Testing Fundamental Gravity with Lunar Laser Ranging

Simone Dell'Agnello (for the SCF_Lab Team)
INFN-LNF, Via Enrico Fermi 40, Frascati (Rome), 00044, Italy

INFN-LNF, Frascati, February 10, 2014

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

www.lnf.infn.it
DIVISIONE RICERCA
tel. + 39 06 9403 2730
+ 39 06 9403 8036
fax + 39 06 9403 2475
email: Simone.DellAgnello@lnf.infn.it

SCF_Lab Team @INFN-LNF

Simone Dell'Agnello, Delle Monache G., Vittori R., Boni A., Cantone C., Ciocci E., Lops C., Martini M., Patrizi G., Tibuzzi M., Maiello M., Currie D., Bianco G., Intaglietta N., Salvatori L., Contessa S., Porcelli, L., Tuscano, P., Mondaini, C.

INFN-LNF, Frascati (Rome), Italy

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SCF_Lab

Satellite/Lunar/GNSS laser ranging and altimetry **C**haracterization **F**acilities' **Lab**oratory

Acknowledgments

We acknowledge important support/contracts from/with:

ASI,

ESA & Galileo,

Italian Ministry of Defense/Air Force,

ISRO

Outline

- Introduction to Satellite and Lunar Laser Ranging
- Lunar Laser Ranging to laser retroreflectors
- SCF_Lab Research Infrastructure @ INFN-LNF
- Science program and SCF_Lab Activities
- Lunar mission opportunities

Introduction to Science

- Improved Test of Gravity with refined analysis of, and LLR data from, **Apollo and Lunokhod reflectors**
  - Launched 1969-1972, NASA, ROSKOSMOS.
  - Uninterrupted LLR data since 69. By ILRS; also ASI-Matera from 2010
  - Accurate thermal-optical-orbital modeling. With Maryland
  - General Relativity analysis. **PEP** with CfA (USA)
  - New theories of gravity and Solar System constraints with IST Lisbon, Univ. Porto
- Improved Tests of Gravity (up to x100) and improved Selenodesy (lunar interior) – **MoonLIGHT**
- New Enabling Technology for Gravity, Planetary Exploration and Geodesy - **INRRI**
- Independent missions, though part of unitary program

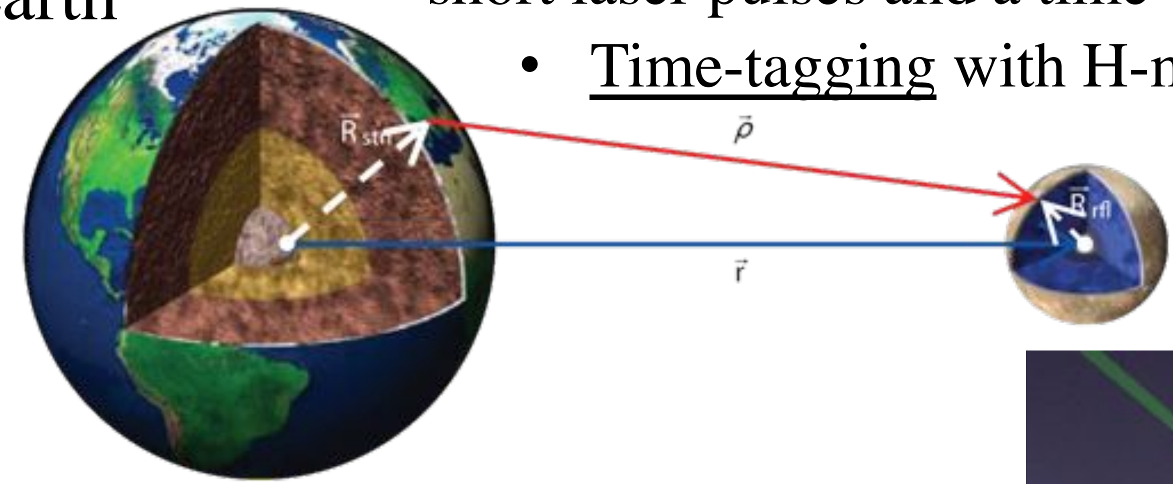
Satellite Laser Ranging (SLR)
Lunar Laser Ranging (LLR)

Time of Flight (ToF) measurements

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

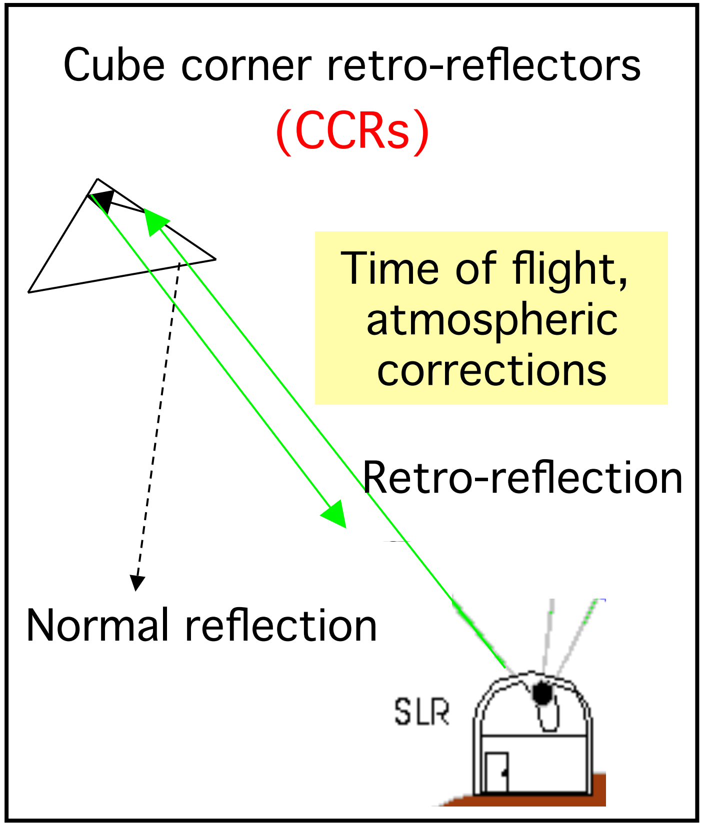
Earth

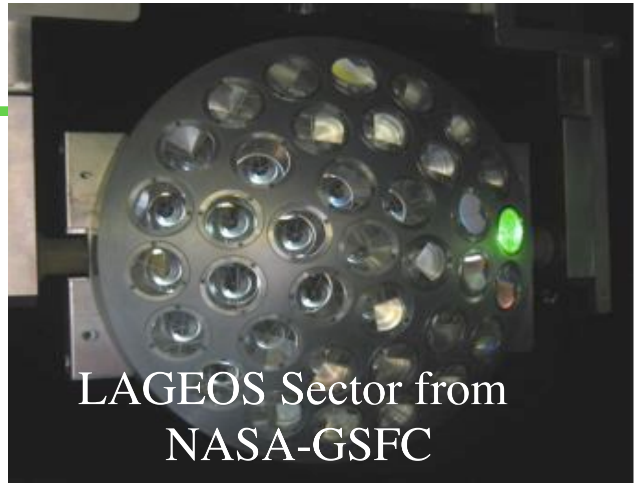


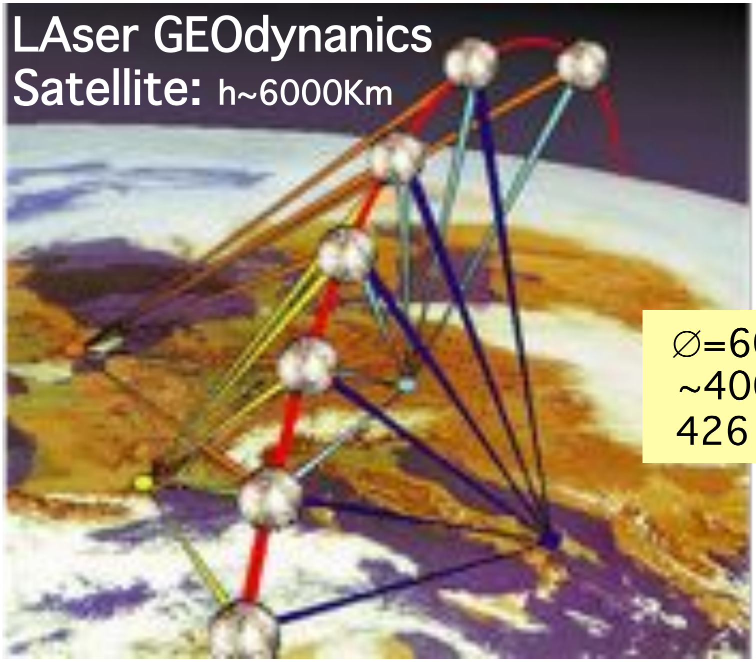
Moon

- **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



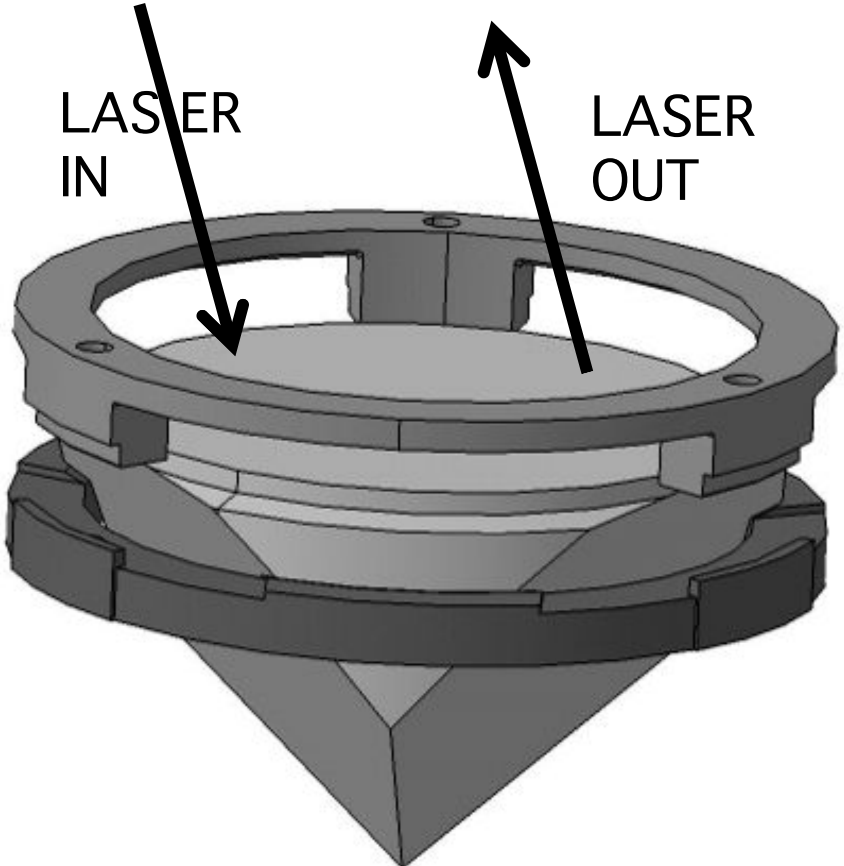


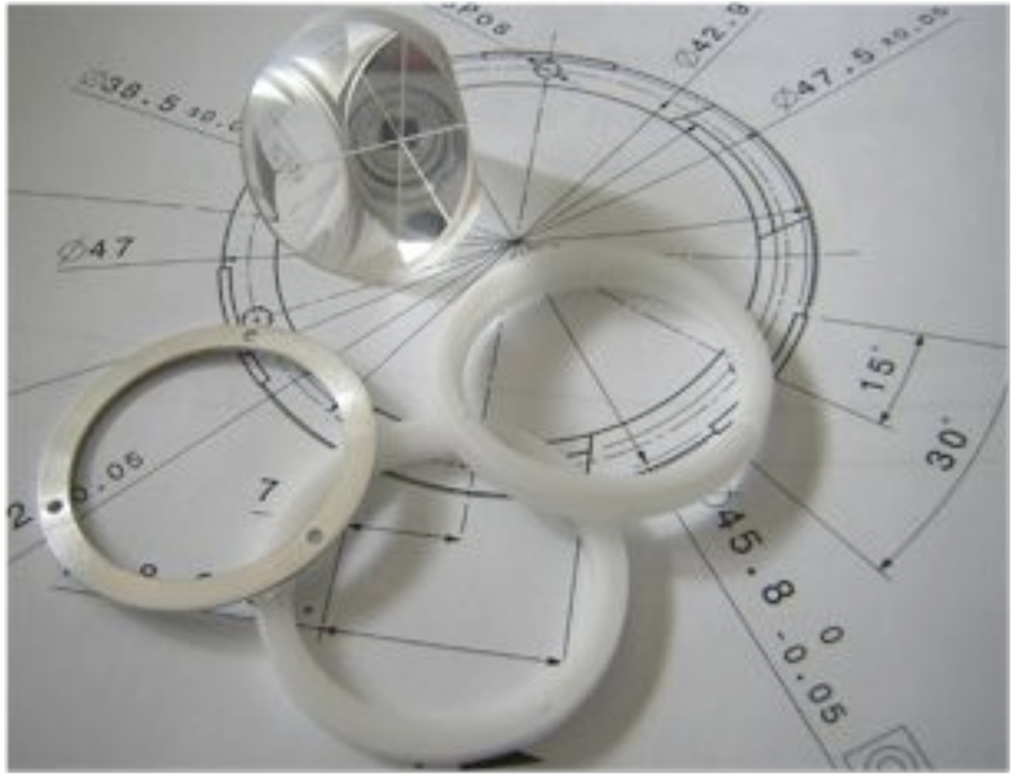


∅=60 cm
~400 Kg
426 CCRs

(Precise). AND. (cost-effective) distance measurement in space

Cube Corner laser Retroreflectors (CCRs)

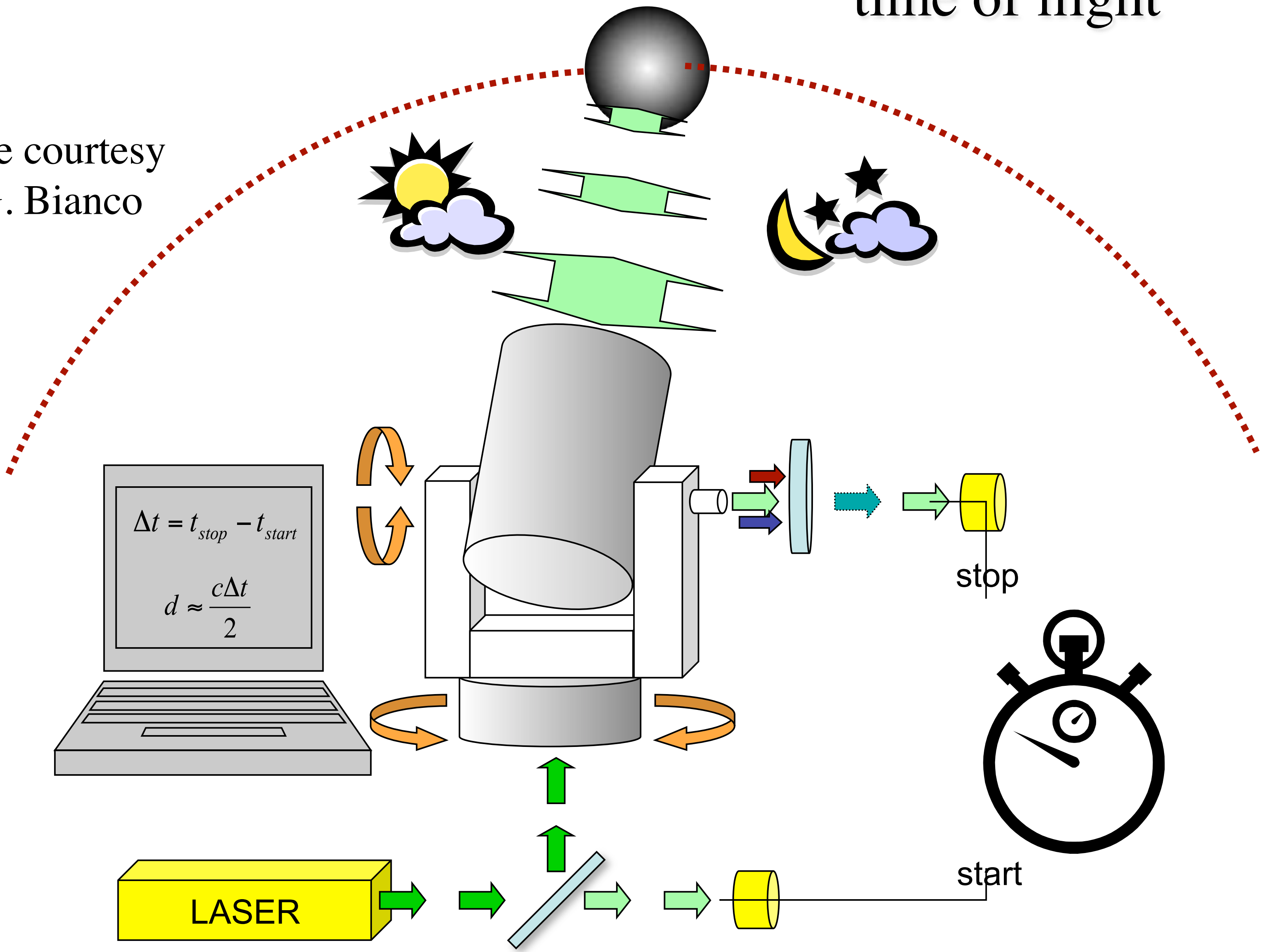




Triple total internal reflection around the corner

SLR concept: laser, receiving telescope; clock; time of flight

Slide courtesy of G. Bianco



LLR/SLR vs. ground survey/alignment

An ILRS station is like a gigantic *total station* theodolite measuring angles & distances of CCRs in ordinary surveys and alignements on Earth. For example to build large physics installations, like particle physics experiments (ATLAS, KLOE, CDF, ..) and particle beam accelerators (LHC, DAFNE, Tevatron, …)

