEP can only be tested LLR

Limits on $1/r^2$ deviations in the Solar System

Current limits on additional Yukawa potential: **$\alpha \times$ (Newtonian-gravity) $\times e^{-r/\lambda}$**

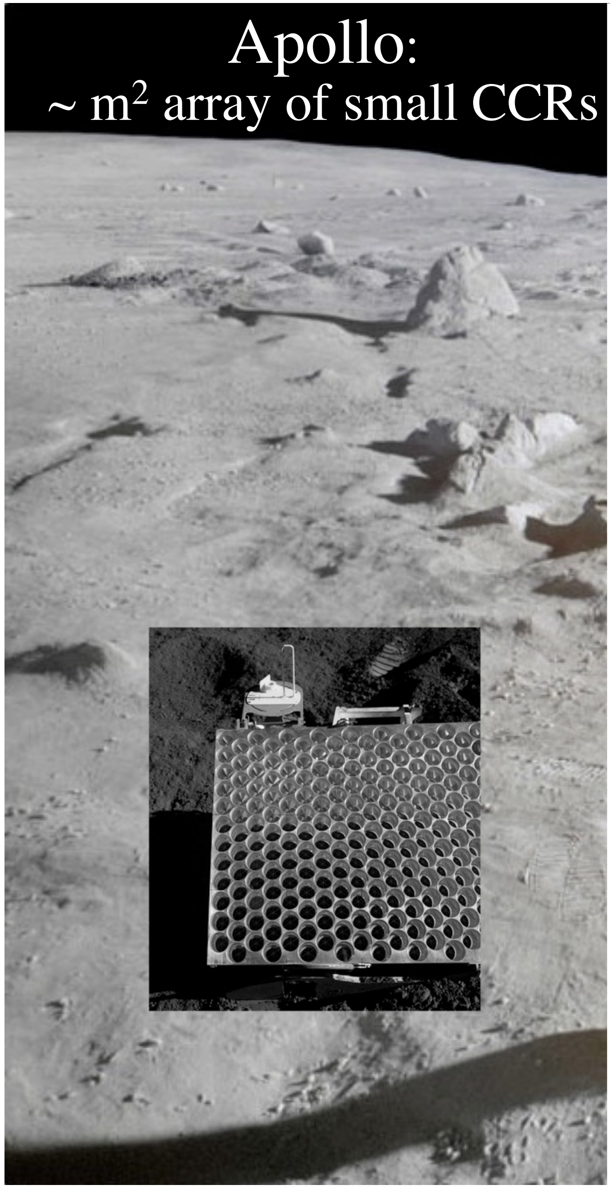
MoonLIGHT designed to provide accuracy of 100 μm on the space segment (the CCR).

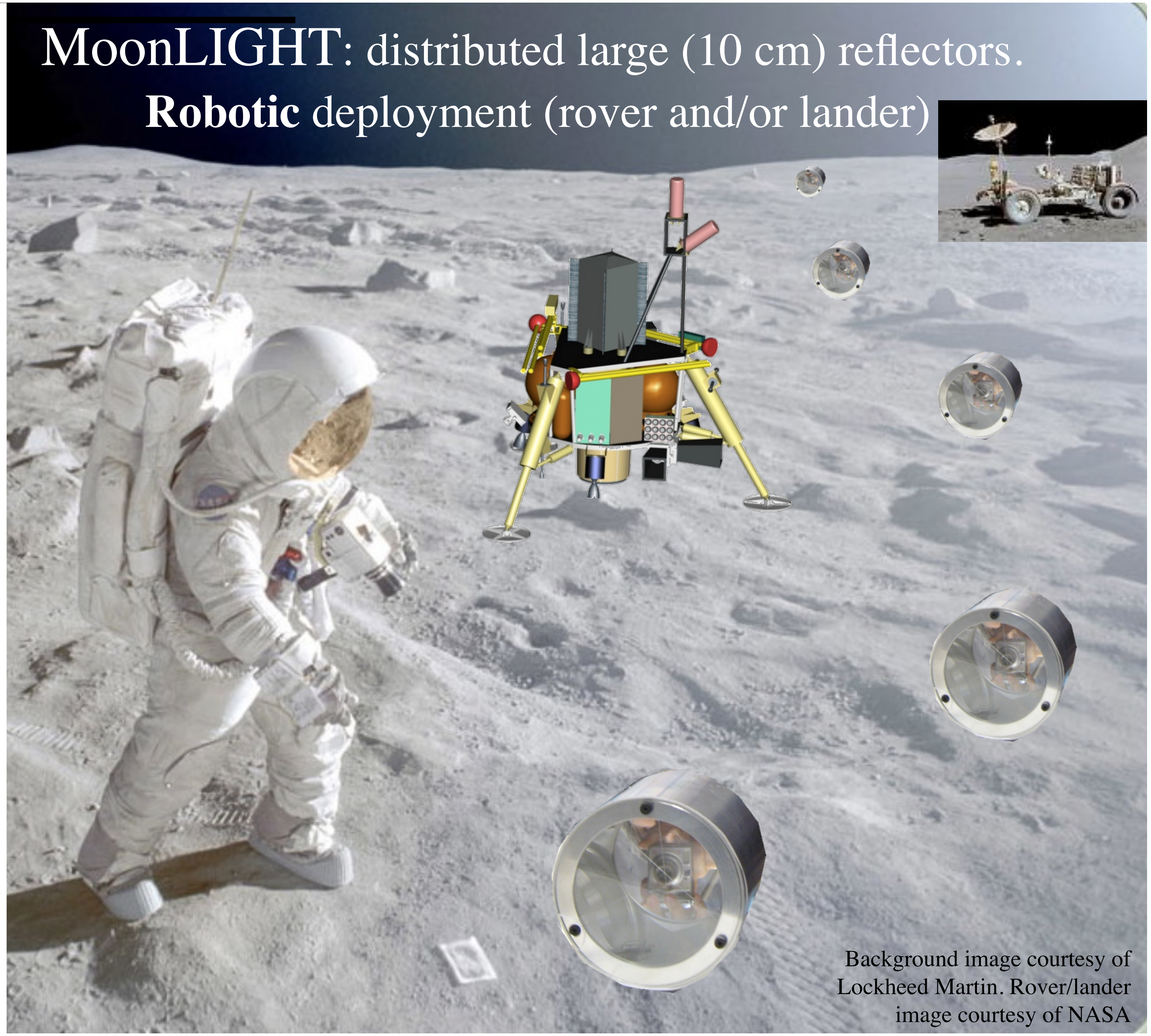
If the other error sources on LLR will improve with time at the same level then a MoonLIGHT CCR array will improve limits from $\sim 10^{-10}$ to 10^{-12} at scales of 10^6 meters



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

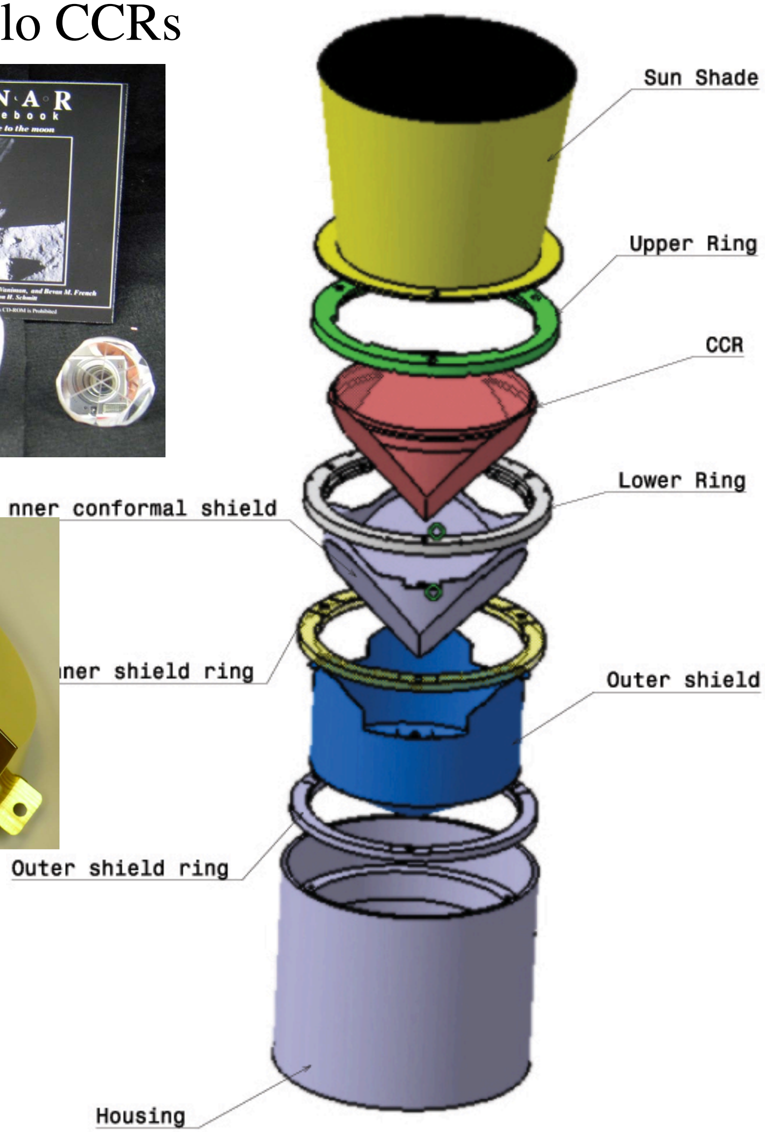
MoonLIGHT: large, single, distributed reflectors