Leica TC2002. Great instrument:
ToF theodolite with IR laser
0.1-0.2 mm (after interferometer calibration)
few microrad accuracy

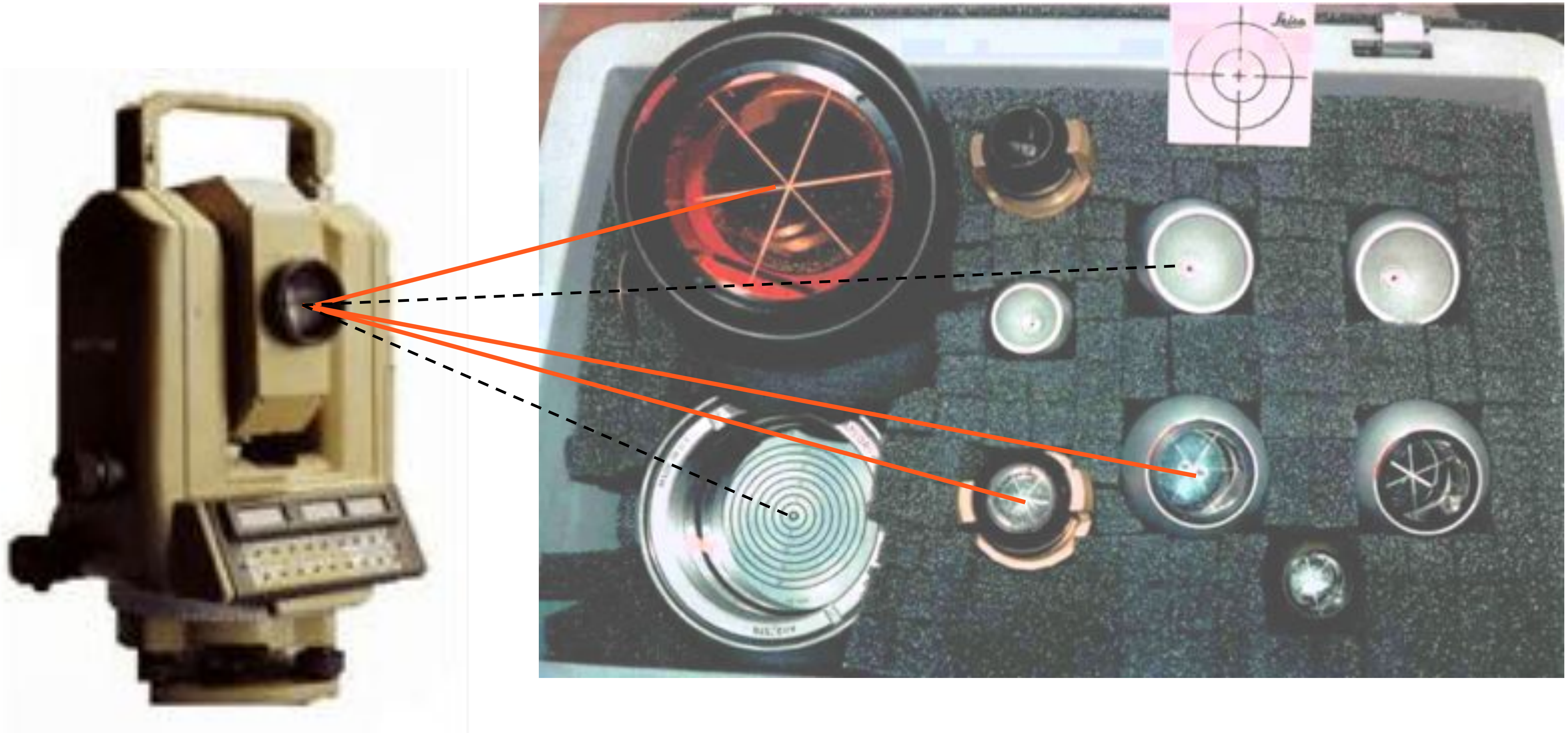
However, surveys for particle physics usually done indoor at approximately isothermal conditions, over short baselines (2 to hundreds of meters). With LLR/SLR things are completely different

Cube Corner laser Retroreflectors (CCRs)

So-called “prisms” used for ground measurements by “geometers”, for ex mounted inside opened spheres, with the corner coincident with the center of the sphere

Taylor-Hobson sphere for measurements of angles

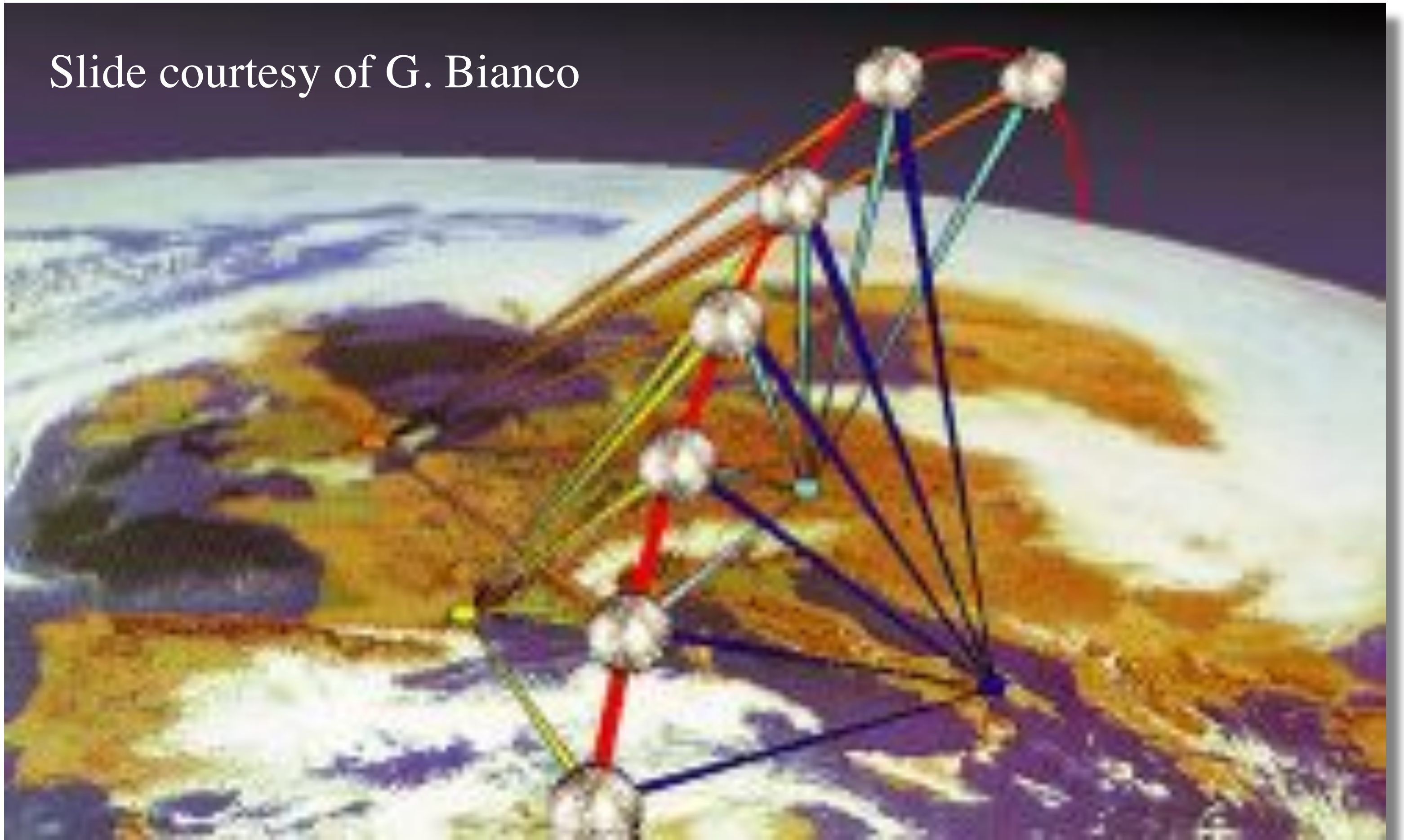
On ground: theodolite (or laser "tracker"), retroreflector, time-of-flight



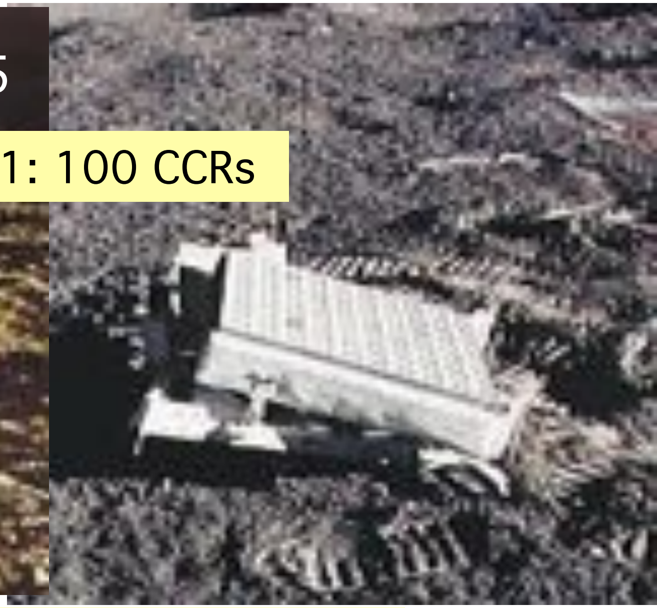
Usato for positioning metrology of large physics installations and Experiments like KLOE particle physics experiment at the LNF DAΦNE accelerator and ATLAS/CMS @CERN

SLR concept

ILRS stations: Matera, Herstmonceux, Graz, OCR



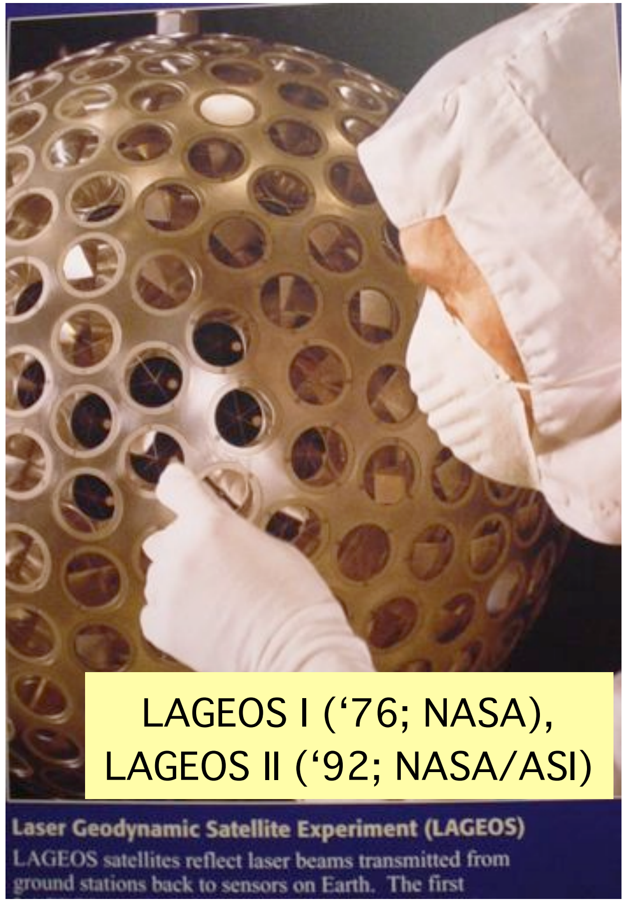
APOLLO 11, 14, 15



Apollo 11: 100 CCRs

Flight payload for GPS-2 @INFN-LNF:

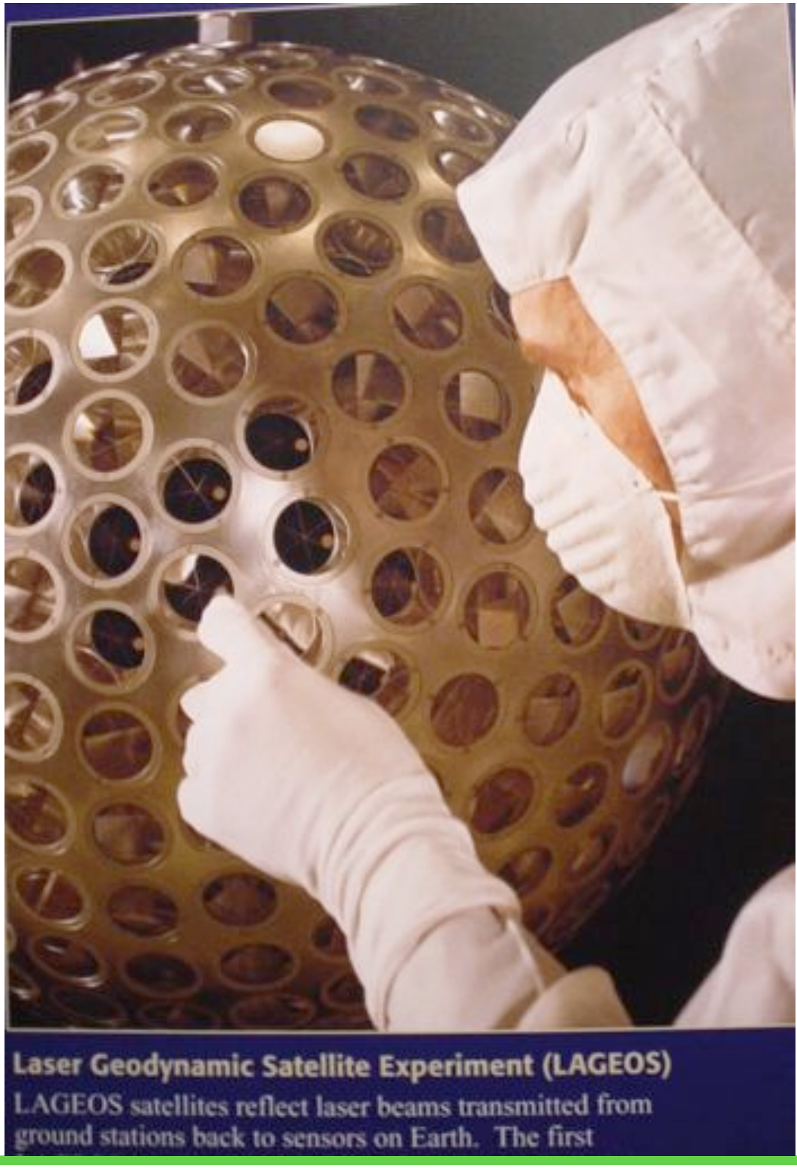
32 CCRs (property of Univ. Maryland)



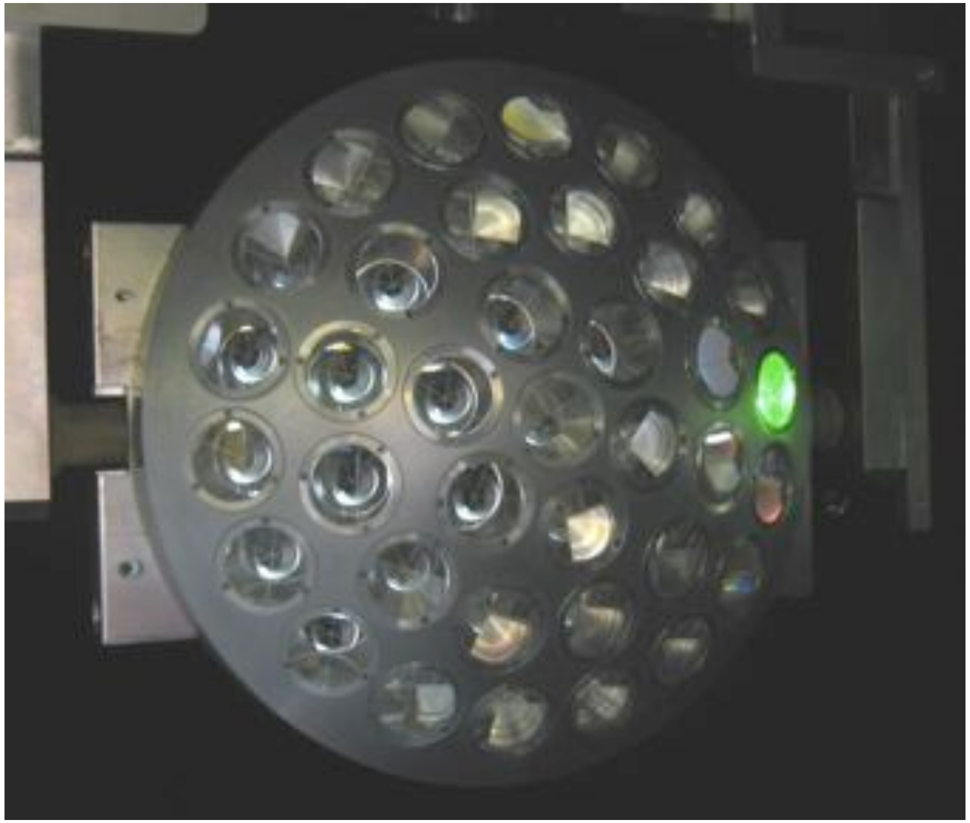
LAGEOS I (‘76; NASA),
LAGEOS II (‘92; NASA/ASI)

Laser Geodynamics Satellites (LAGEOS)

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



LAGEOS "**Sector**", an engineering prototype proporty of NASA-GSFC, SCF-Tested at INFN-LNF



Space geodesy, GNSS, Gravitation

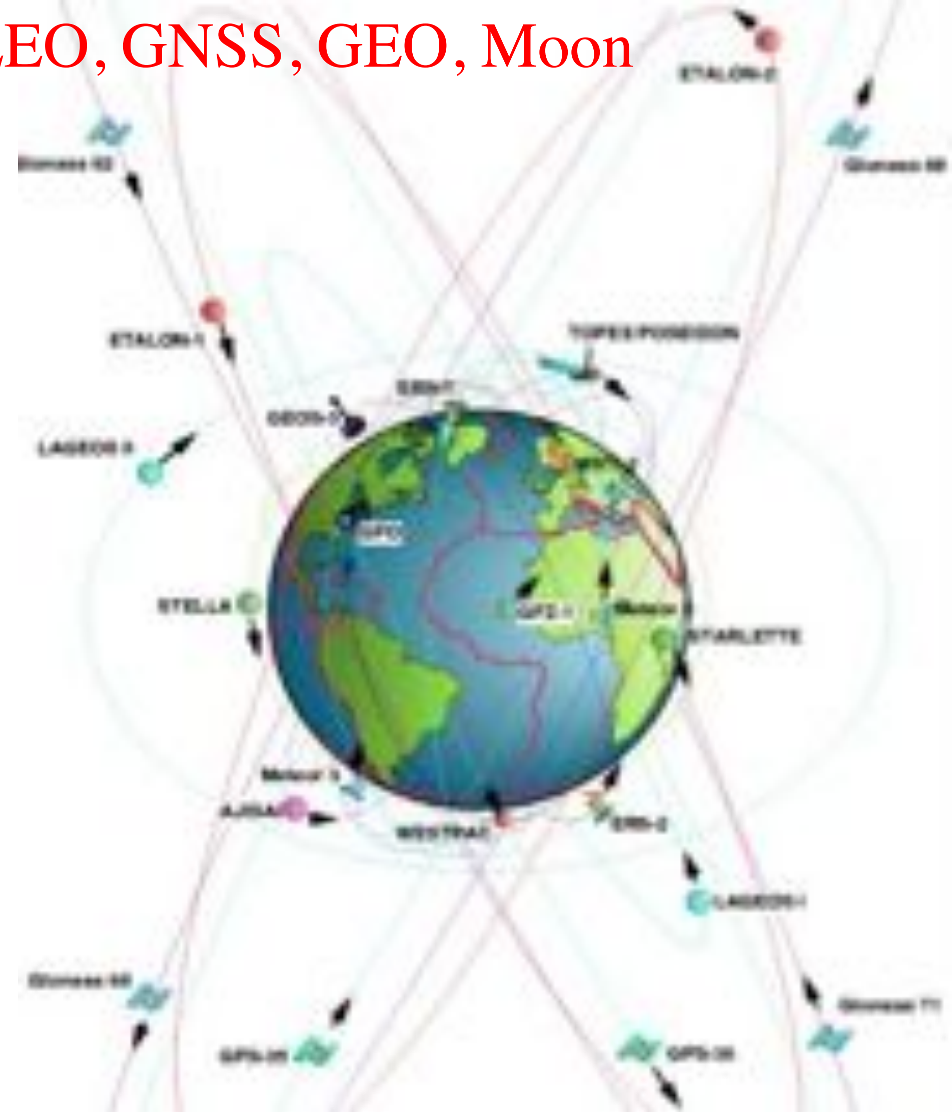
International Terrestrial Reference Frame (ITRF):

- **Geocenter** from SLR
- **Scale** from SLR & VLBI
- **Orientation from** VLBI
- **Distribution w/**GNSS
- DORIS …

LAGEOS

International Laser Ranging Service

SLR CONSTELLATION: LEO, GNSS, GEO, Moon

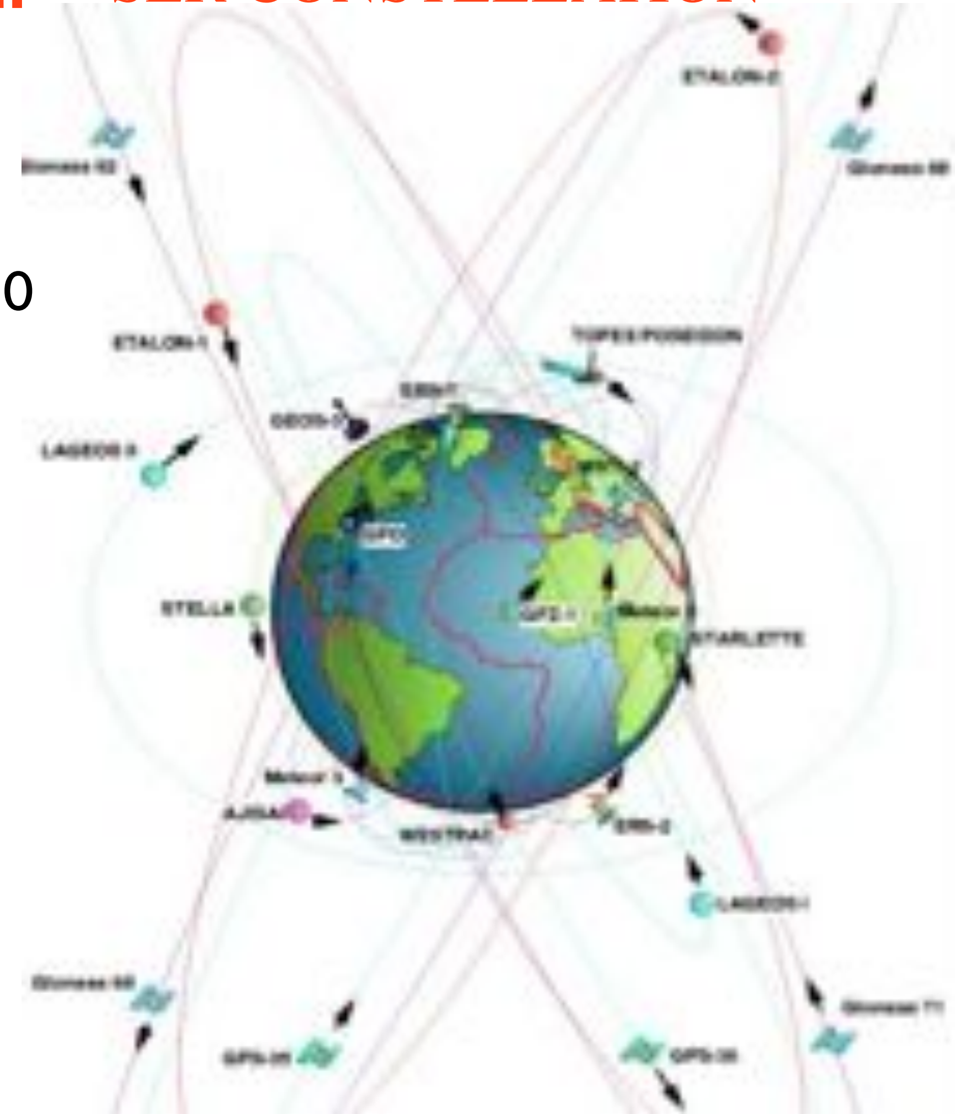


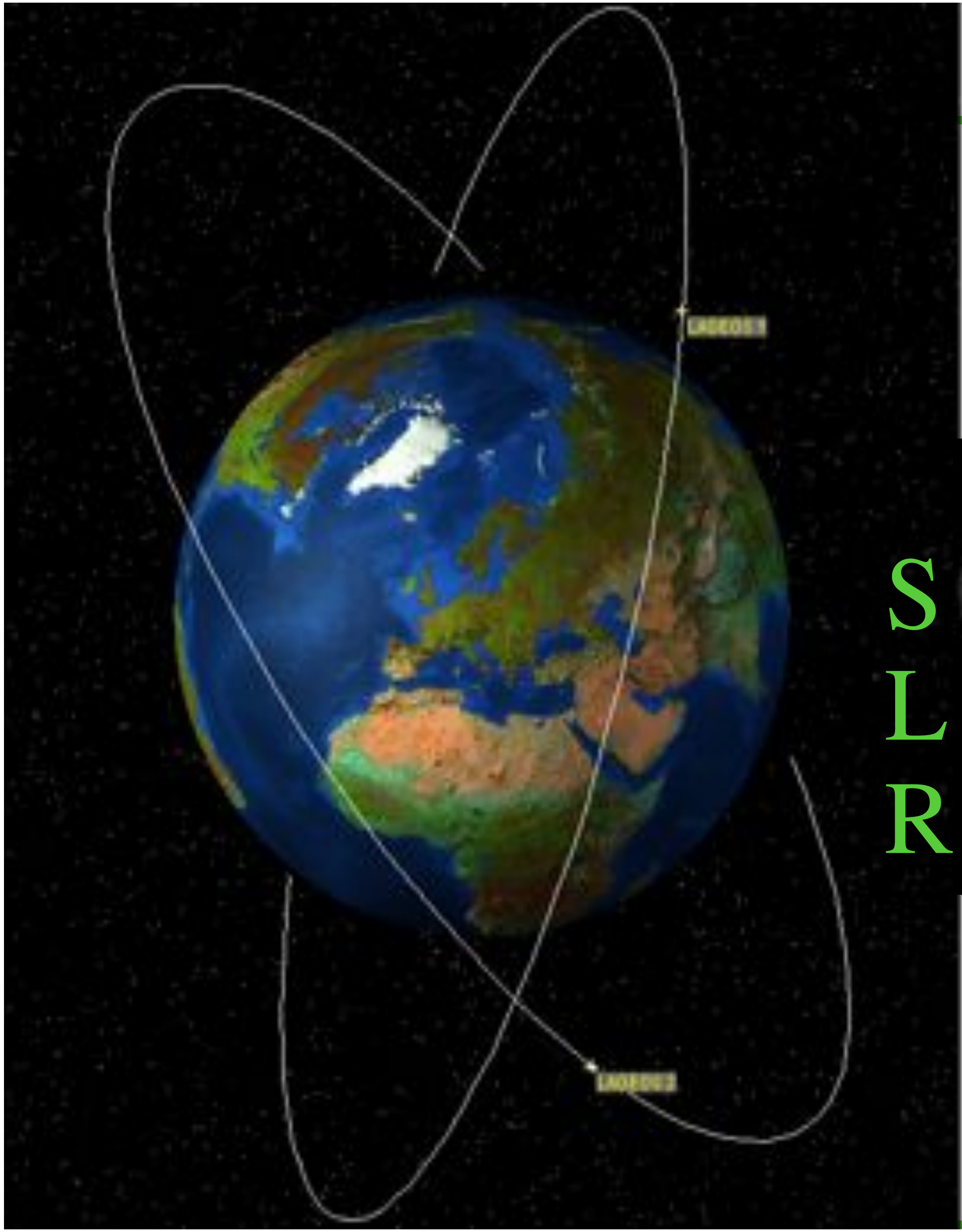
Int. Terrestrial Reference Frame (ITRF)

Space geodesy long-term goal:

- Define and maintain an ITRF with an accuracy of 1 mm and a stability of 0.1 mm/year over a 10-year period
- Now ITRF is about a factor (few to) 10 less accurate/stable