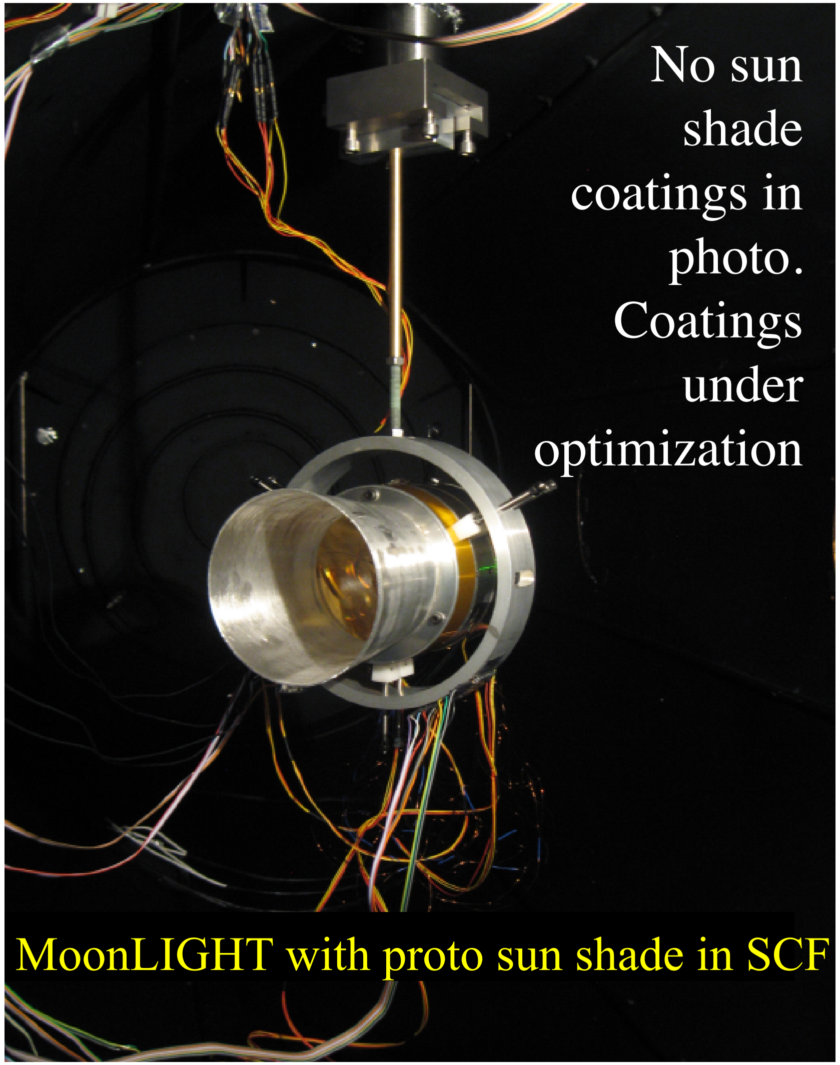




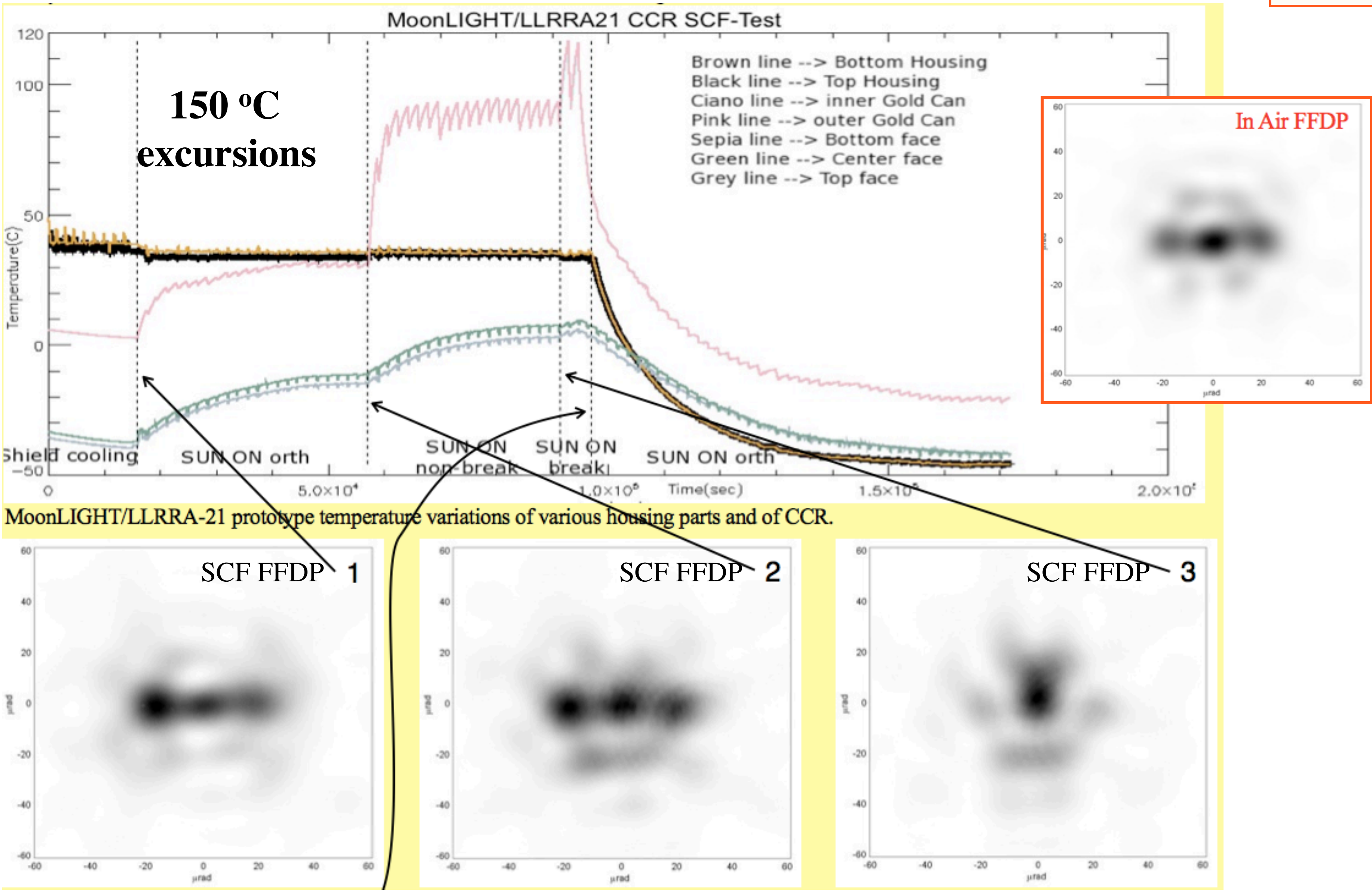
MoonLIGHT/LLRRA-21

1 MoonLIGHT equivalent
to ~50 Apollo CCRs



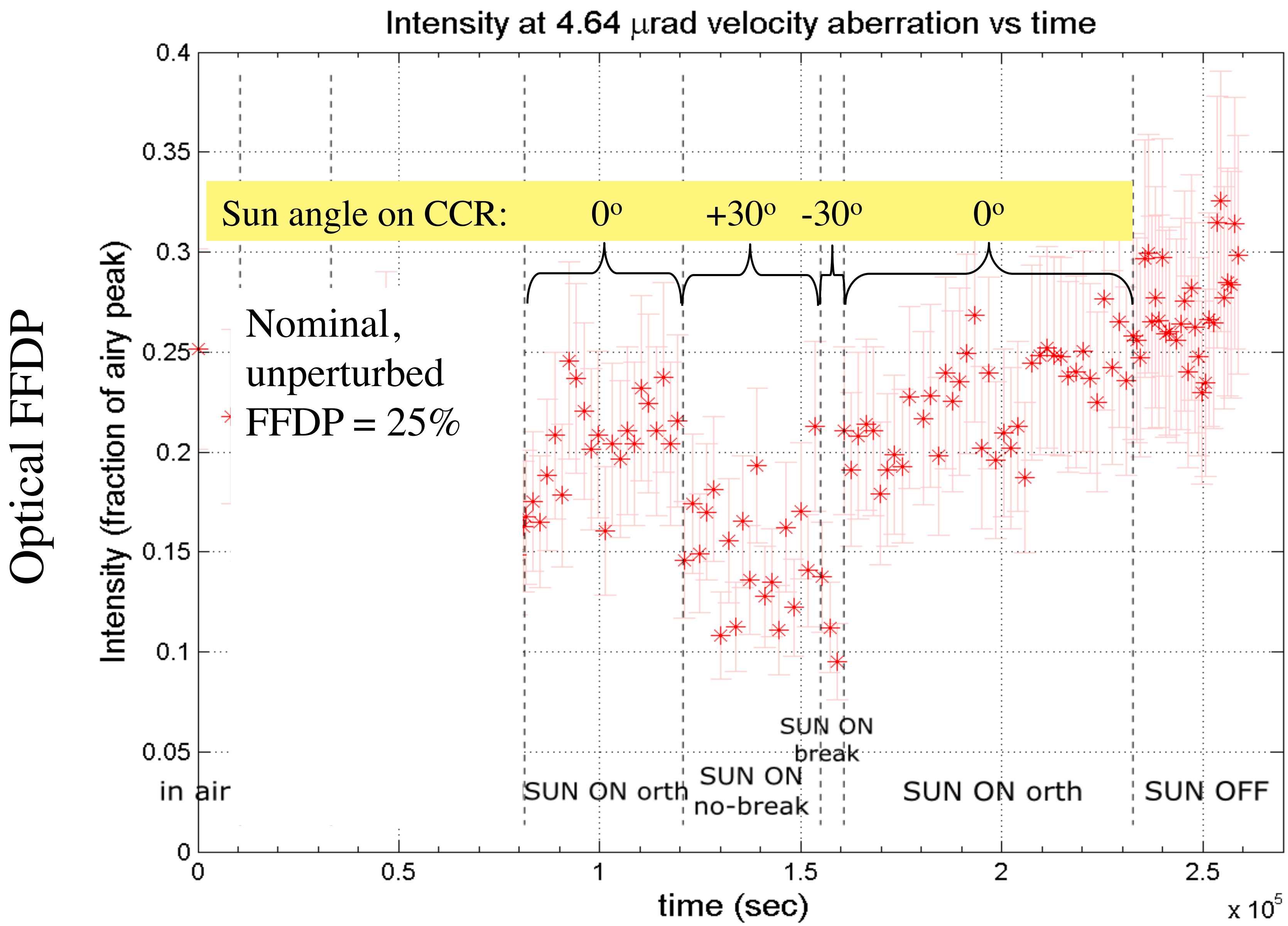


SCF: Temperatures, optical FFDP (no sun shade)



MoonLIGHT/LLRRA-21 prototype temperature variations of various housing parts and of CCR.

SCF: Optical response of MoonLIGHT (no sun shade)

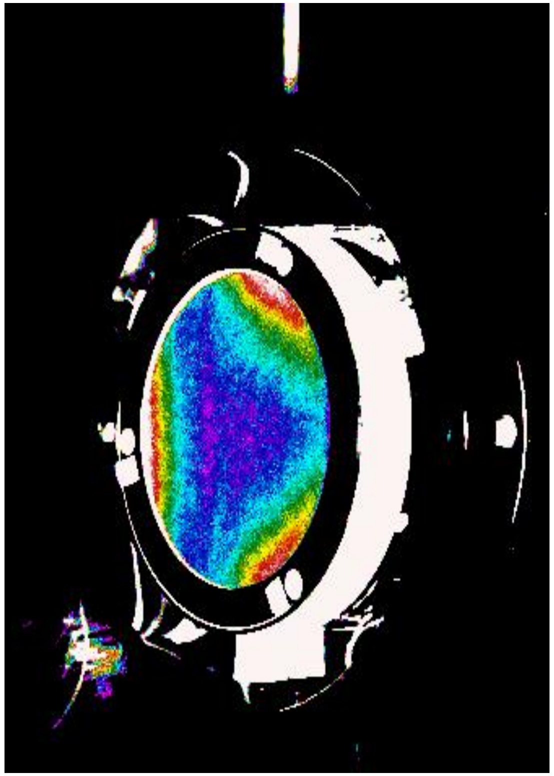


SCF: thermal testing and sw modeling

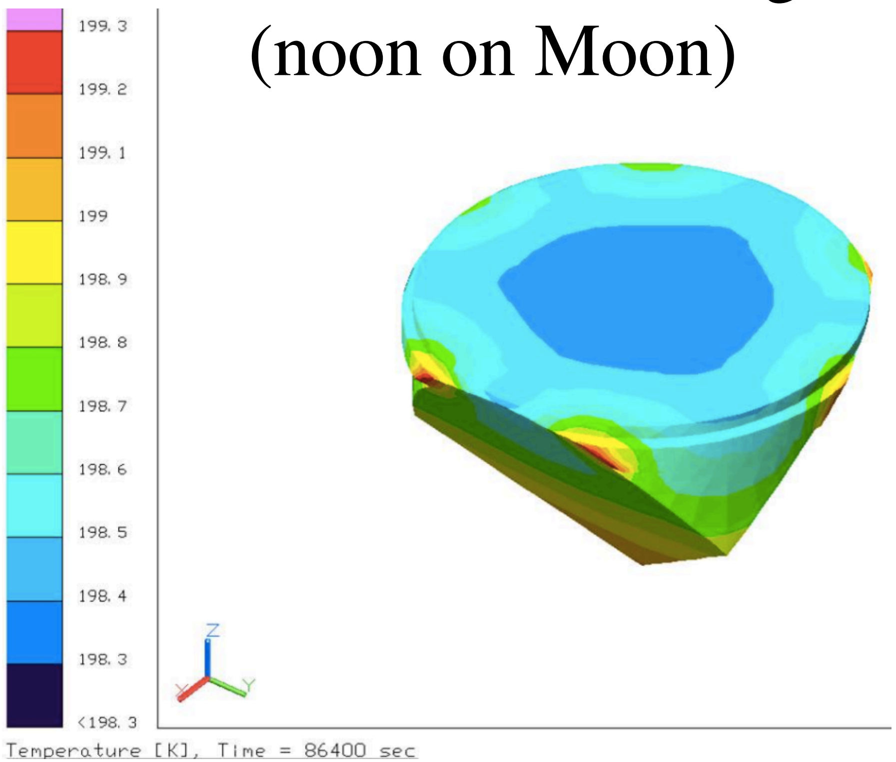
With SCF can measure/model subtle thermal effects, and optimize thermal conductance of retroreflector mounting

SCF-Test

IR Heat Flow Due to Tab Supports



Thermal modeling (noon on Moon)



Constraining GR with spacetime torsion with the Moon and Mercury [RD-7,8,9]

Lunar Laser Ranging (LLR)
measurement of the lunar geodetic precession:
no deviation from general relativity within

0.64% accuracy

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

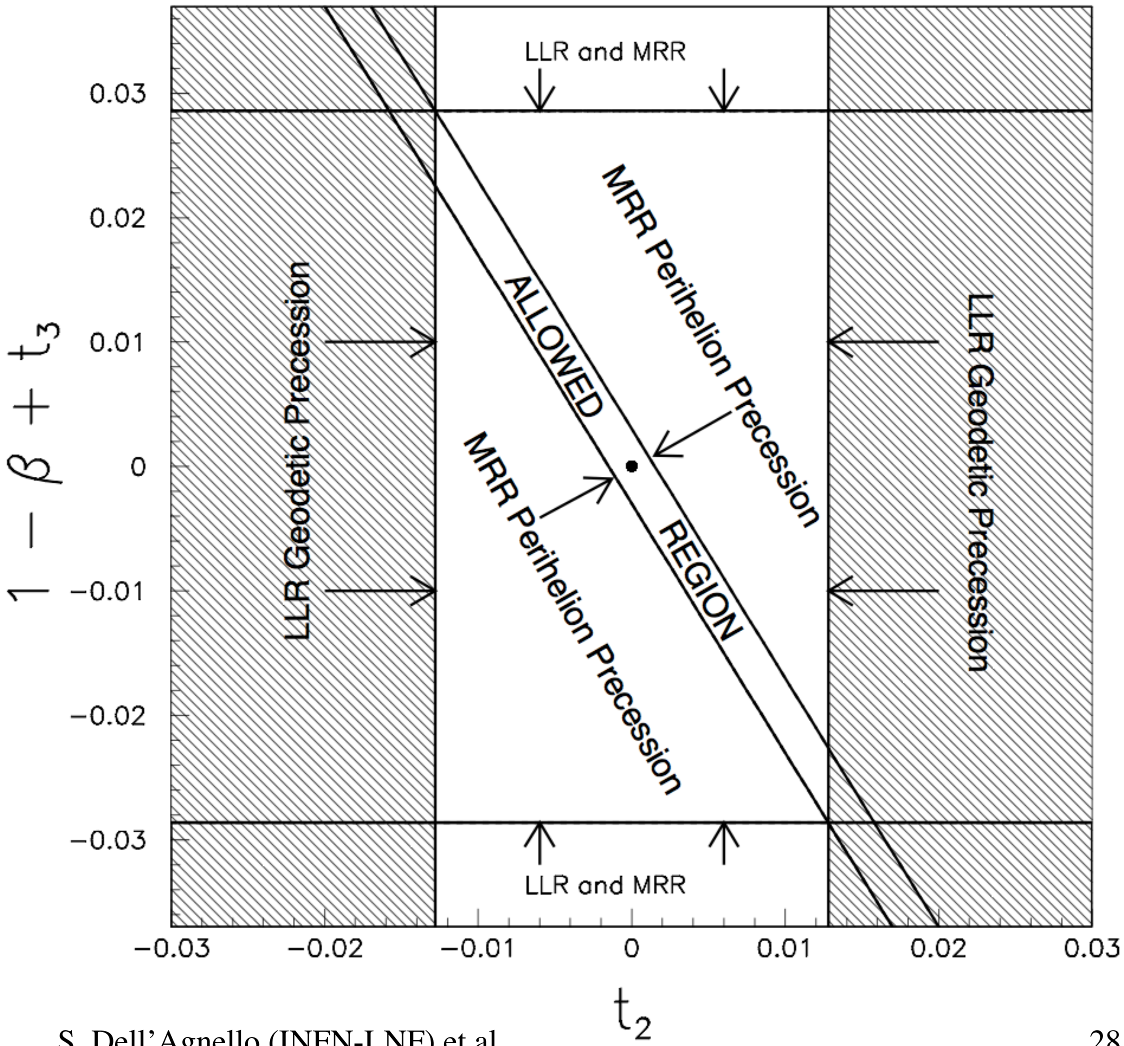
Mercury Radar Ranging (MRR) measurement of Mercury perihelion precession:
no deviation from general relativity within

0.1% accuracy (on β-1)

I. I. Shapiro, Gravitation and Relativity 1989, edited by N. Ashby, D. F. Bartlett, and W. Wyss (Cambridge University Press, Cambridge, England, 1990), p. 313.

$$|1 - \beta + 2t_2 + t_3| < 0.003.$$

$$|t_2| < 0.0128.$$



Constraining spacetime torsion with LLR, GP-B and LAGEOS

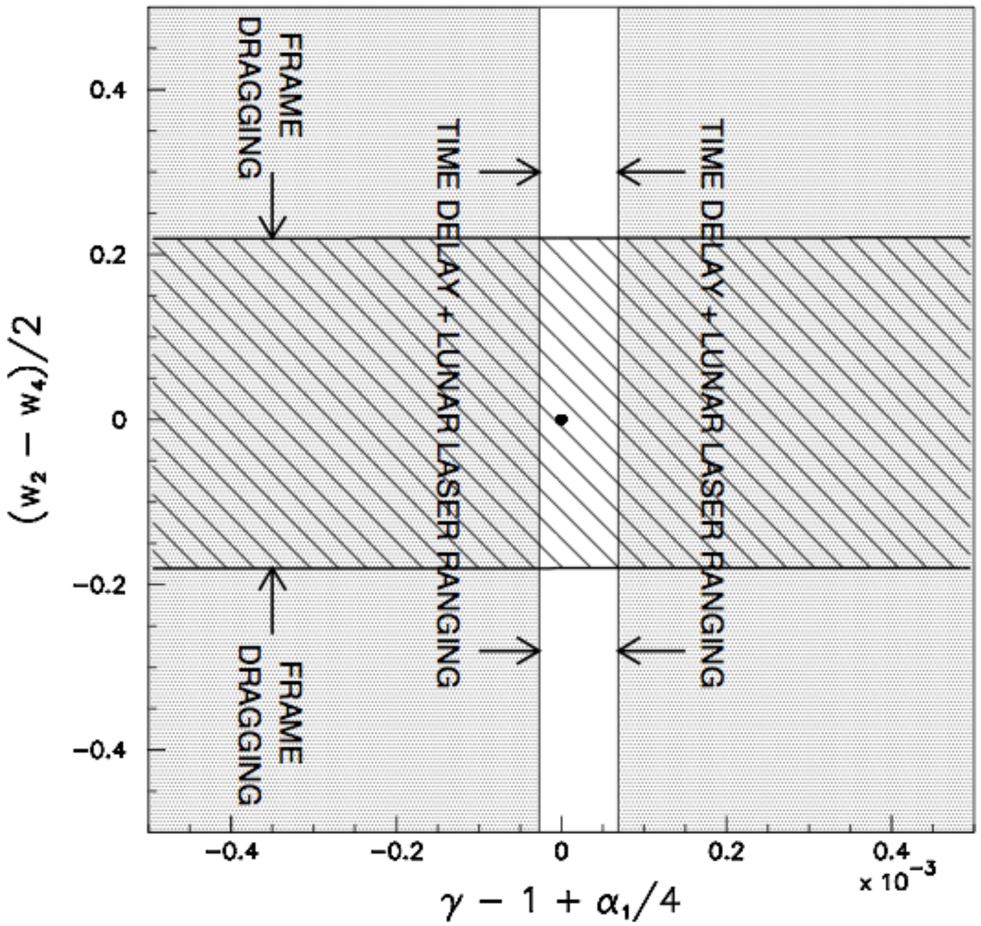
Geodetic Precession by LLR needs to be subtracted to measure both Lense-Thirring (LT) effect and to set torsion limits with LAGEOS. Gravity Probe B (GPB), instead, has measured separately GP & LT

GPB and LAGEOS are complementary LT and torsion experiments. They constrain different linear combinations of 5 additional parameter of the theory, which describe additional FRAME DRAGGING due to SPACETIME TORSION:

$w_1+w_2+w_3-2w_4+w_5$ (GPB)

$(w_2-w_4)/2$ (LAGEOS, node)

See [RD-7,8,9]