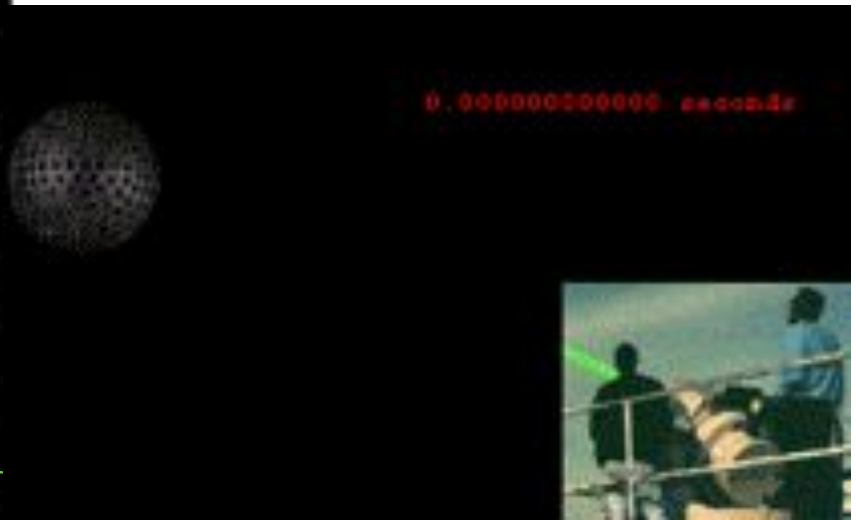
SLR CONSTELLATION





LAGEOS (h ~ 6000 km): ToF ~ 0.05 sec

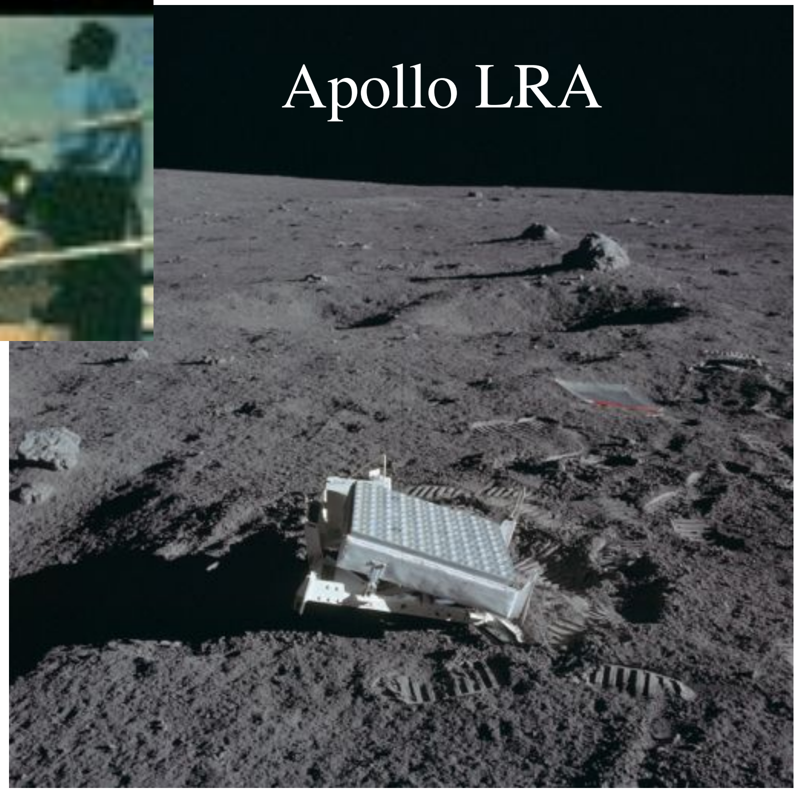
S
L
R



SLR/LLR examples

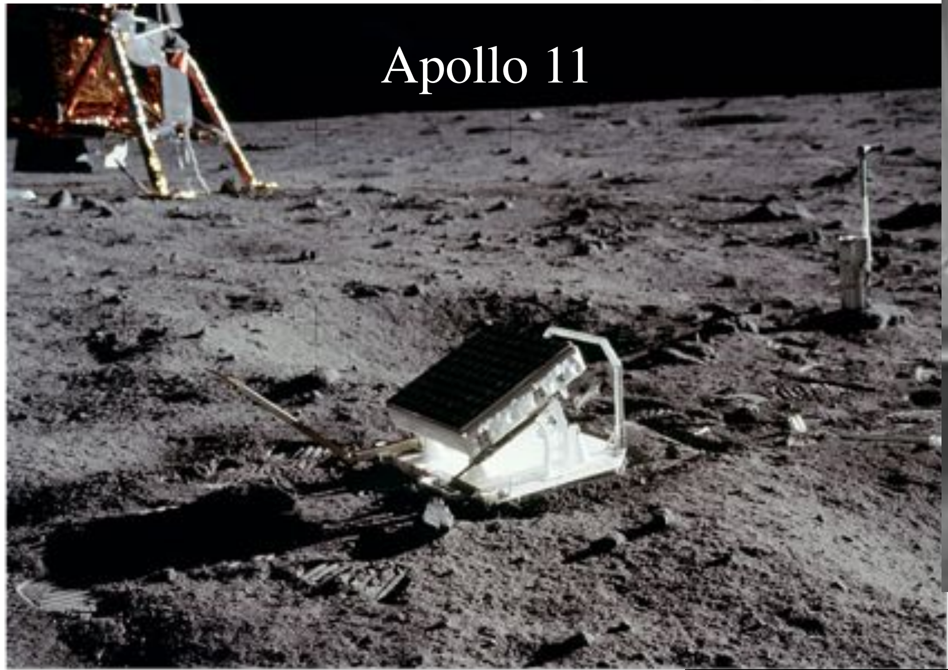
S
L
R

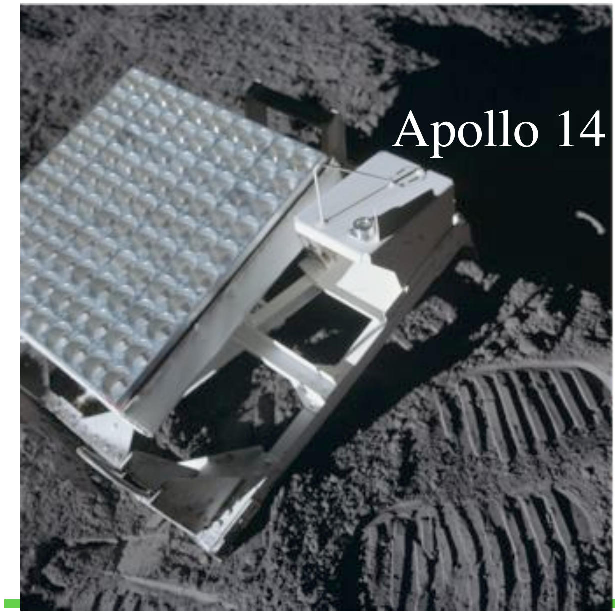
LAGEOS
(h ~ 6000 km):
ToF ~ 0.05 sec

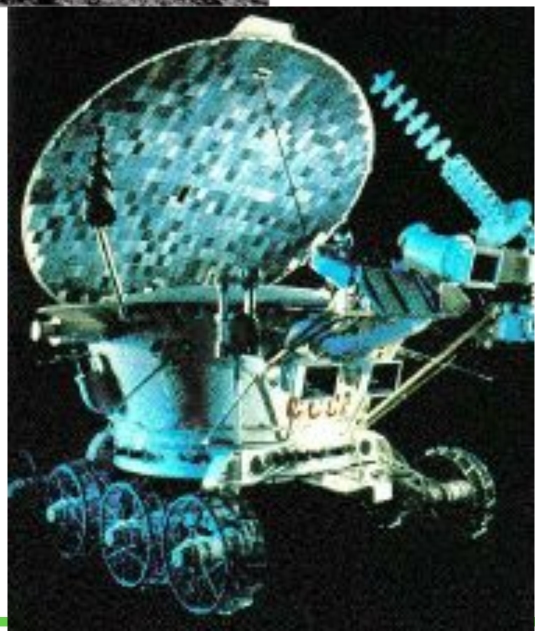


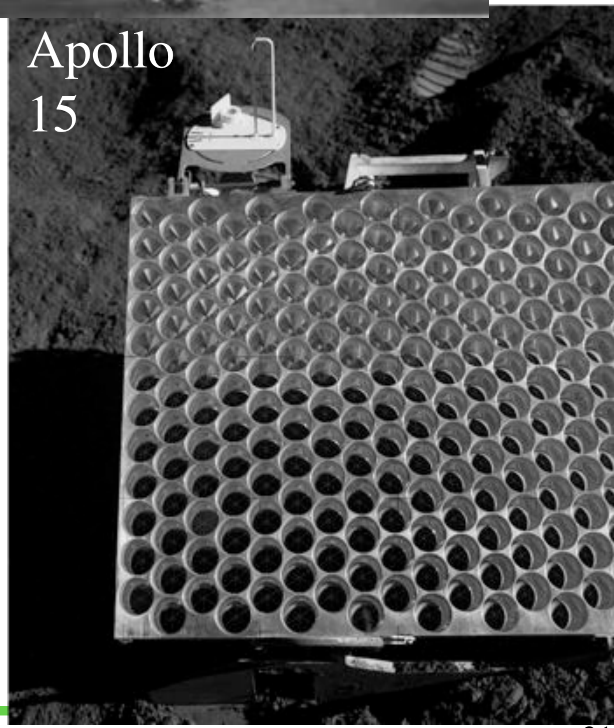
Moon
(d ~ 380000 km):
ToF ~ 2.5 sec

Current LLR arrays







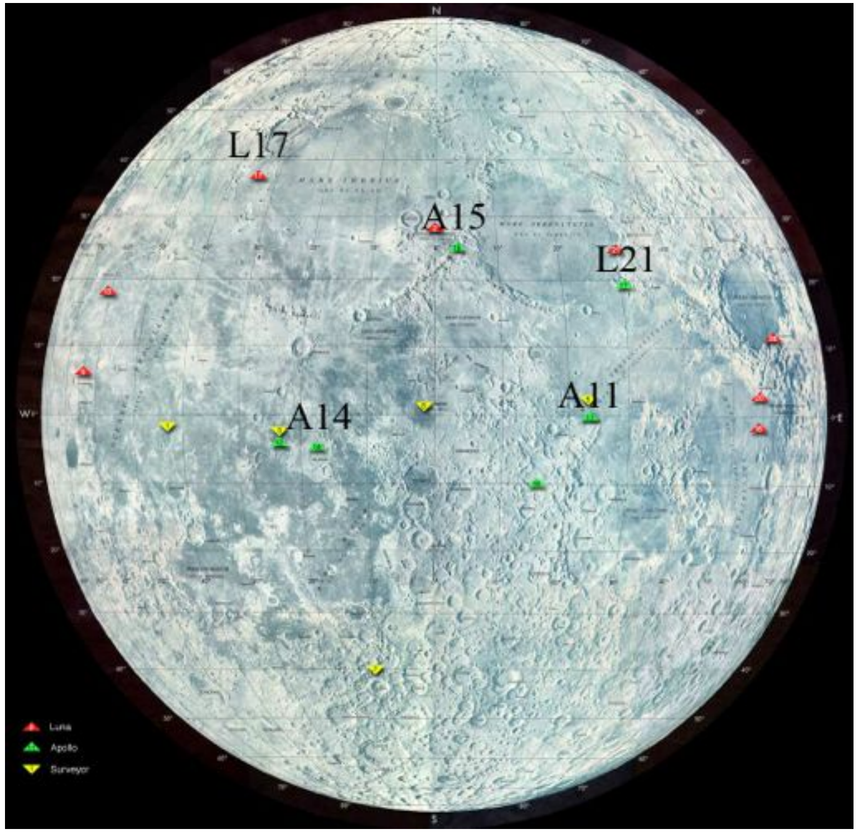


Apollo Missions

- R. H. Dicke et al: laser tracking of Moon with traditional light pulses for gravity testsin the 50s
- Laser invented ~1960

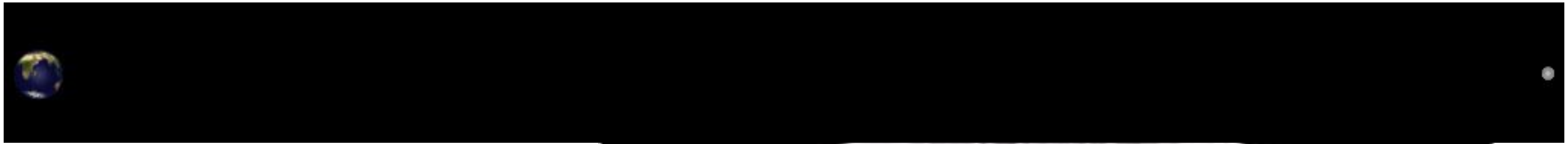
- MIT and URSS shoot laser light to Moon surface in the 60s

- Retroreflectors deployed by Apollo 11, 14, 15

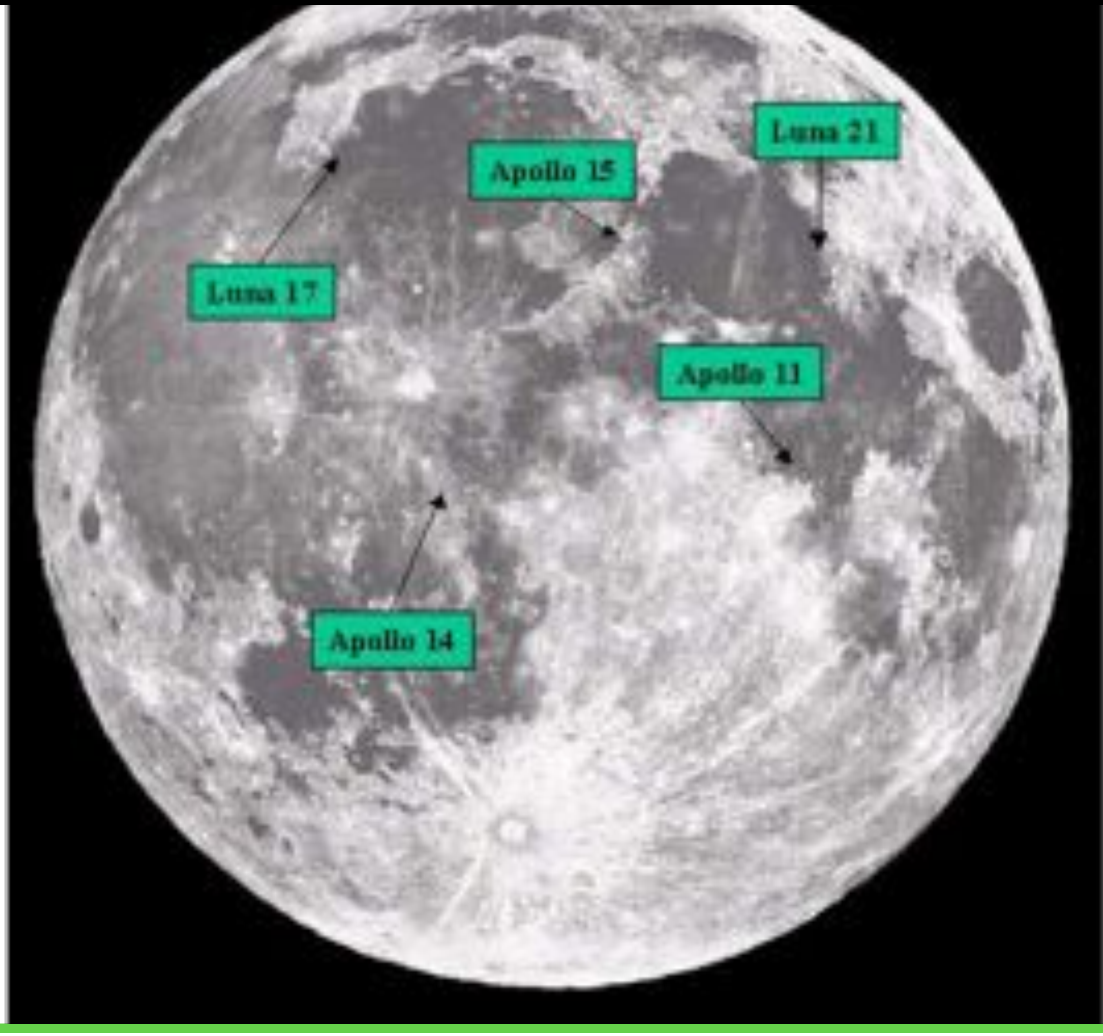


  - Apollo: CCR arrays of fused silica with circular aperture of 3.8 cm diameter each
  - Apollo 11 e 14: used 100 CCRs
  - Apollo 15: 300 CCRs

Lunar Laser Ranging: accurate at ~ 10^{-11} of Earth-Moon distance



Relative sizes and separation of the Earth–Moon.
An LLR pulse takes 1.255 sec for the mean orbital distance.



Locations of 1st Gen. Lunar Retroreflector Arrays

“Centro di Geodesia Spaziale (CGS) *Giuseppe Colombo*”
Matera, Italy
Tri-colocated within ITRF by SLR, VLBI, GNSS

Slide courtesy of G. Bianco

MLRO,
Matera Laser Ranging Observatory
LLR since March 2010
Led by G. Bianco, also
Chairman of ILRS Governing Board

agenzia spaziale italiana

Giuseppe Colombo, 1920-1984

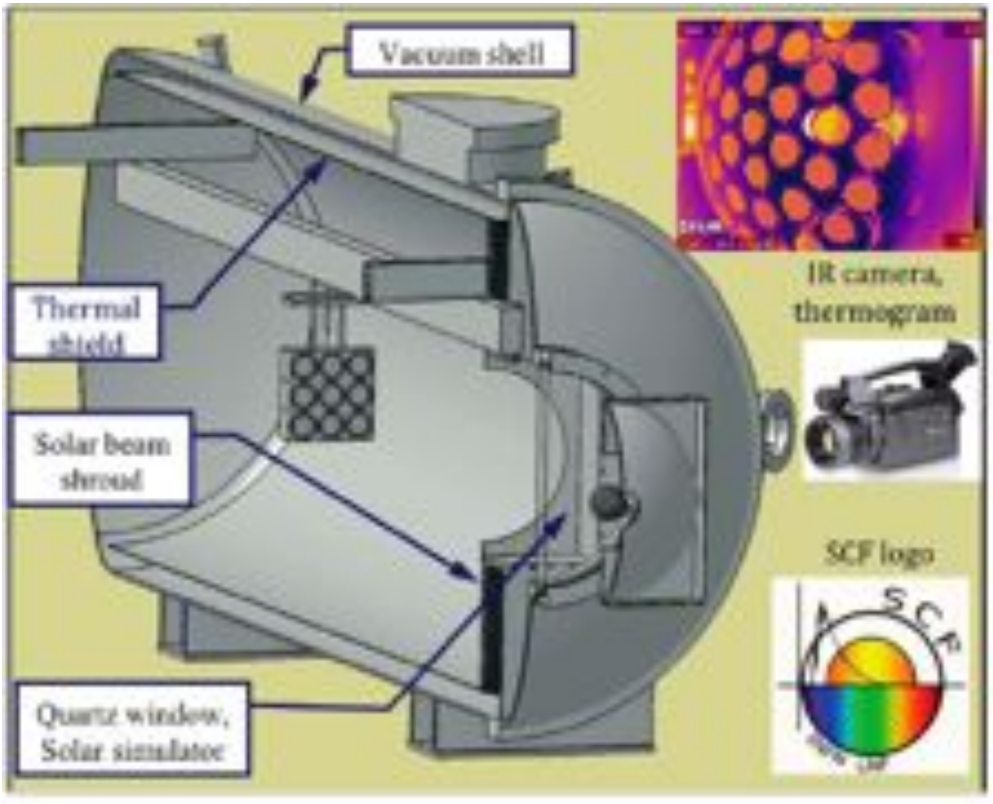
MLRO

3-station colocation, OCA-CERGA, Obs. du Calern, France

(courtesy of)

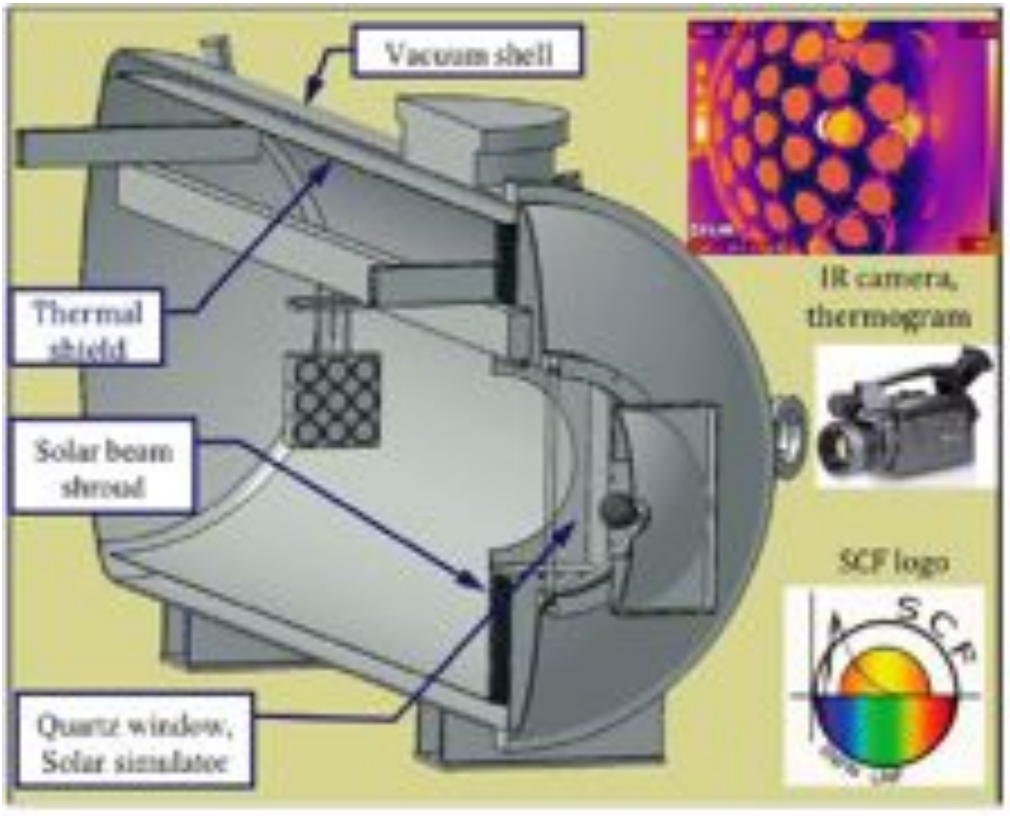
SCF_Lab

Two unique OGSE (Optical Ground Support Equipment) facilities, in clean room to characterize the thermal and optical behavior of laser retroreflectors in lab-simulated space environment (532, 633, 1064 nm)

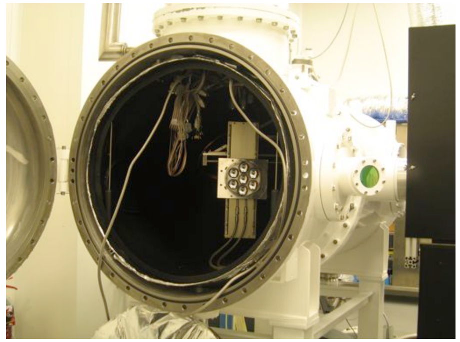


SCF_Lab @INFN-LNF

Two world-unique **OGSE** (Optical Ground Support Equipment) facilities in a clean room to characterize the space segment of laser ranging altimetry. *In 'INFN jargon': "test beam of laser retroreflector detectors"*

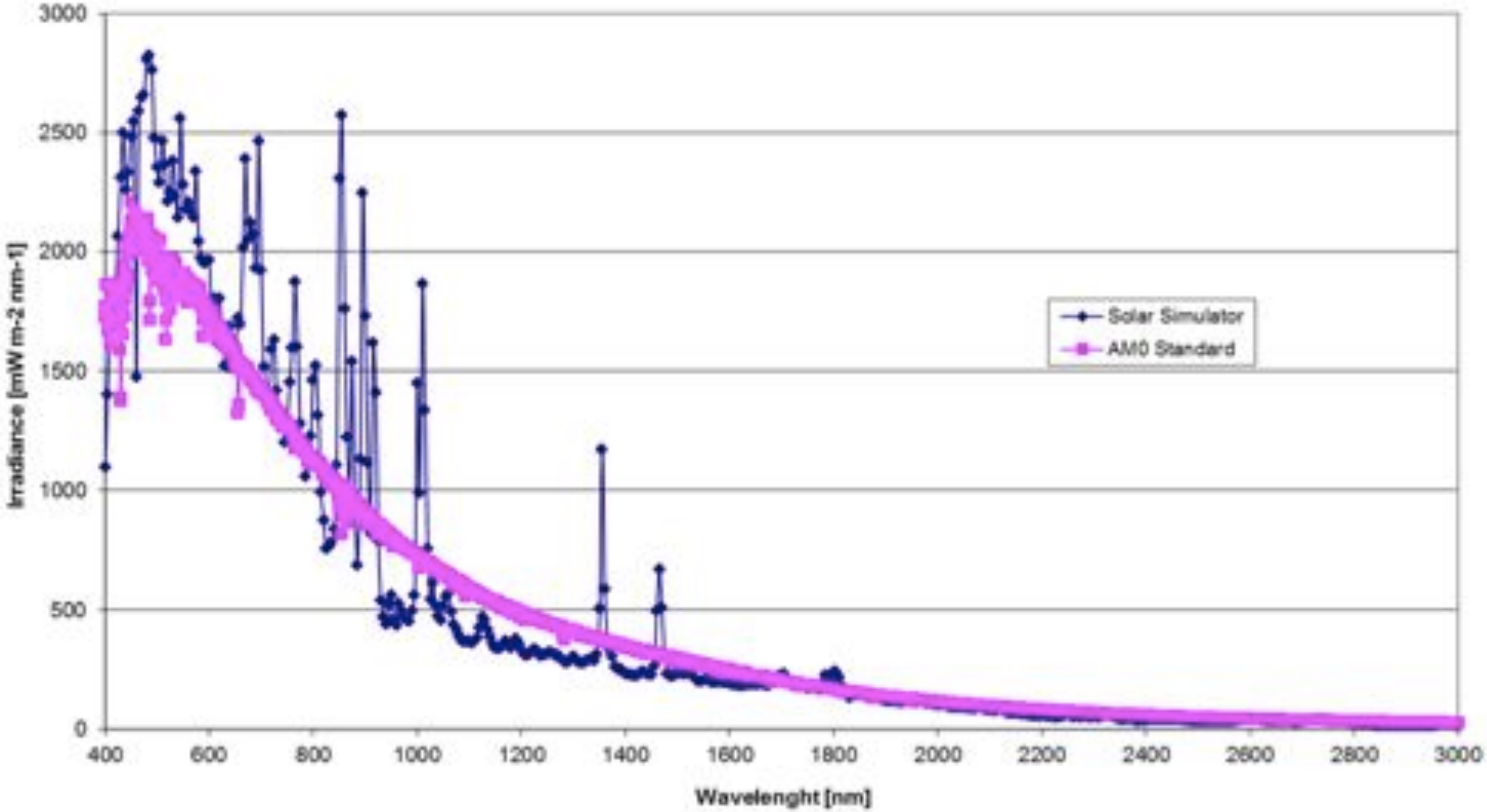


SCF for SLR/LLR/ GNSS/ Altimetry (RD-1, RD-2)



SCF-G for GNSS (RD-10)

Two AM0/space Solar Simulators



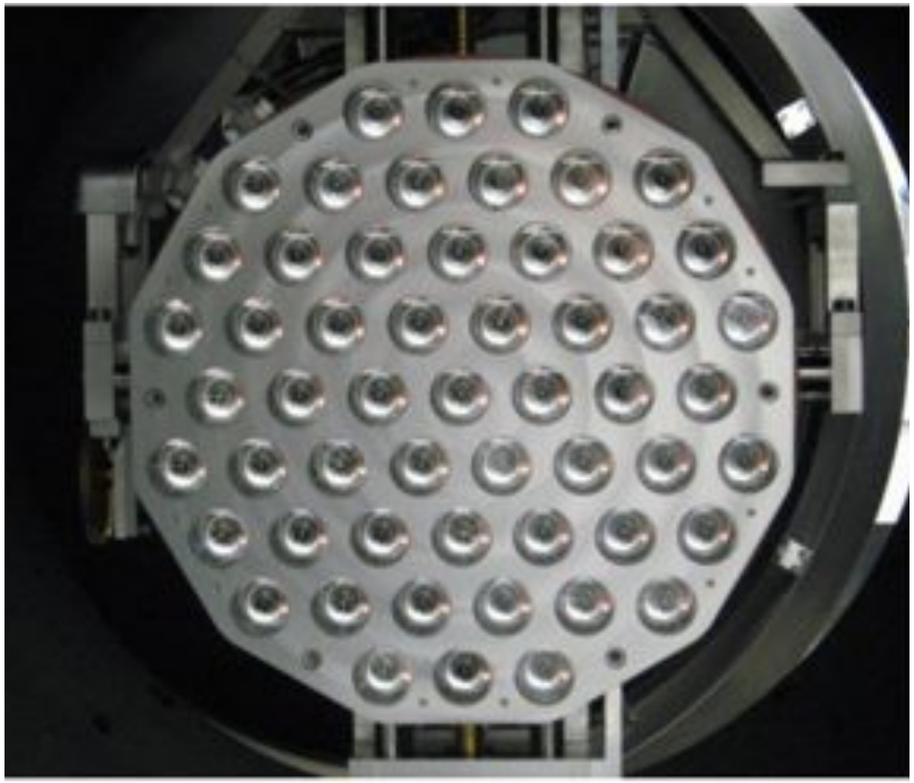
Optical measurements: FFDP & Interferometry

SCF_Lab measurements

- Far Field Diffraction Pattern (FFDP) measurement in Air of all 55 CCR
- SCF-Test
- Simulated orbital measurement

Introduced interferometric measurements from a commercial fizeau interferometer

GPS/Galileo laser Retroreflector Array (GRA)

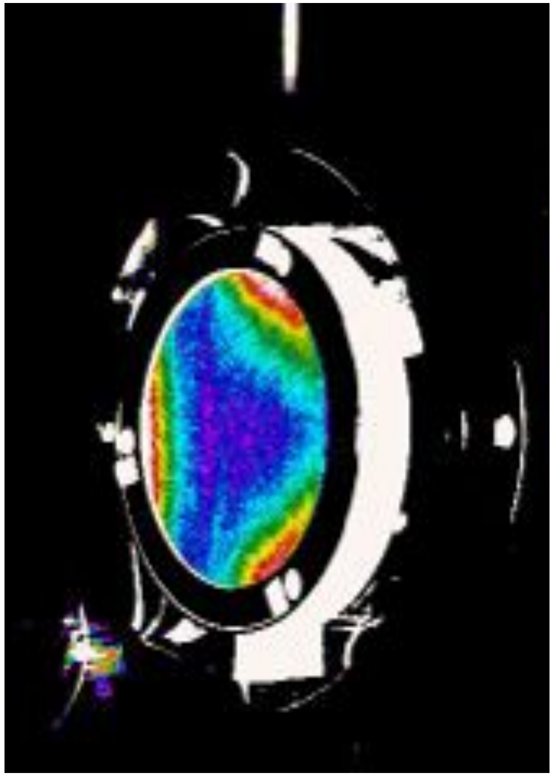


SCF: thermal IR testing and sw modeling

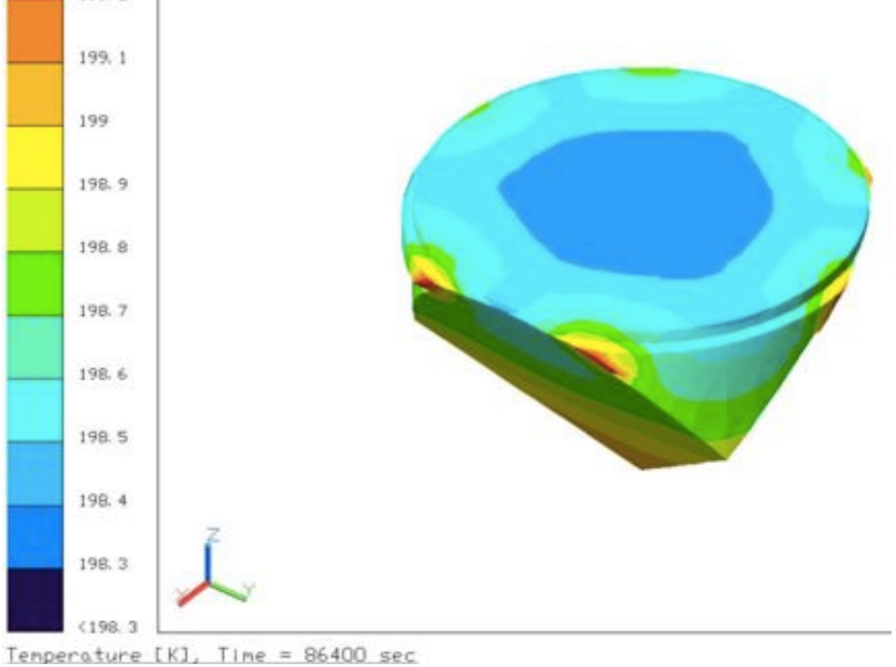
With SCF can measure/model subtle thermal effects, and optimize thermal conductance of retroreflector mounting