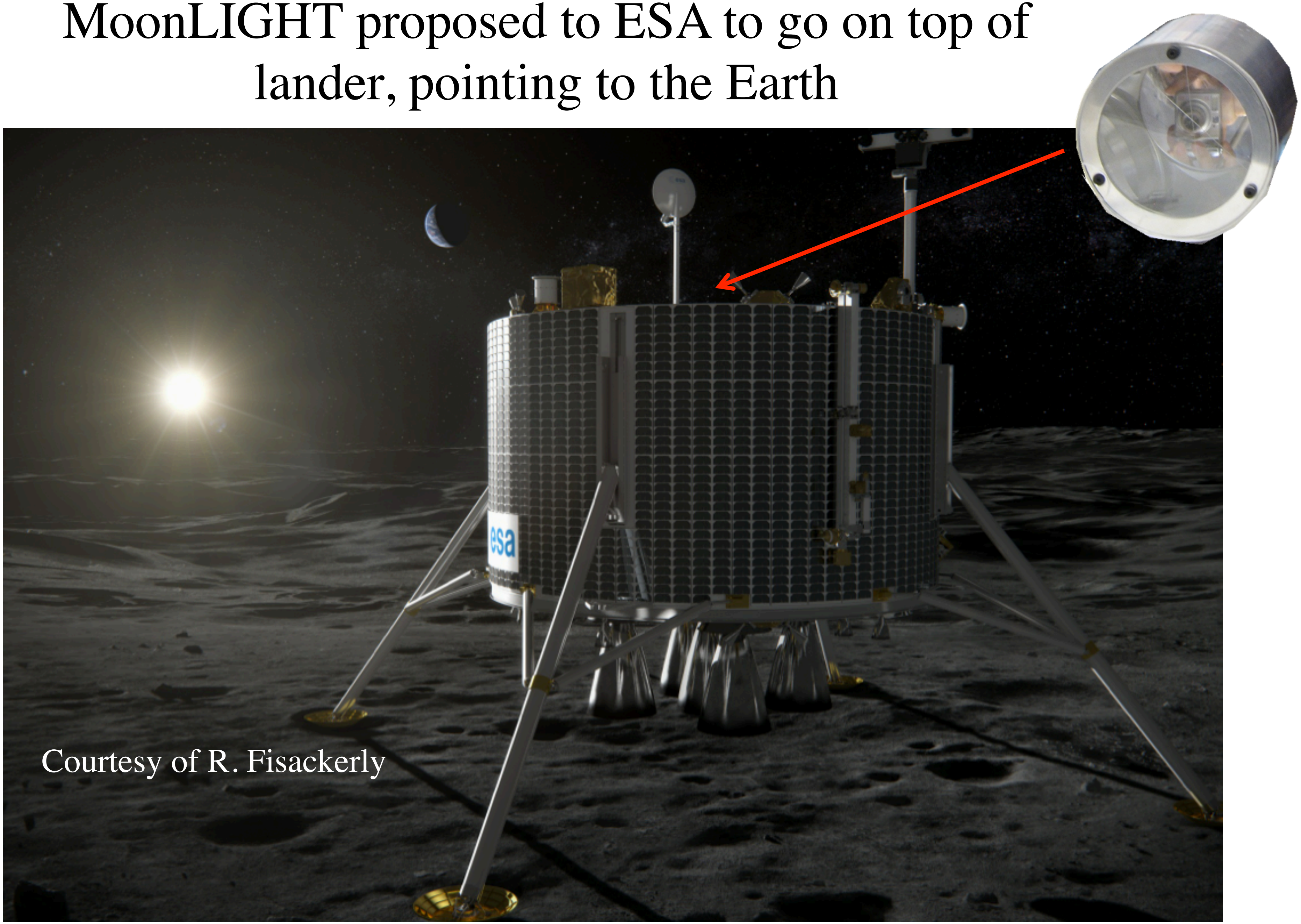
Opportunities for lunar missions

- Development of MoonLIGHT/LLRRA21 at TRL = 6.5
  - Apollo/LAGEOS heritage and SCF_LAB testing

- Proposal/agreements for missions opportunities:
  - ESA lunar lander
  - Lunar Google X Prize (several US teams and 1 Italian team)
  - JAXA's SELENE-2: signed scientific agreement with LLR team
    - SCF-Test of Japanese single, large hollow reflector
    - MoonLIGHT/LLRRA21 as backup, Currie and Dell'Agnello as Co-I's
  - ISRO/ROSCOSMOS Chandrayaan-2
  - MAGIA orbiter, former ASI Phase A study, now proposal for ESA S-class

ESA mission to the South Pole of the Moon

MoonLIGHT proposed to ESA to go on top of lander, pointing to the Earth



MoonLIGHT will:

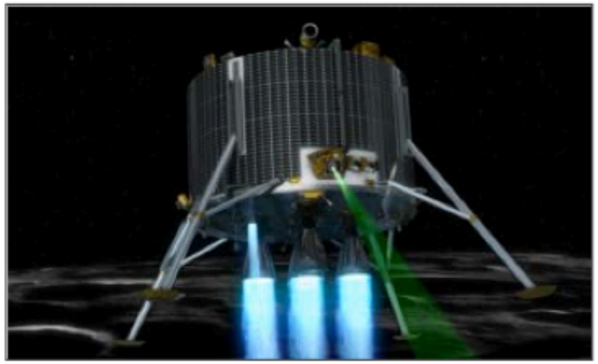
- Determine how precise landing was at meter level in a ~month
- Be a precursor for astronaut exploration, like LLR in 1960's for Apollo
- Test GMD: General Relativity and Selenodesy

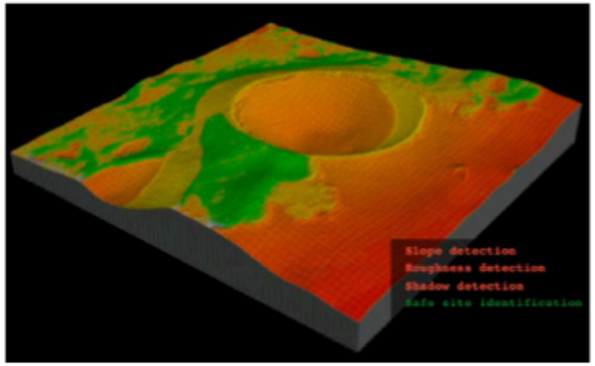
Preparing for Future Exploration

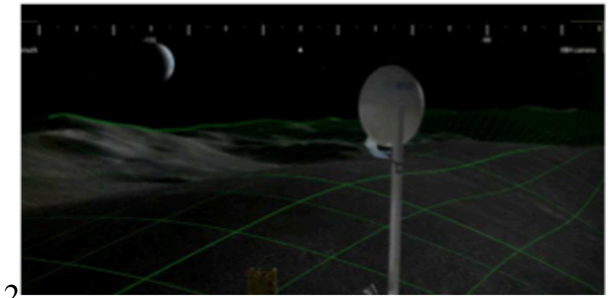
human spaceflight and operations

PRIMARY TECHNOLOGICAL OBJECTIVE
Prove key European technologies for future robotic and human lander missions

- PRECISE LANDING with advanced Guidance, Navigation and Control
- SAFE LANDING with Hazard Detection and Avoidance





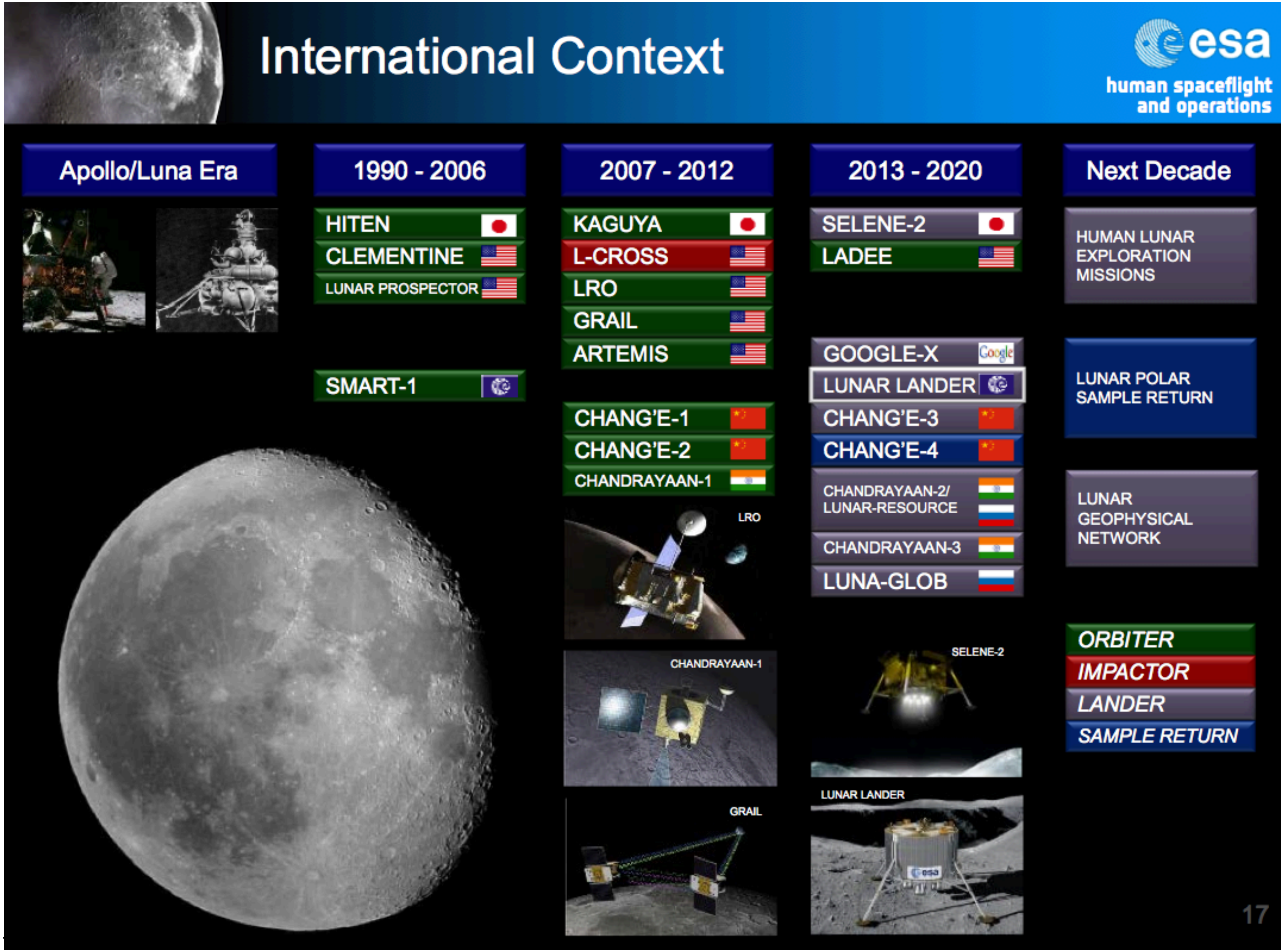


Courtesy of R. Fisackerly

SURFACE MISSION OBJECTIVE
Operate & survive on the Moon gathering data for preparing future human exploration

- INVESTIGATE the Lunar environment & its effects, and potential resources
- OPERATE on the Lunar surface, carry out