SCF-Test

IR Heat Flow Due to Tab Supports



Thermal modeling (noon on Moon)



SCF-Test/Revision-ETRUSCO-2 (ASI-INFN)

- Laboratory-simulated space conditions. Concurrent/integrated:
  - Dark/cold/vacuum
  - **Sun/Albedo AM0 simulators** (2) and Earth IR simulator
  - Non-invasive IR and contact **thermometry**
  - **Laser interrogation and sun perturbation at varying angles**
  - Payload **thermal control**, **roto-translations**
  - Critical orbit configurations (worst-case thermal-optical behavior)
- Deliverables / Retroreflector Key Performance Indicators (KPIs)
  - **Thermal behavior (**τ_{CCR}, thermal relaxation time)
  - **Optical response: Far Field Diffraction Patter, (near-field) Wavefront Fizeau Interferogram**
- Integrated thermal-optical simulations (upon request)

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

The SCF-Test (background IP of INFN)

J. Adv. Space Res. **47** (2011) 822–842

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

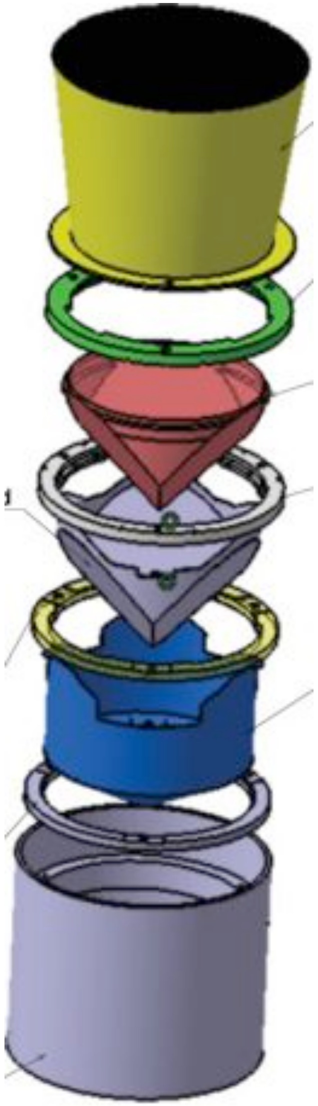
S. Dell'Agnello [a,*], G.O. Delle Monache [a], D.G. Currie [b], R. Vittori [c,d], C. Cantone [a], M. Garattini [a], A. Boni [a], M. Martini [a], C. Lops [a], N. Intaglietta [a], R. Tauraso [e,a], D.A. Arnold [f], M.R. Pearlman [f], G. Bianco [g], S. Zerbini [h], M. Maiello [a], S. Berardi [a], L. Porcelli [a], C.O. Alley [b], J.F. McGarry [i], C. Sciarretta [g], V. Luceri [g], T.W. Zagwodzki [i]

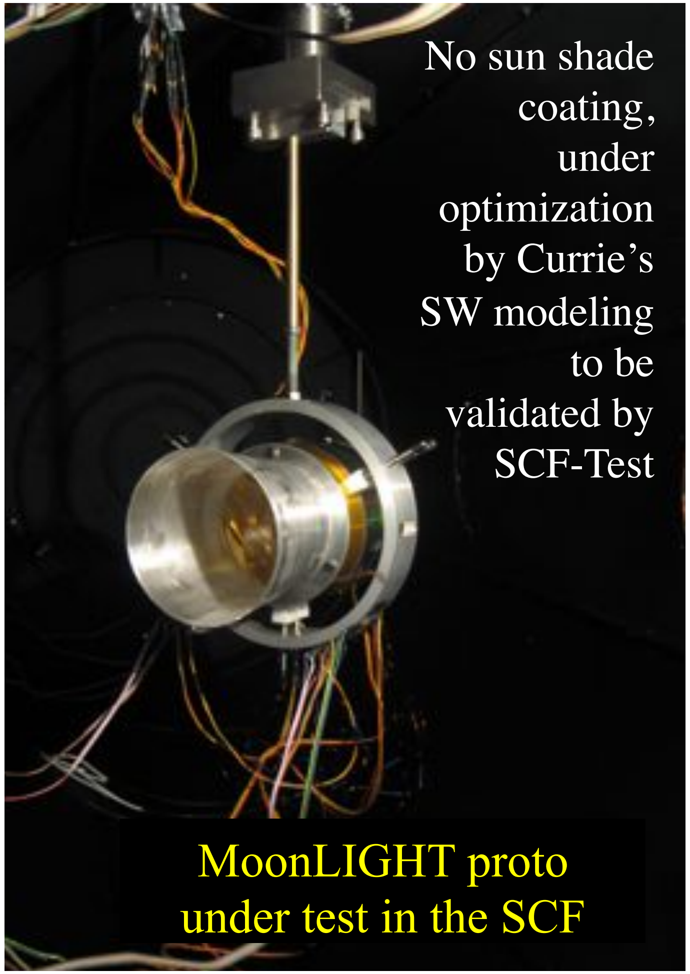
[a] *Laboratori Nazionali di Frascati (LNF) dell'INFN via E. Fermi 40, 00044 Frascati, Rome, Italy*
[b] *University of Maryland (UMD), Department of Physics, John S. Toll Building, Regents Drive, College Park, MD 20742-4111, USA*
[c] *Aeronautica Militare Italiana, Viale dell' Università 4, 00185 Rome, Italy*
[d] *Agenzia Spaziale Italiana (ASI), Viale Liegi 26, 00198 Rome, Italy*
[e] *University of Rome "Tor Vergata", Dipartimento di Matematica, Via della Ricerca Scientifica, 00133 Rome, Italy*
[f] *Harvard-Smithsonian Center for Astrophysics (CfA), 60 Garden Street, Cambridge, MA 02138, USA*
[g] *ASI, Centro di Geodesia Spaziale "G. Colombo" (ASI-CGS), Località Terlecchia, P.O. Box ADP, 75100 Matera, Italy*
[h] *University of Bologna, Department of Physics Sector of Geophysics, Viale Berti Pichat 8, 40127 Bologna, Italy*
[i] *NASA, Goddard Space Flight Center (GSCF), code 694, Greenbelt, MD 20771, USA*

Setting CCR standards @SCF_Lab

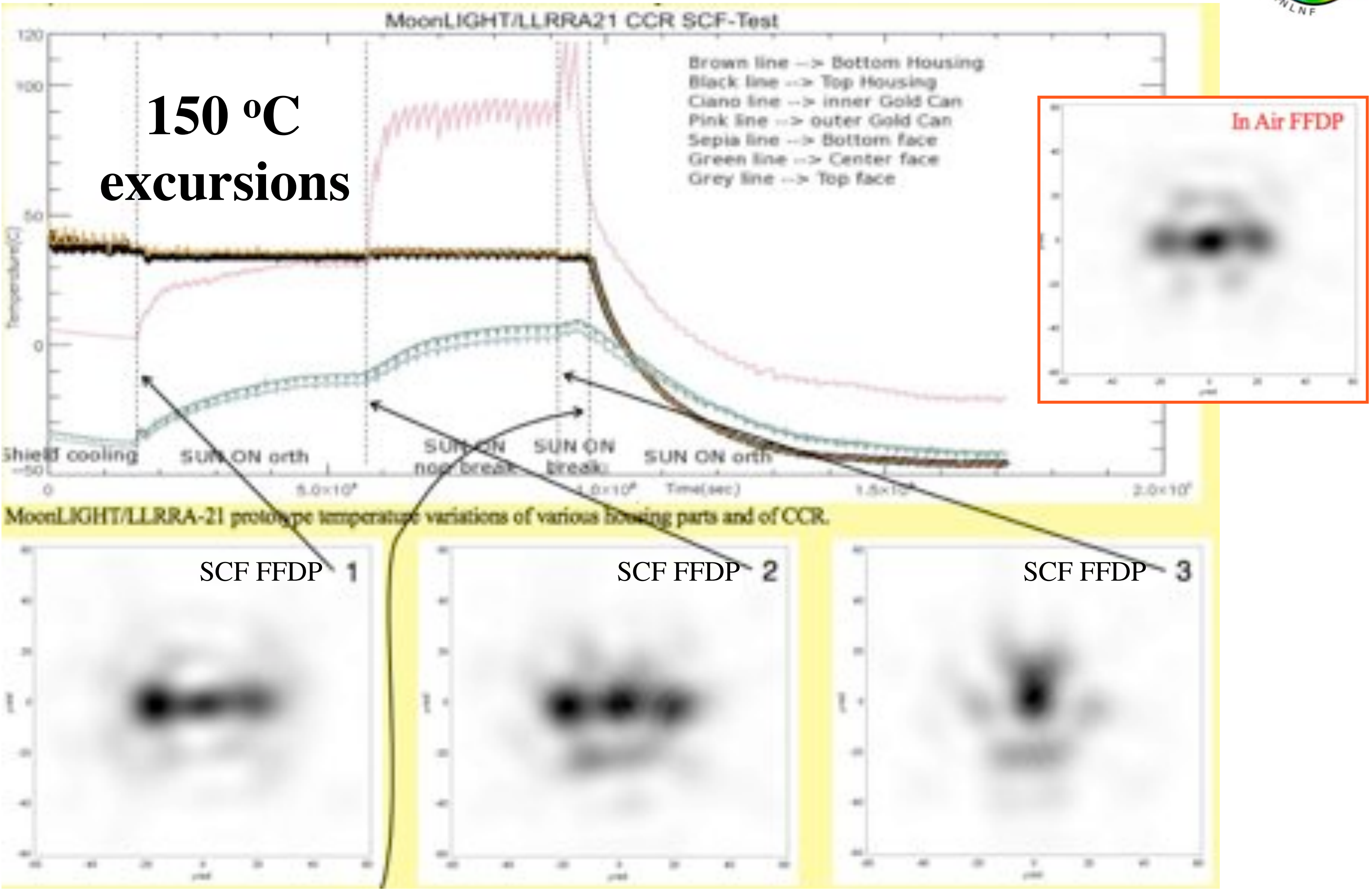
Some young people of the SCF_LAB Team.

SCF-Test of MoonLIGHT prototype

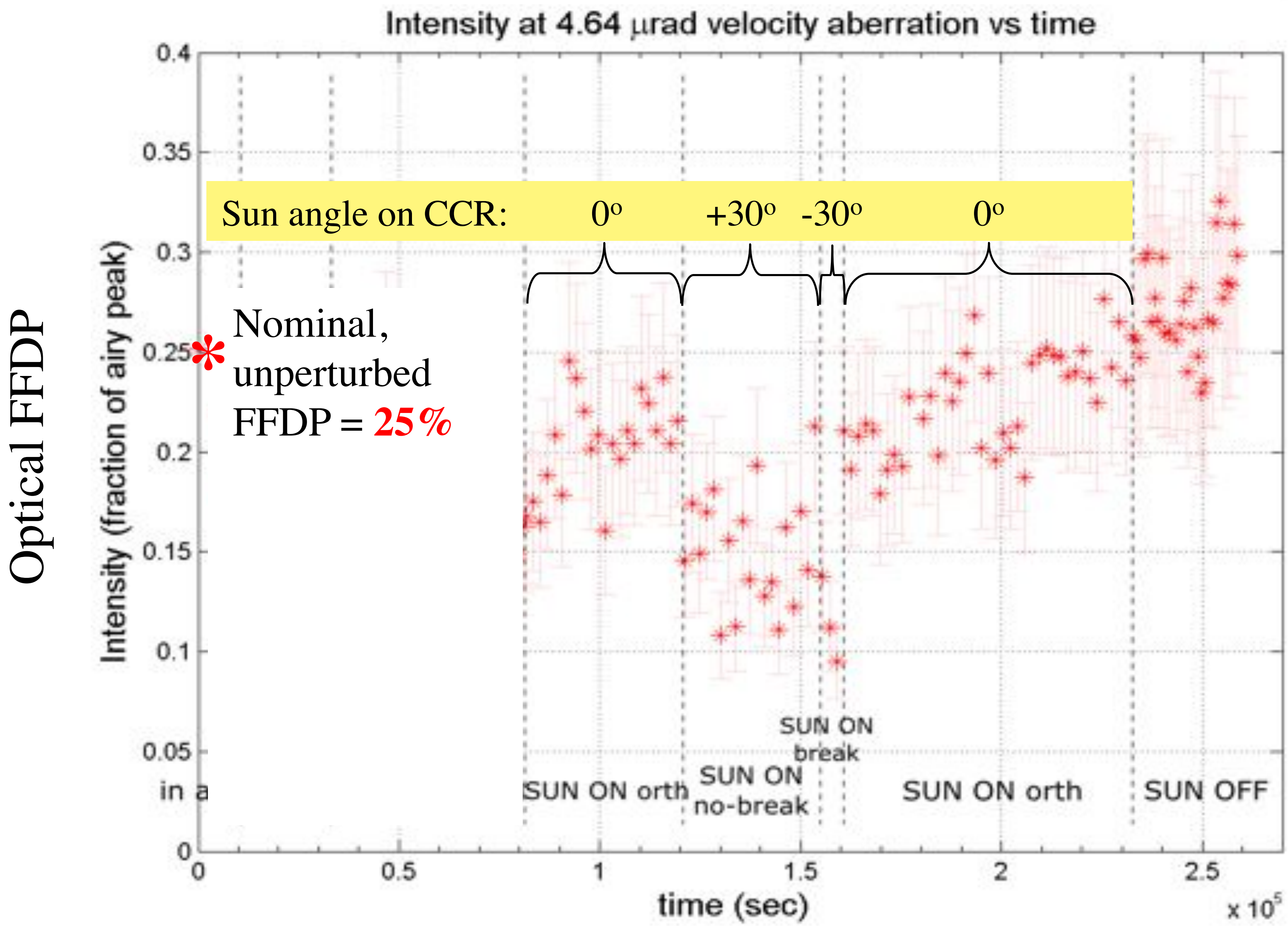




SCF: CCR Temperatures, optical FFDP (no sunshade)



SCF: Optical response of MoonLIGHT (no sun shade)



Experiment of INFN National Scientific Committee 2 (CSN2) for 2013-2018:

MoonLIGHT-2

Moon Laser Instrumentation for General relativity High accuracy Tests – Phase 2

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

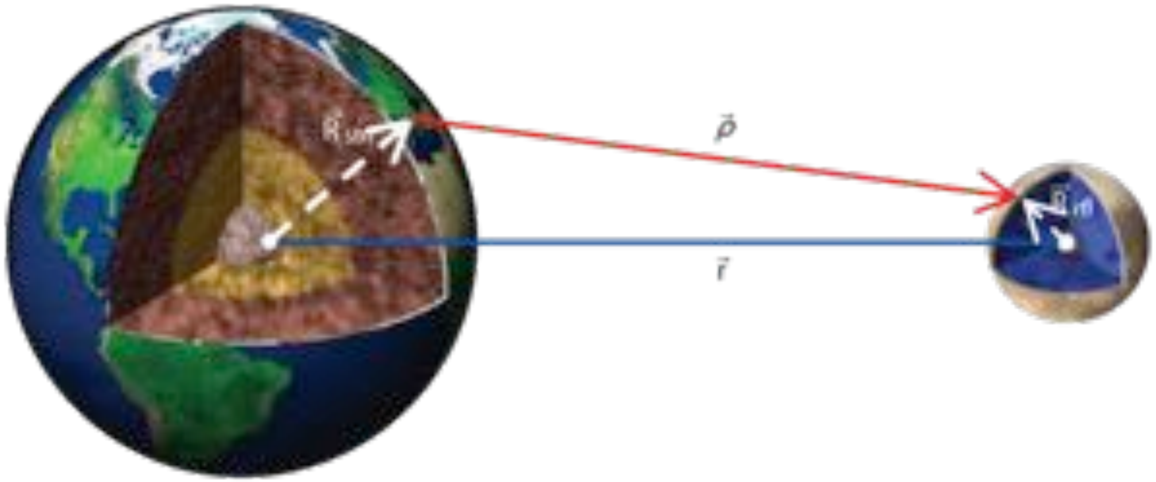
SCF_Lab

Satellite/Lunar/GNSS laser ranging and altimetry **C**haracterization **F**acilities **Lab**oratory