Courtesy of R. Fisackerly



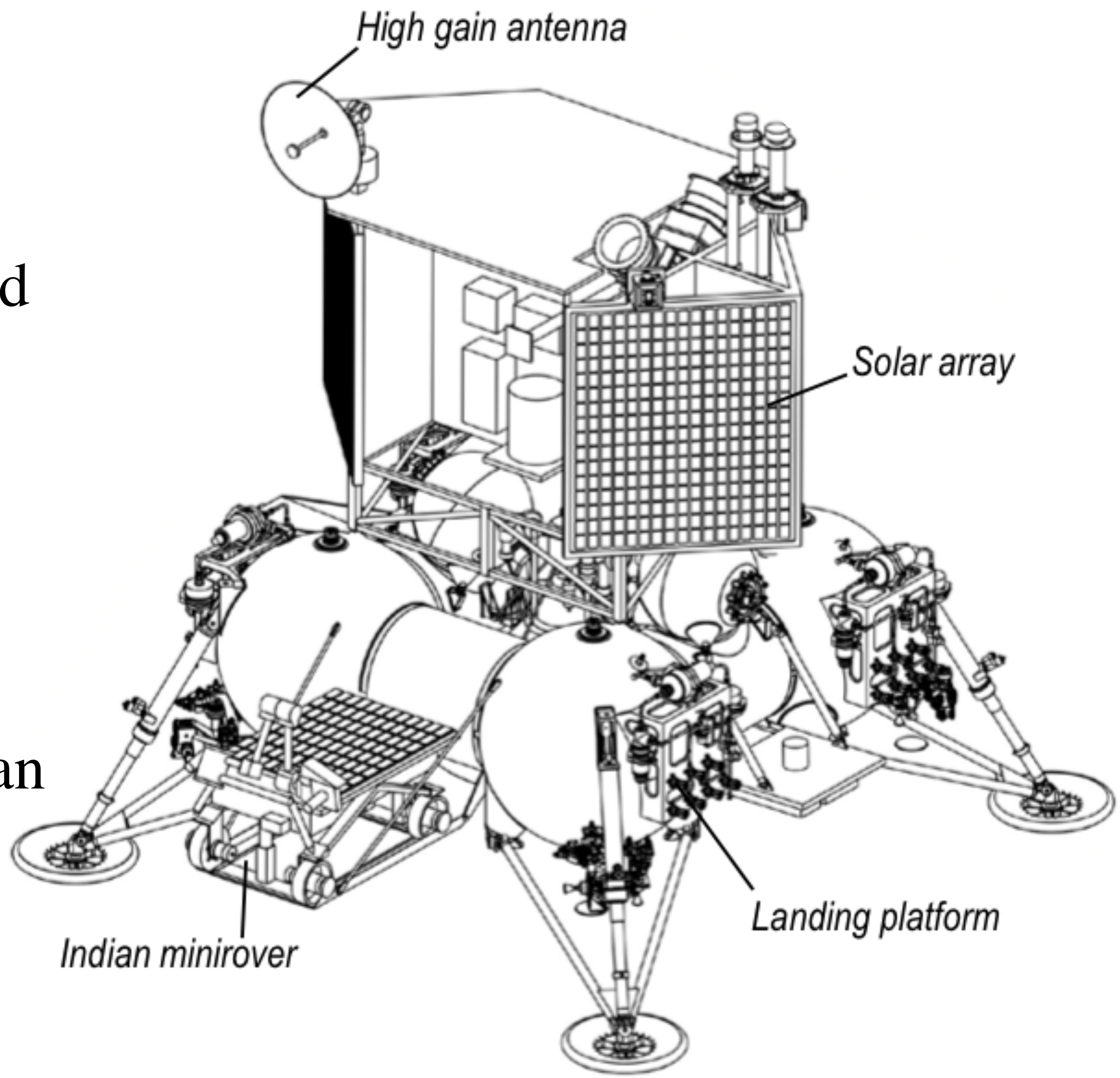
S.

ISRO-ROSCOSMOS Chandrayaan-2 mission to the Moon

- Chandrayaan-1 orbiter discovered recently that water is forming on the Moon surface thanks to solar wind and polar cold traps (and more ….)

- Indian rocket launcher
- Indian orbiter.

- Russian lander and Indian MiniRover in picture



Japan-Italy-US agreement on SELENE-2 LLR

Scientific Cooperation Agreement
of
RISE (Research In SElenodesy) Project, National Astronomical Observatory of Japan
and
University of Maryland
and
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati

January 30, 2012.

Dr. Hirotomo Noda
Principal Investigator of SELENE-2 LLR
RISE project, National Astronomical Observatory of Japan
Hirotomo Noda Date 30. January 2012

Professor Sho Sasaki
Project Manager of RISE Project, National Astronomical Observatory of Japan
Sasaki Date 30 January, 2012

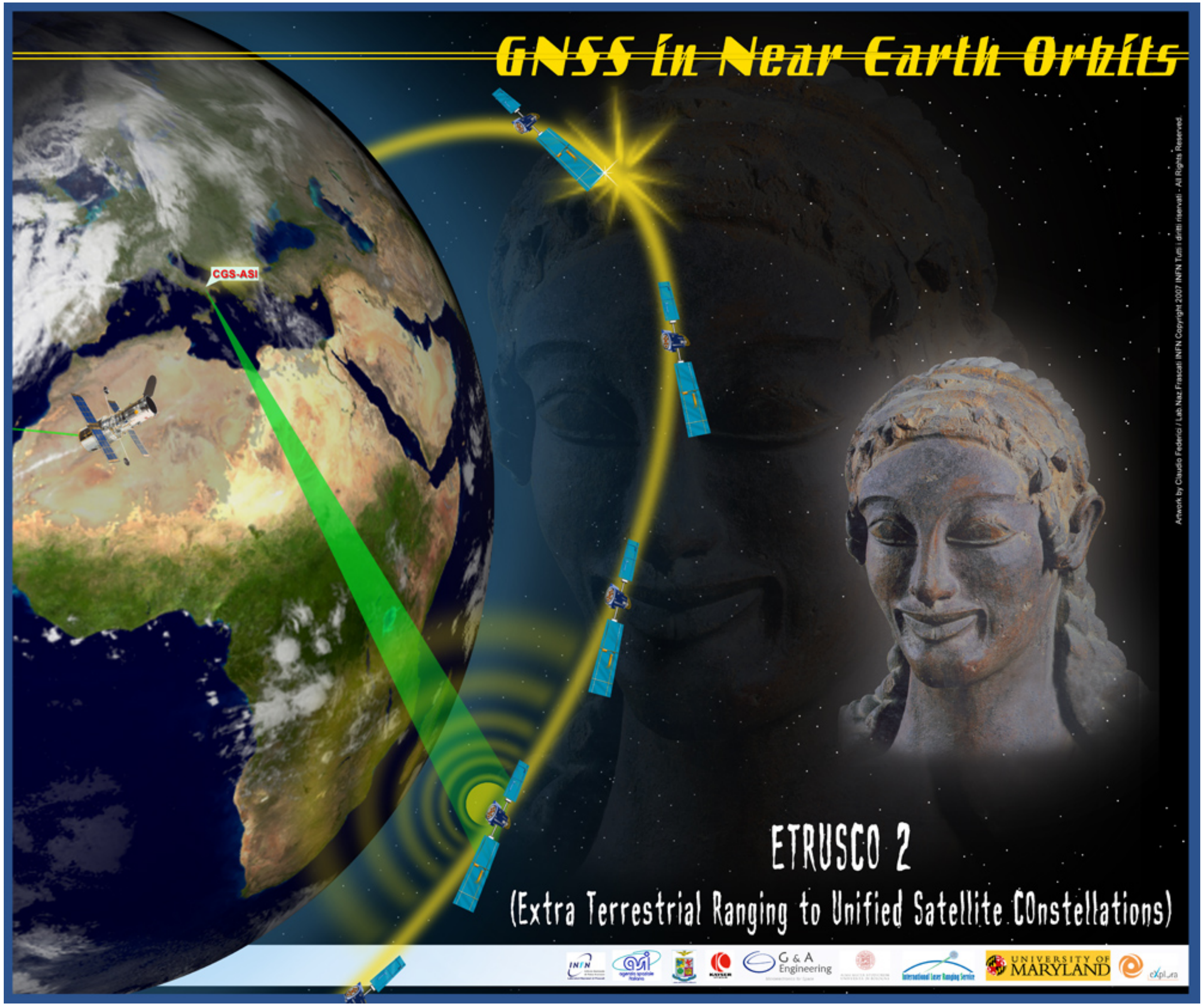
Professor Douglas Currie
Principal Investigator of LLRRA-21
Univ. of Maryland, College Park
NASA Lunar Science Institute
Date 4 October 2011

10/3/11
AUTHORIZING UNIVERSITY OFFICIAL
Jill Frankenfield, Contract Manager
Research Administration & Advancement
University of Maryland, College Park, MD 20742
Phone 301-405-6269/Fax 301-314-9569
email oraa@umd.edu

Dr. Simone Dell'Agnello
Responsible for of SCF Facility
Leader of MoonLIGHT-ILN Experiment of INFN-CSNV
Leader of ETRUSCO-2 Project of Technological Development of ASI and INFN
INFN-LNF
Frascati, Italy
Dell'Agnello Simone Date 26/October/2011

ETRUSCO-2: ASI-INFN project for GNSS, 2010-13 [RD-10]

Optimized for Galileo and GPS-3

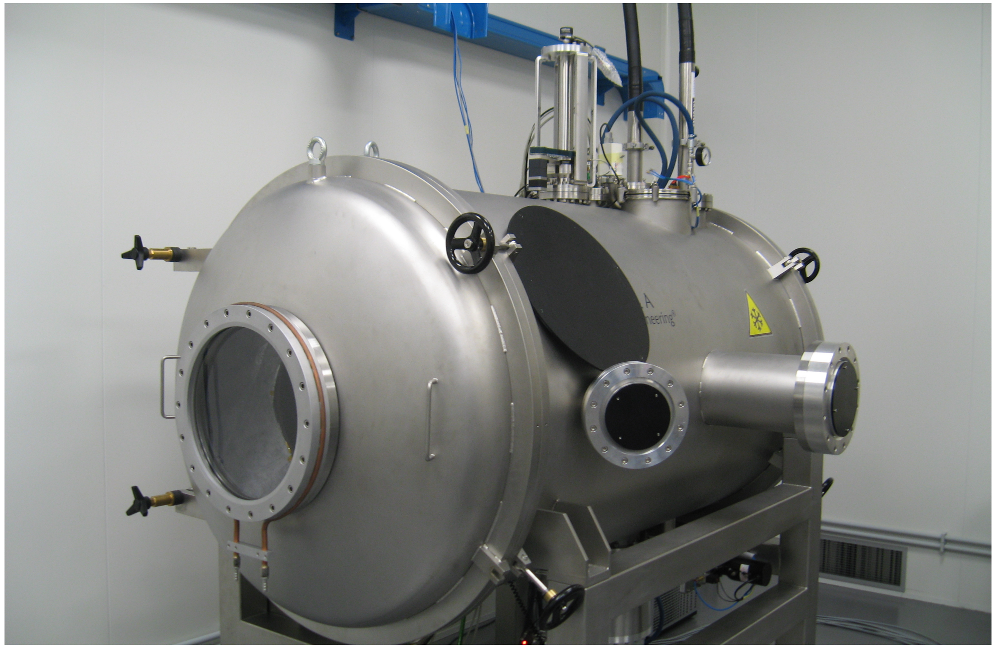


PI:
S. Dell'Agnello

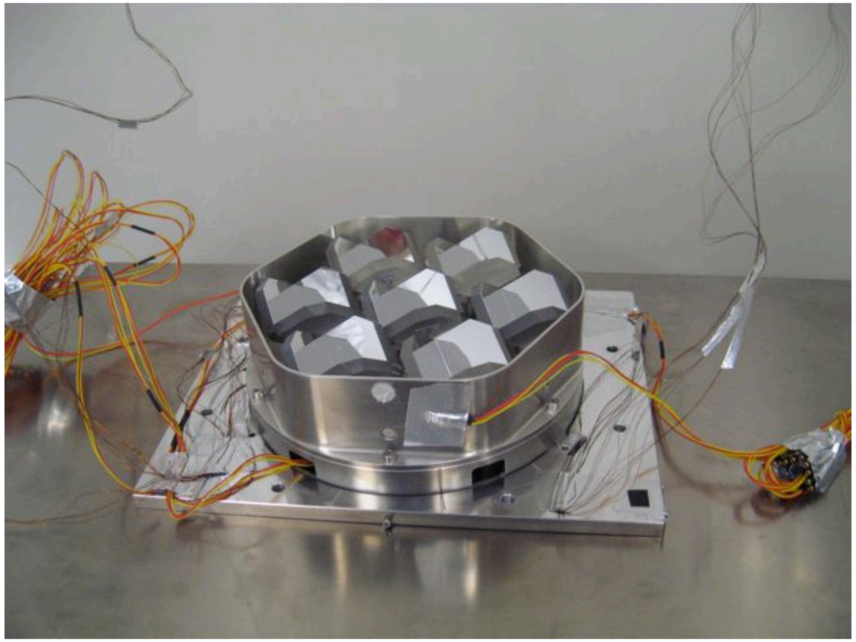
Co-PIs:
R. Vittori, ESA
G. Bianco, ASI

ETRUSCO-2 (ASI-INFN): 2.4 M€, 2010-2013

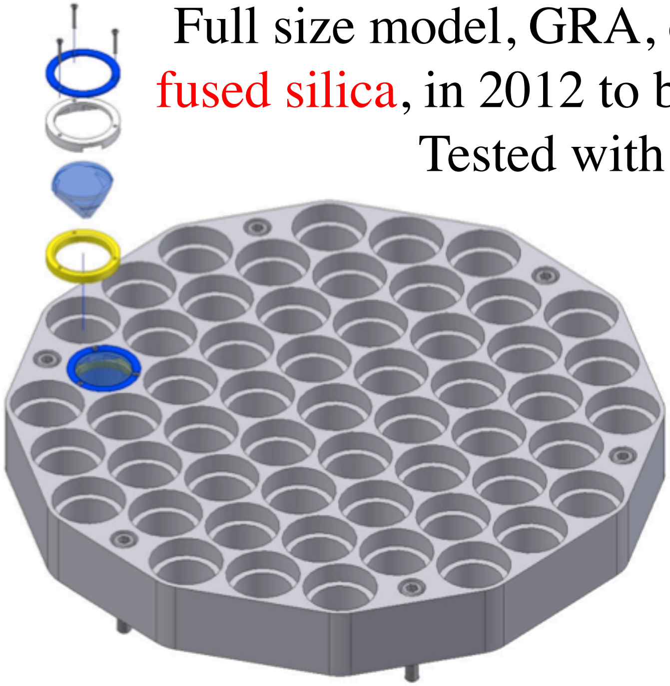
- New SCF-G, optimized for GNSS
- Two new GNSS retroreflector payloads



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

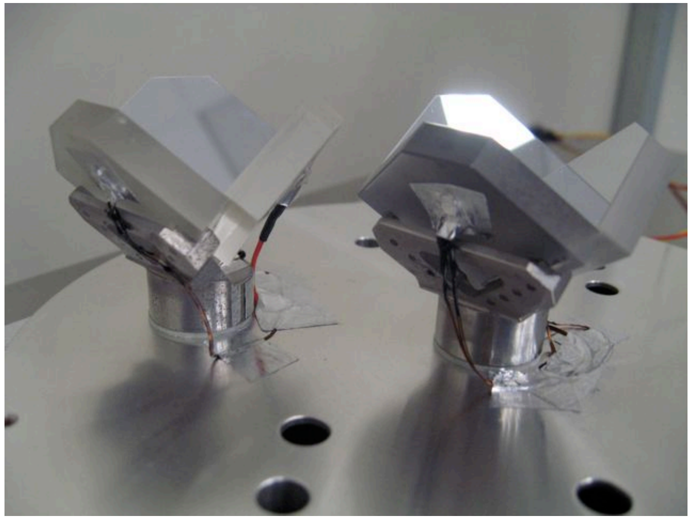


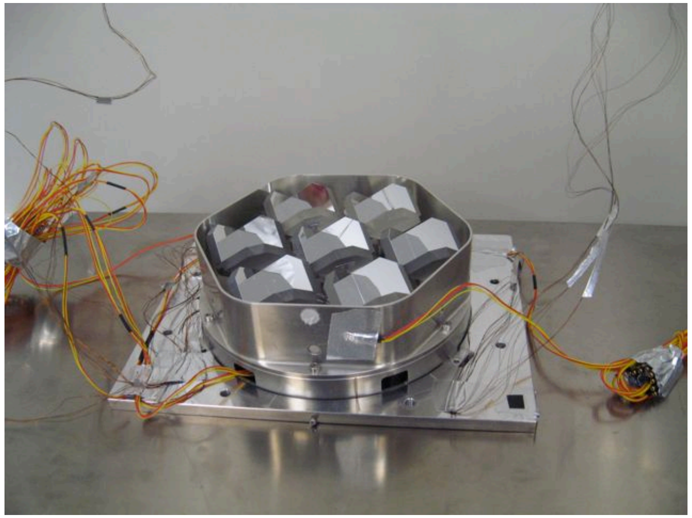
Full size model, GRA, of solid fused silica, in 2012 to be SCF-Tested with SCF-G

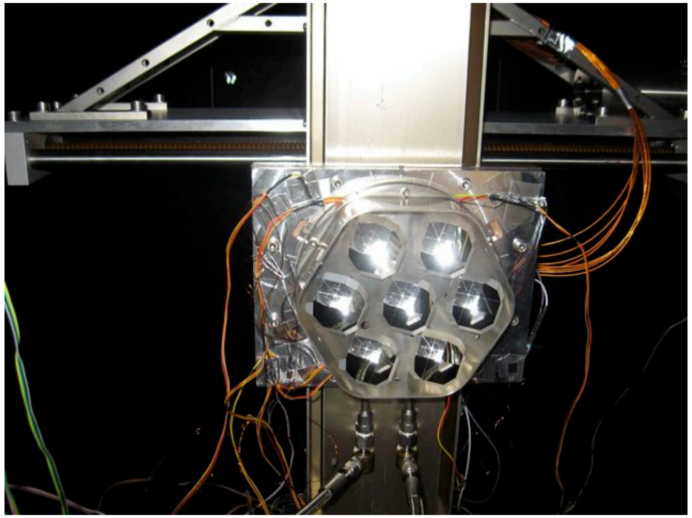


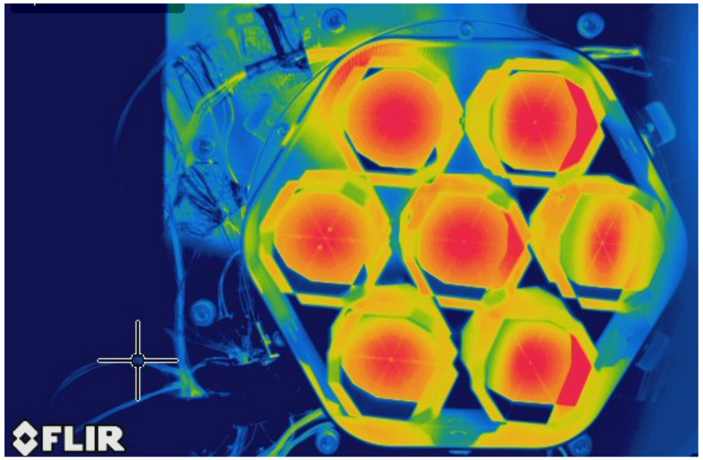
Hollow-reflector technology tested at SCF_LAB

(Japanese SELENE-2 CCR will be hollow; backup CCR will be MoonLIGHT if hollow will not pass SCF-Test)

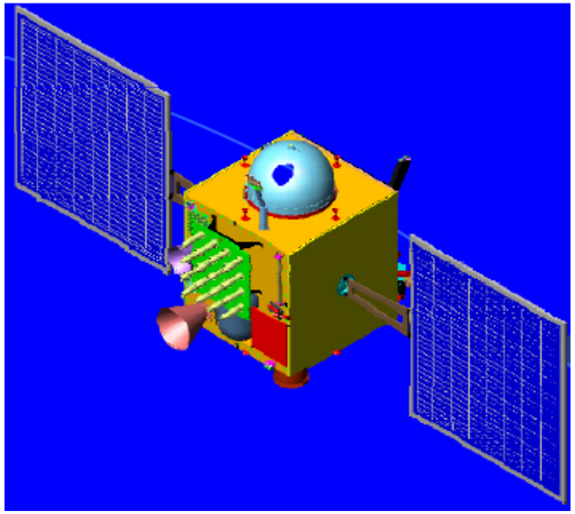








Global Navigation Satellite System (GNSS)