Lunar Laser Ranging (LLR) Science

- Suite of precision tests of General Relativity (GR) with single experiment
- Study of lunar geophysics (Selenodesy)
- Lunar Geophysical Network (LGN)

ITRF:
ILRS, IGS, IVS, IDS stations



IMRF:
Apollo/Lunokohd, MEX, Astrobotic, C-ILN/GLXP, SELENE-2, Chandrayaan-2, LGN landers/rovers

ITRF/IMRF: International Terrestrial/Moon Reference Frame

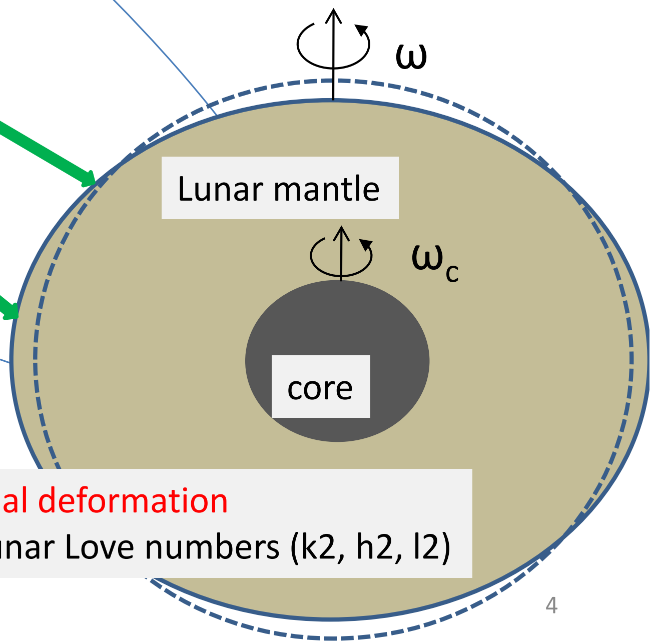
LLR science GR and Selenodesy

Science with LLR

Observable
- Ranges between Earth/lunar surface

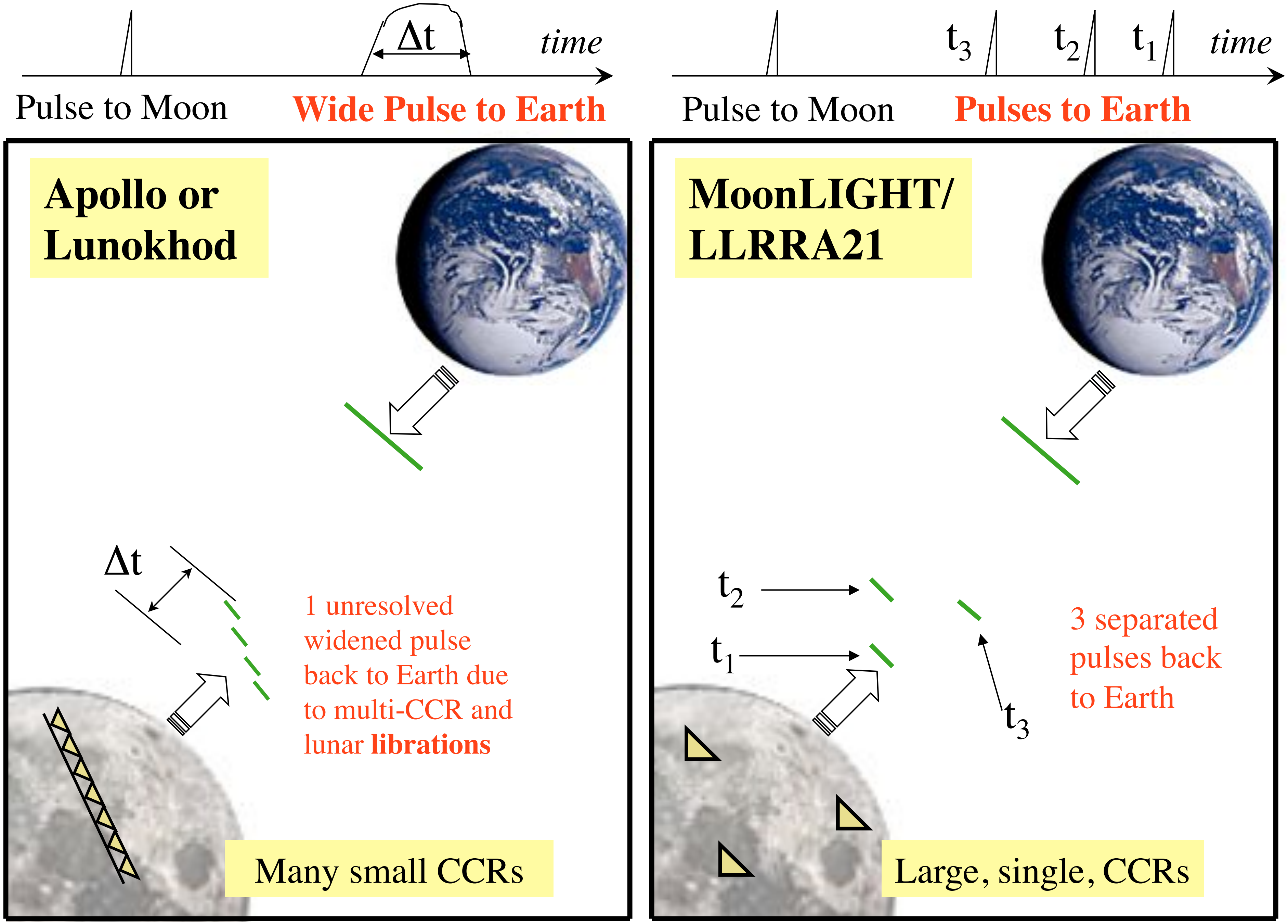
Rotation (difference from Cassini state)
- Total moment of inertia(MOI)
- Dissipation by core-mantle coupling & oblate fluid core
- core MOI/mantle MOI ratio

Lunar orbit
- Lunar GM
- $\dot{G}/G$
- Gravitational physics

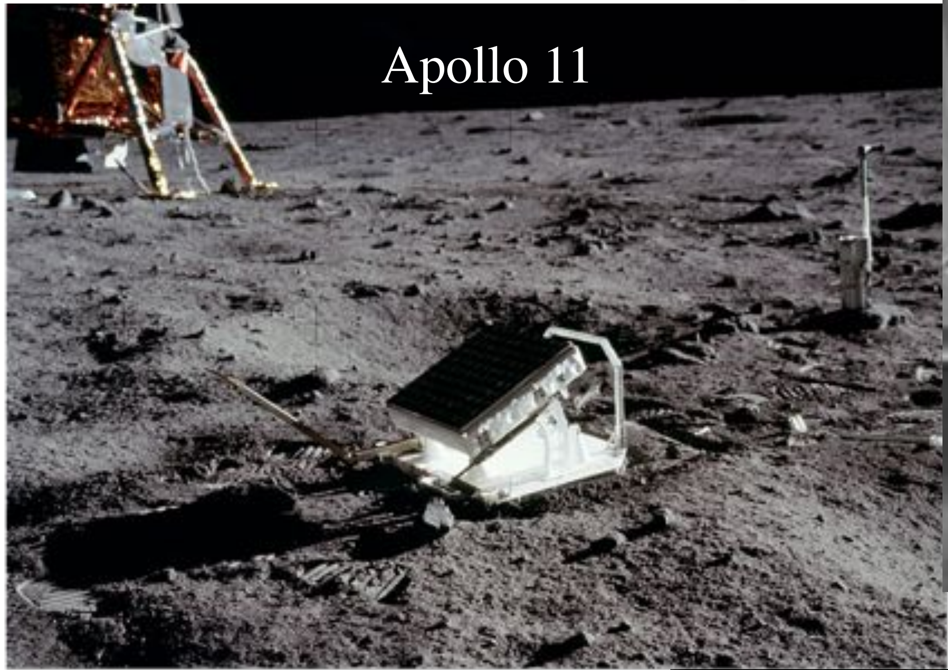


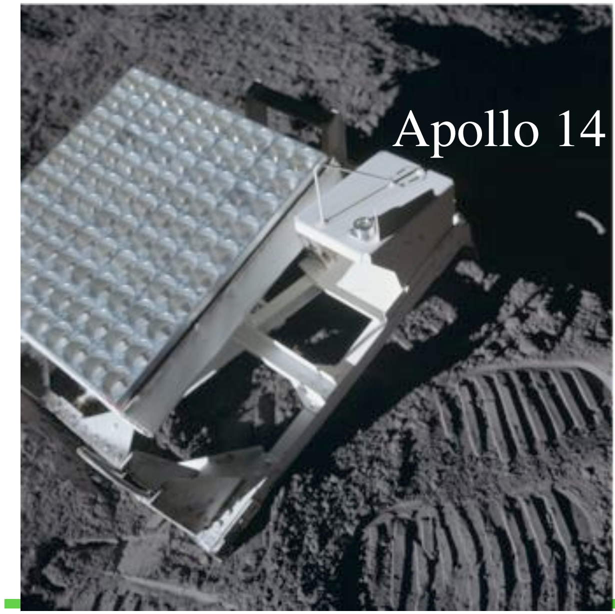
Tidal deformation
- Lunar Love numbers (k2, h2, l2)

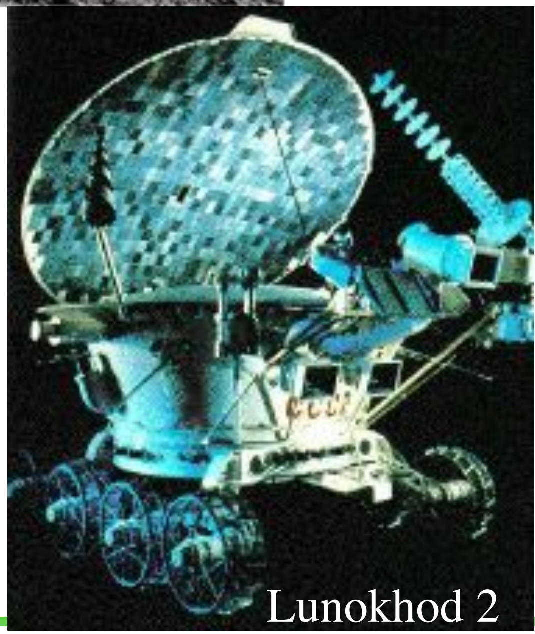
Final goals:
- radius and state of the lunar core
- bulk composition of the Moon

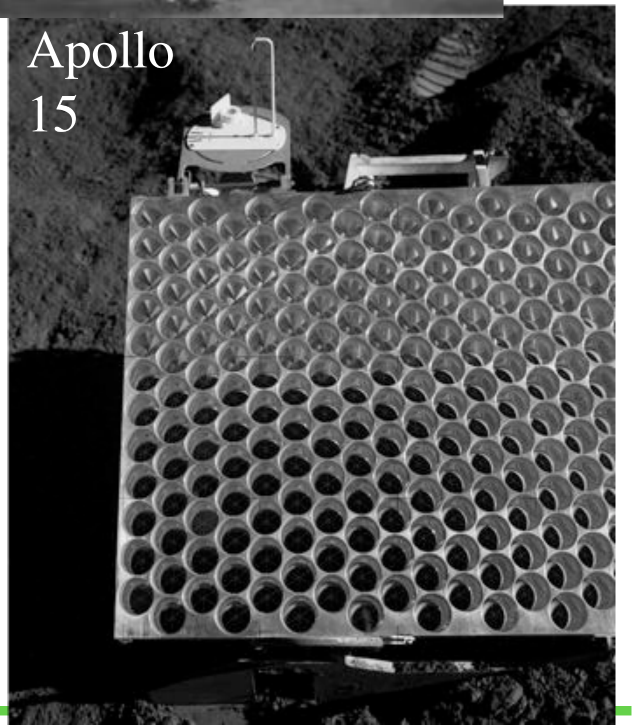

Δt
time
Pulse to Moon
Wide Pulse to Earth
Apollo or Lunokhod
Δt
1 unresolved widened pulse back to Earth due to multi-CCR and lunar **librations**
Many small CCRs
t_3
t_2
t_1
time
Pulse to Moon
Pulses to Earth
MoonLIGHT/ LLRRA21
t_2
t_1
t_3
3 separated pulses back to Earth
Large, single, CCRs