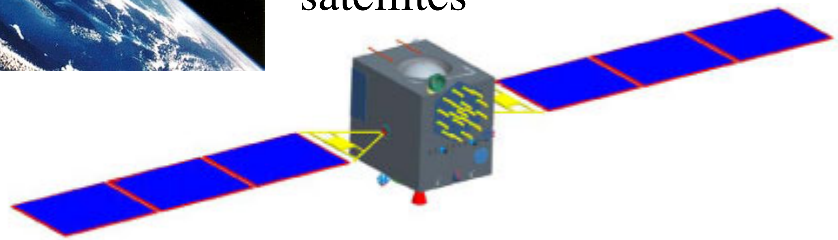


Indian IRNSS: 7 regional satellites

American GPS: 24 global satellites

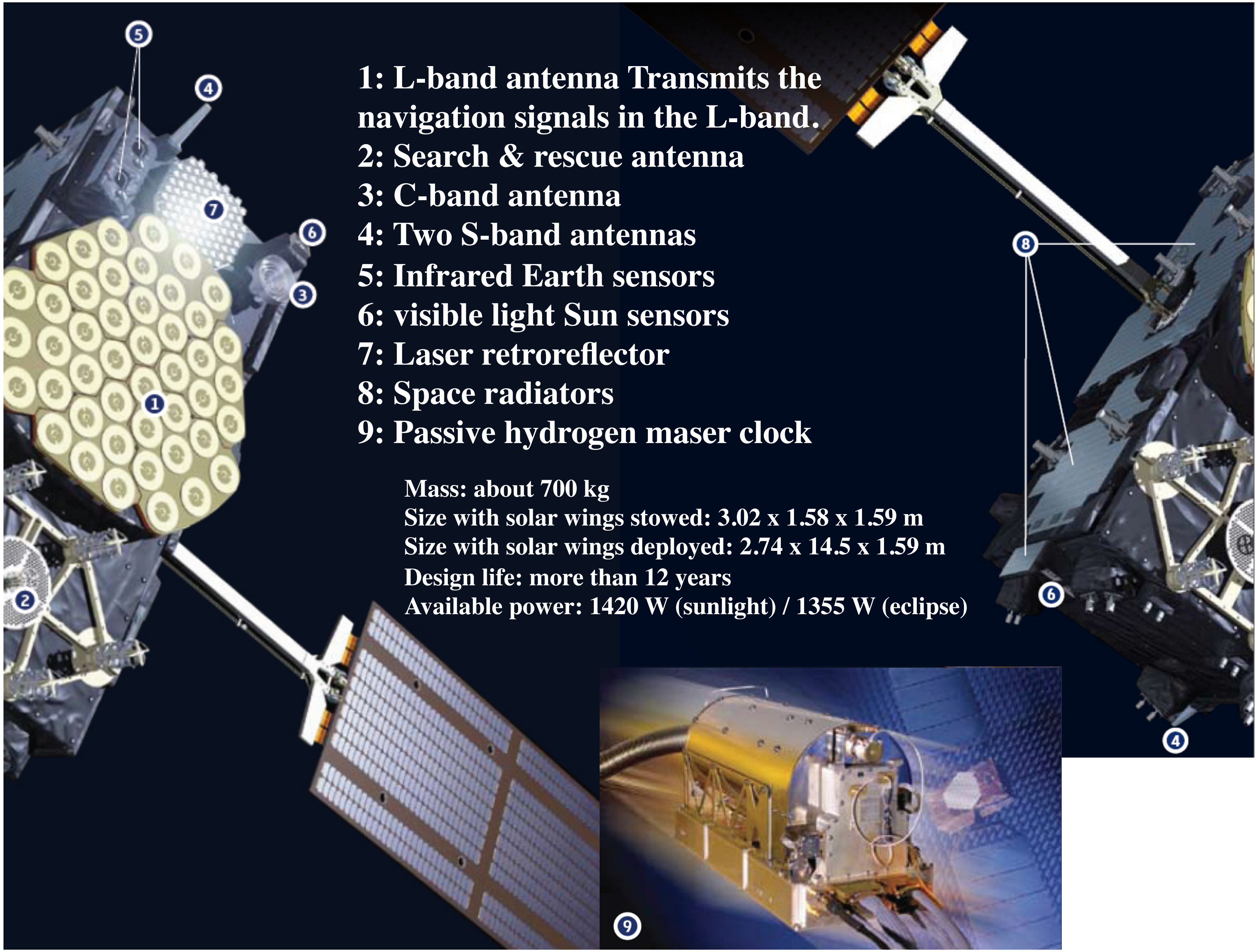
Japanese QZSS: 3 regional satellites

Chinese COMPASS: 30 global and 5 regional satellites

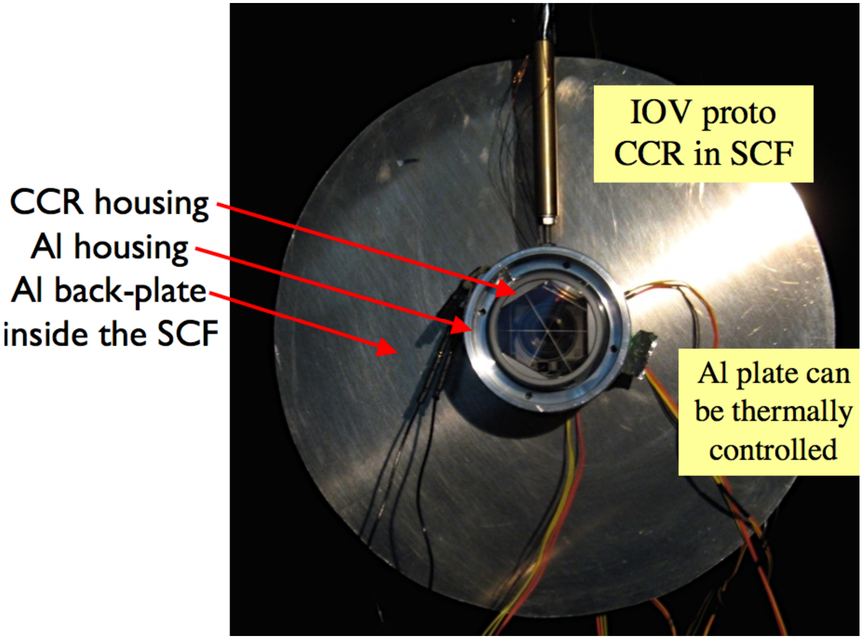


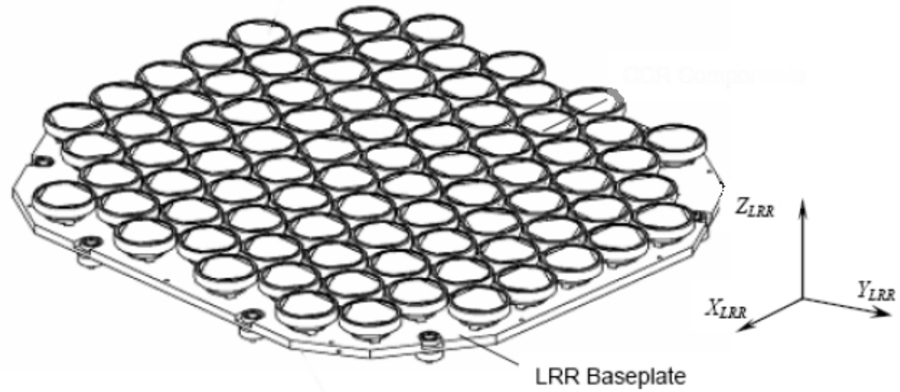
Russian GLONASS: 24 global satellites

Galileo: external anatomy of the IOV satellite



SCF-Test of Galileo IOV retroreflector [RD-10]





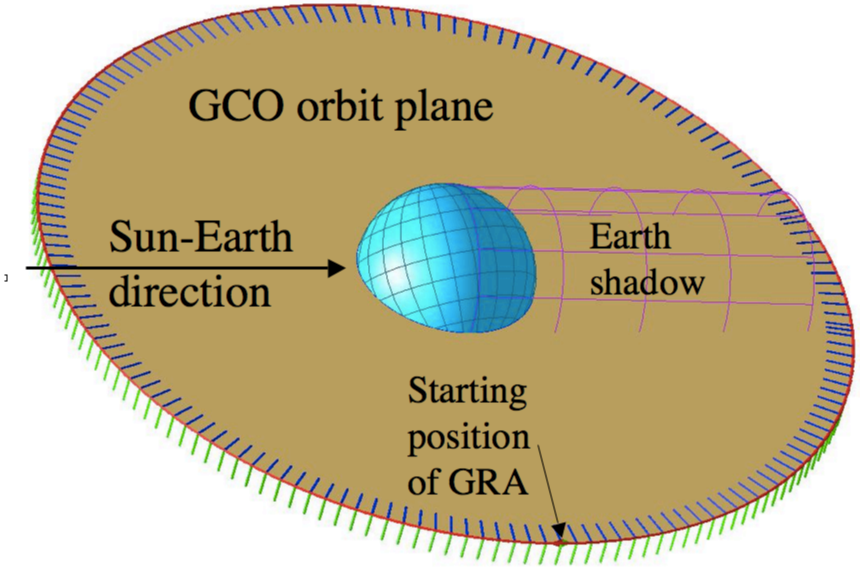
SCF-Test of Galileo Critical half-Orbit (GCO)

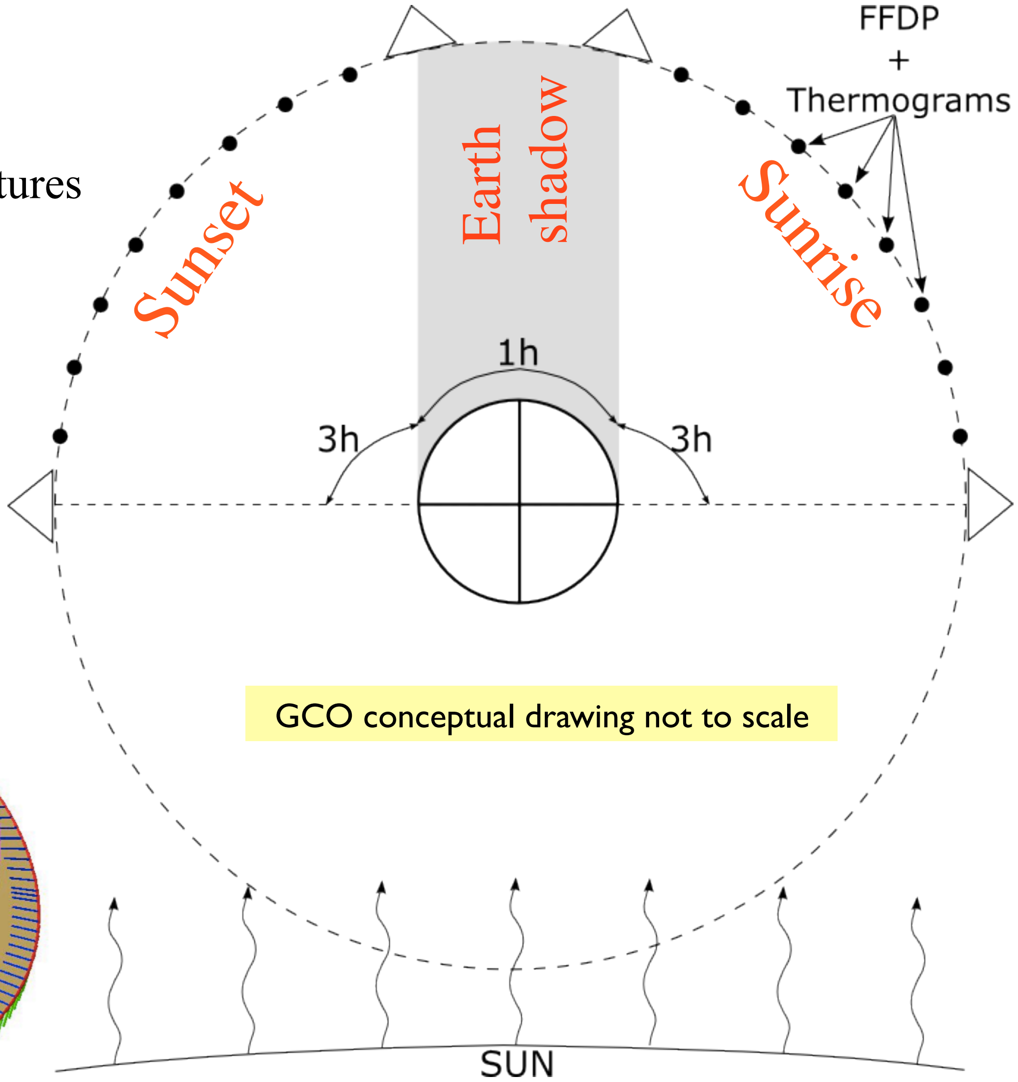
GCO: GNSS orbit whose angular momentum is orthogonal to the Sun-Earth direction

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

Galileo orbit:

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



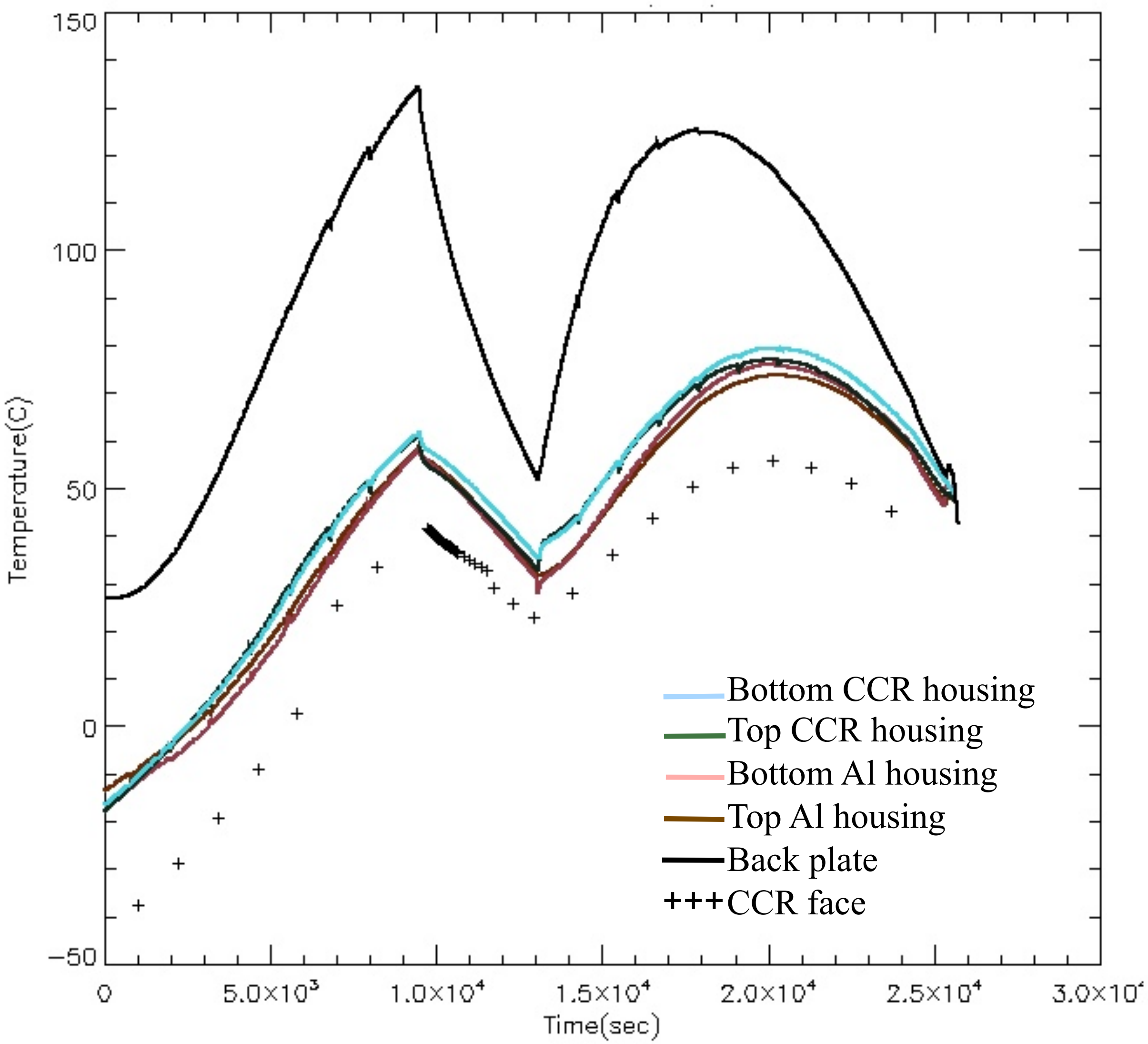


SCF-Test: Galileo reflector temperature along orbit

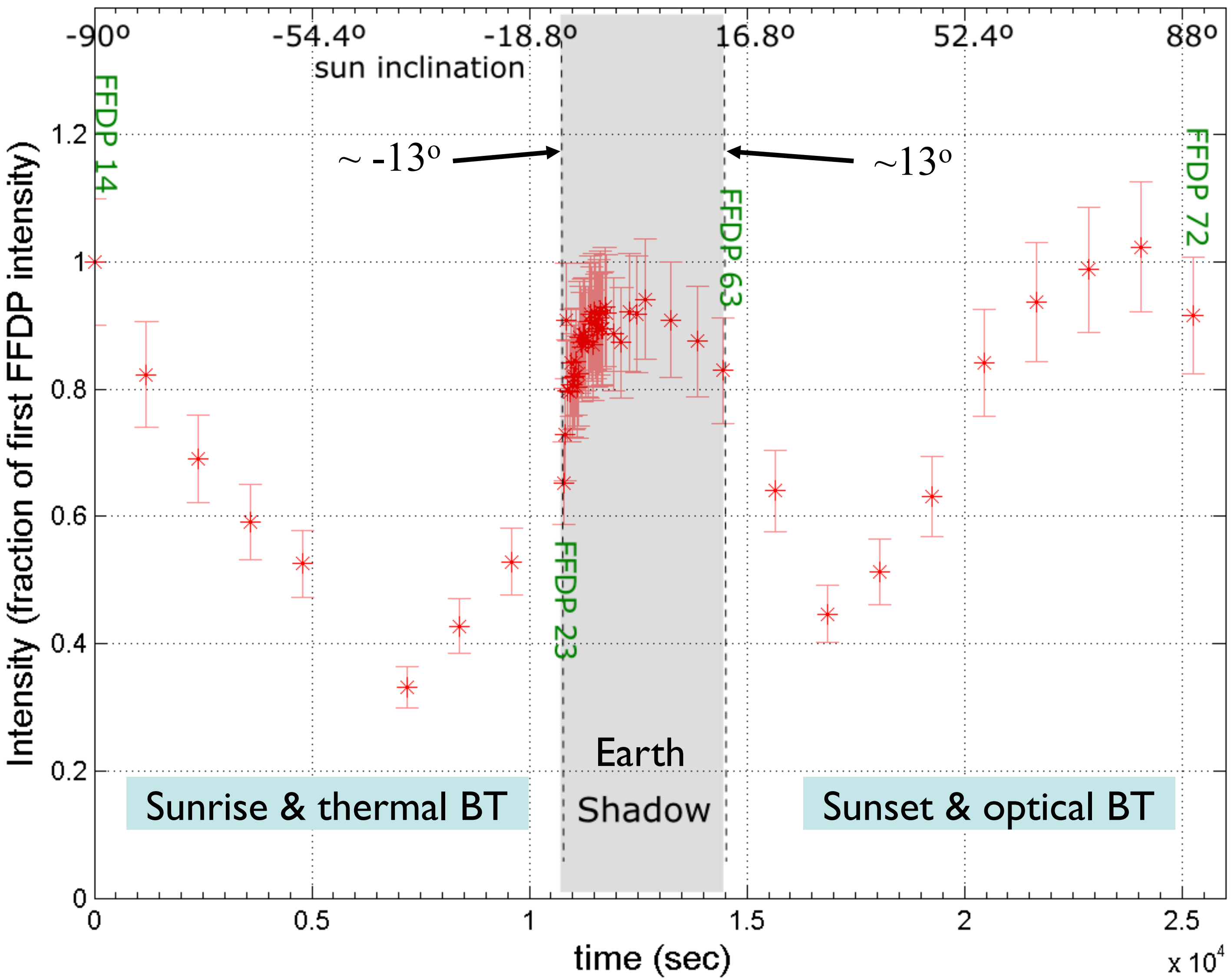
Measured temperatures vs. time (& sun inclination):

- 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



SCF-Test: Galileo optical response along critical orbit



SCF_LAB contracts/proposals, external funds

- Funds: 3+ M€, ~80% by external agencies, ~20% by INFN
- MoonLIGHT (Moon Laser Instrumentation for General relativity High-accuracy Tests):
  - Fundamental and interdisciplinary physics INFN experiments
- ETRUSCO-2 (on Galileo, 2.4 M€)
  - ASI-INFN contract, unification of SLR and GNSS
- ETRUSCO-IOV (in progress, € TBC):
  - ESA contract, SCF-Test of Galileo In-Orbit Validation Satellites
- ETRUSCO-IRNSS (in progress, € TBC):
  - ISRO contract, SCF-Test of Indian Regional Navigation Satellite System

SCF_LAB on-going proposals

- MoonLIGHT products/payload:
  - ESA lunar lander
  - ESA S-Class mission MAGIA
  - JAXA Lunar lander
  - Lunar Google X Prize
  - Chandrayaan-2

Spare slides for questions/comments

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

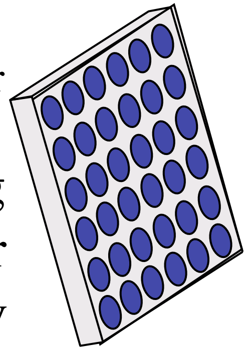
Current dominant error on LLR

Libration rotations up to ~8°
(effect of *e* and *i* of Moon orbit).
Current accuracy of ~ 2 cm

Laser Pulse

far corner

Libration
Multi-reflector
array



near corner

Past
(Apollo)

fat laser pulse:
return uncertainty
dominated by pulse

Present
(Apollo)

medium laser pulse:
return uncertainty
dominated by array libration

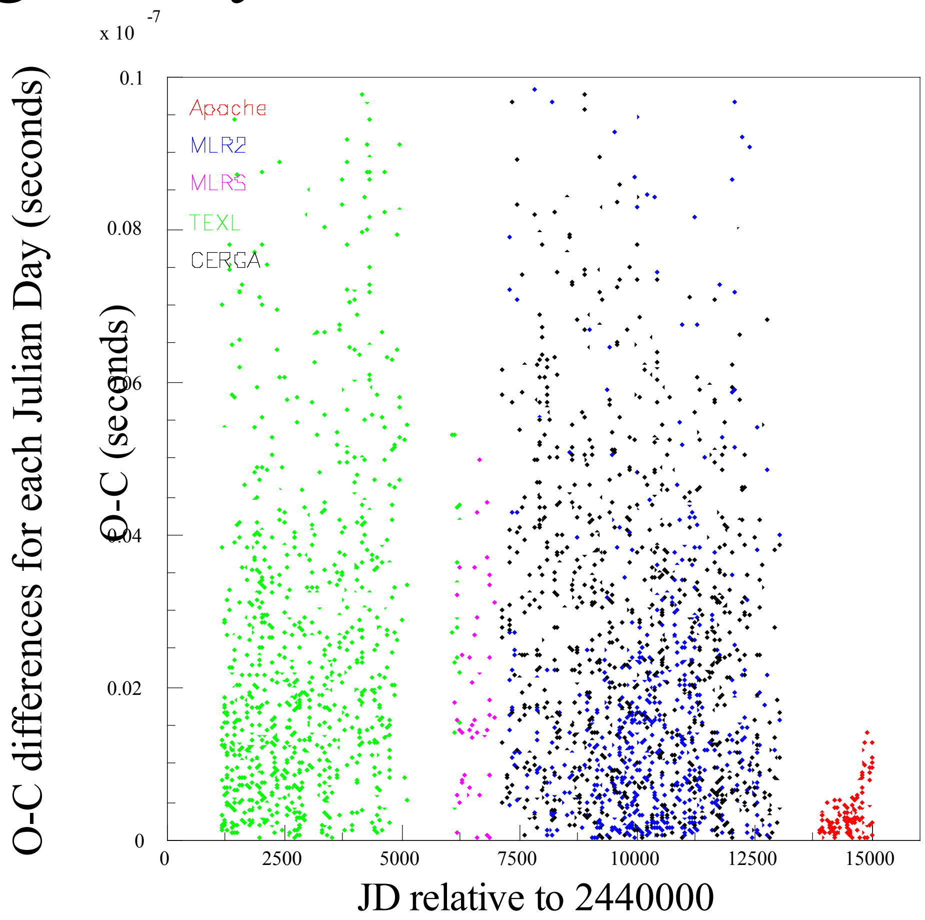
Future
(MoonLIGHT)

short laser pulse:
return uncertainty
dominated by pulse
Shorter pulses can be done

LLR ToF residuals with PEP, the Planetary Ephemeris Program by CfA

Data by station from 1969 to 2009

The model parameter estimates are refined by minimizing the residual differences, weighted least-squares sense, between observations (O) & model predictions by PEP (C= Computation)



Within a single day, differences between (O-C)'s should have a very small variation. We study the quantity |max(O-C)-min(O-C)| for days where multiple measurements were recorded for Apollo 11, 14 and 15

Another application and EU flagship programme: GMES - Observing our planet for a safer world

Managing natural resources and biodiversity, observing the state of the oceans, monitoring the chemical composition of our atmosphere: all depend on accurate information delivered in time to make a difference. The European initiative for the **G**lobal **M**onitoring for **E**nvironment and **S**ecurity (GMES) will provide data to help deal with a range of disparate issues including climate change and border surveillance. Land, sea and atmosphere - each will be observed through GMES, helping to make our lives safer.

The purpose of GMES is to deliver information on environment and security which correspond to identified **user needs**

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 realisation of the TRS.

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