Current LLR arrays

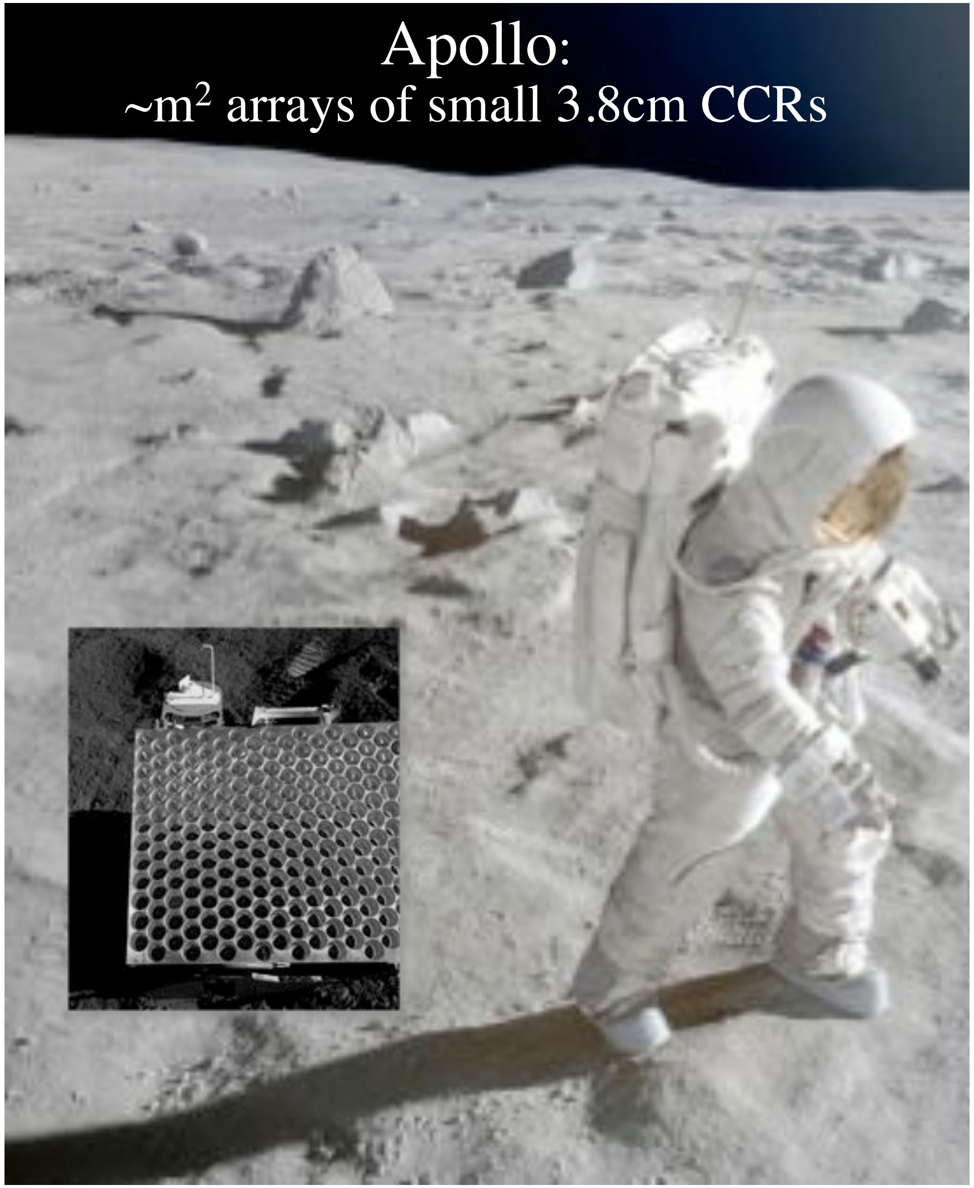




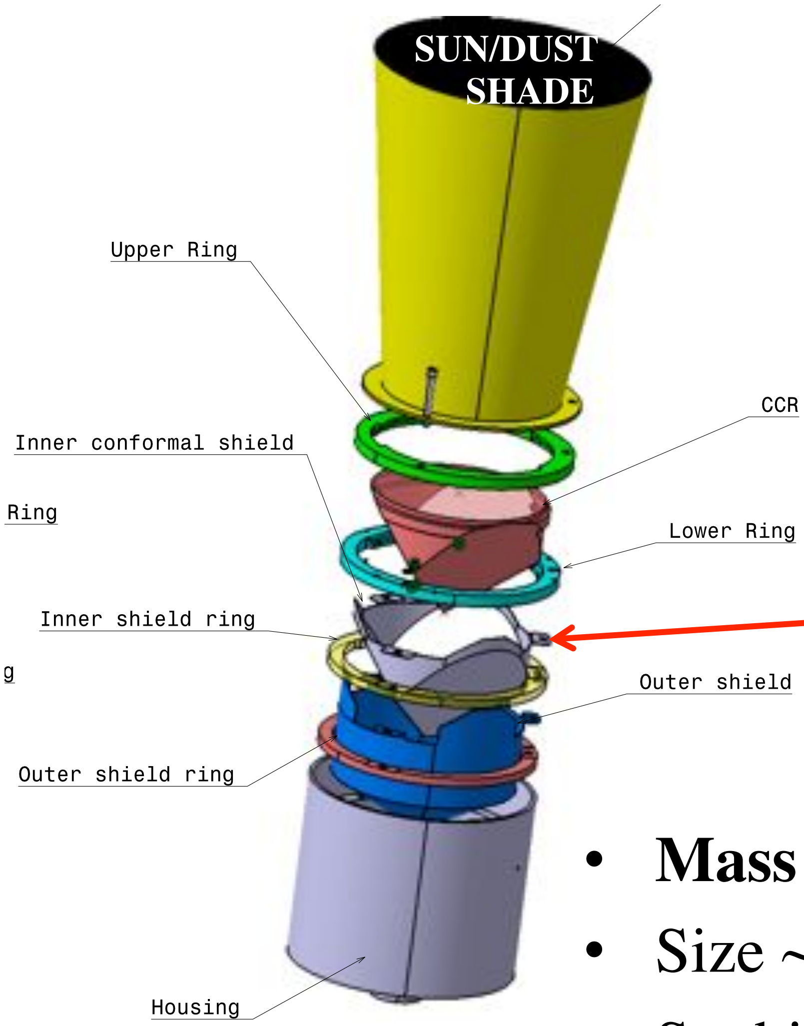




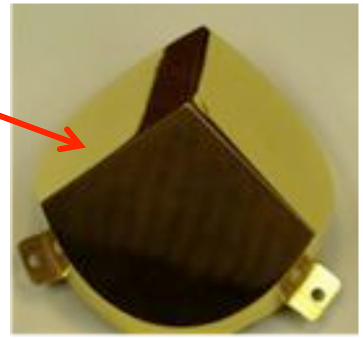
MoonLIGHT / LLRRA21 (cartoon no to scale)



MoonLIGHT cube corner reflector (CCR)



INNER
CONFORMAL
THERMAL SHIELD
(Au-Ag coated)

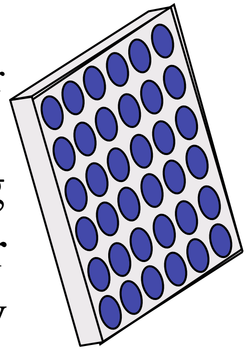


- **Mass ~ 1.7 kg**
- Size ~ 150mm (r) x 300mm (h)
- Sophisticated thermal design (sun heat shade, 2 internal heat shields), tight optical specs

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



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

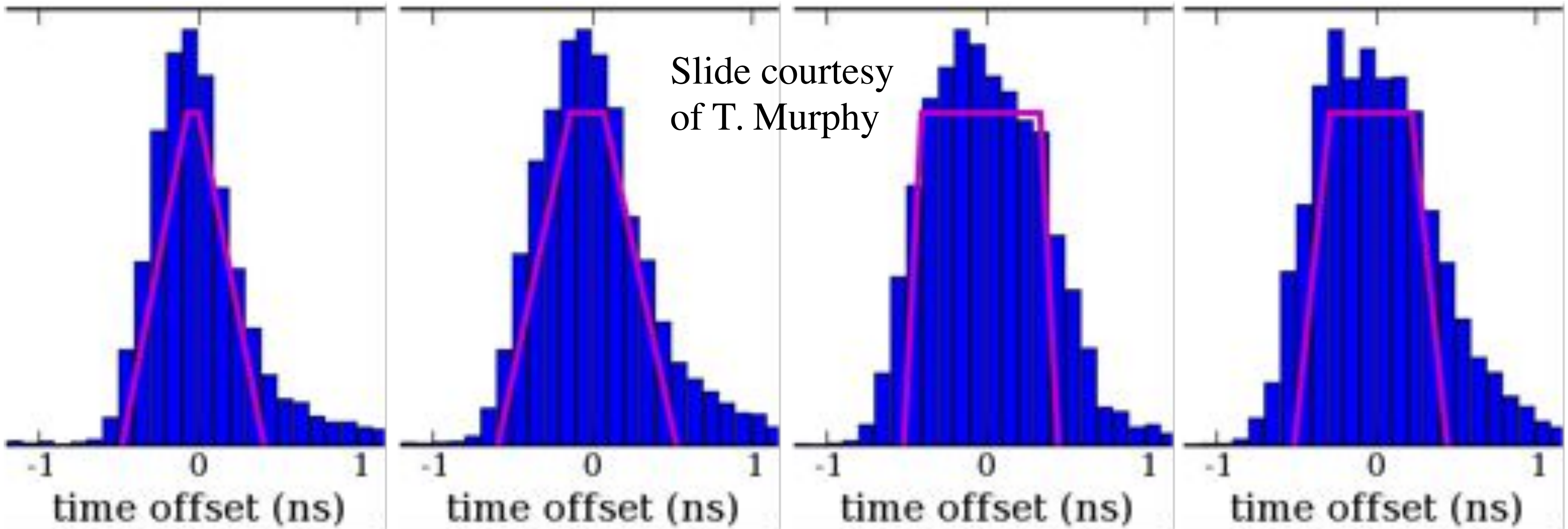
Slide
courtesy of
S. Merkowitz

Sensing Array Size/Orientation of Apollo reflectors

Effect of multi-CCR array orientation due to lunar librations

Apollo 11 | Apollo 15

2007.10.28 | 2007.10.29 | 2007.11.19 | 2007.11.20

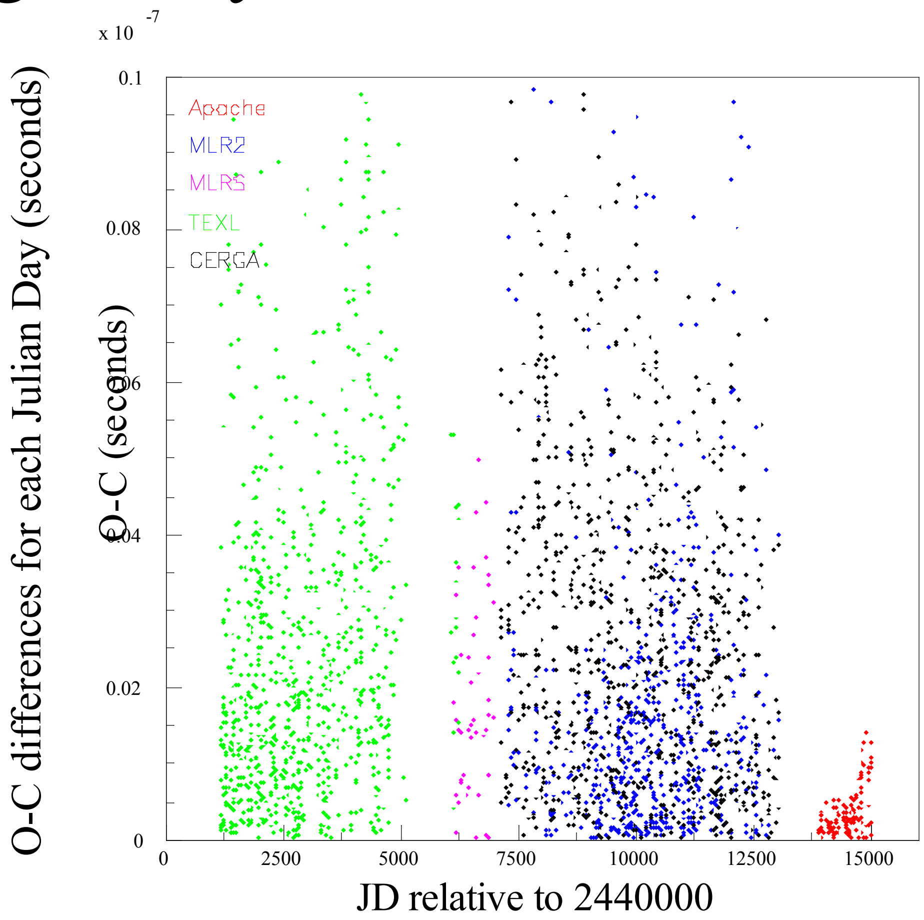


Apollo arrays: to get 2 cm range out of +/- 1 nsec ToF distribution, thousands of laser returns are needed. With MoonLIGHT: with just 1 return we get a mm/sub-mm range

LLR 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

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**

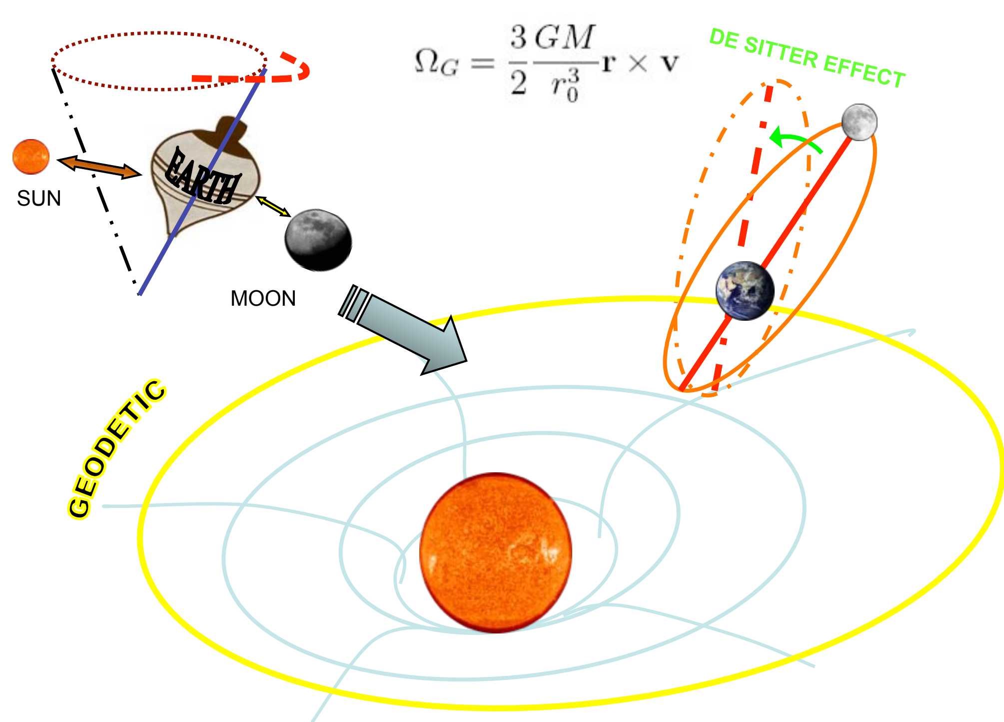
Number of laser returns to make a “standard” ~2-cm LLR range:

- **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 with CfA’s software (Planetary Ephemeris Program): ~ 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

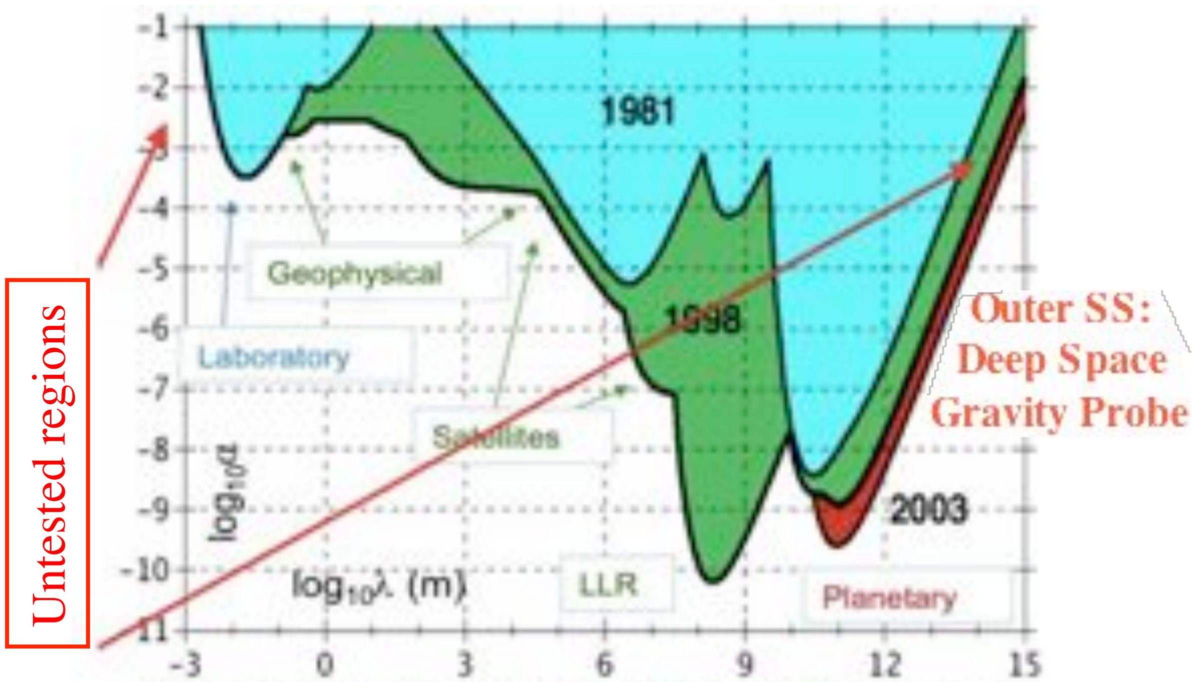
Limits on $1/r^2$ deviations in the Solar System

MoonLIGHT designed to provide accuracy of 100μm or better on tspace segment (the CCR), if deployed by drilling the regolith (Lunar Google X Prize, Astrobotic mission)

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

Limits on additional Yukawa potential:

$\alpha \times$ (Newtonian-gravity) $\times\ e^{-r/\lambda}$



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

Unique to LLR: test Strong EP (and PPN β)

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:

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

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

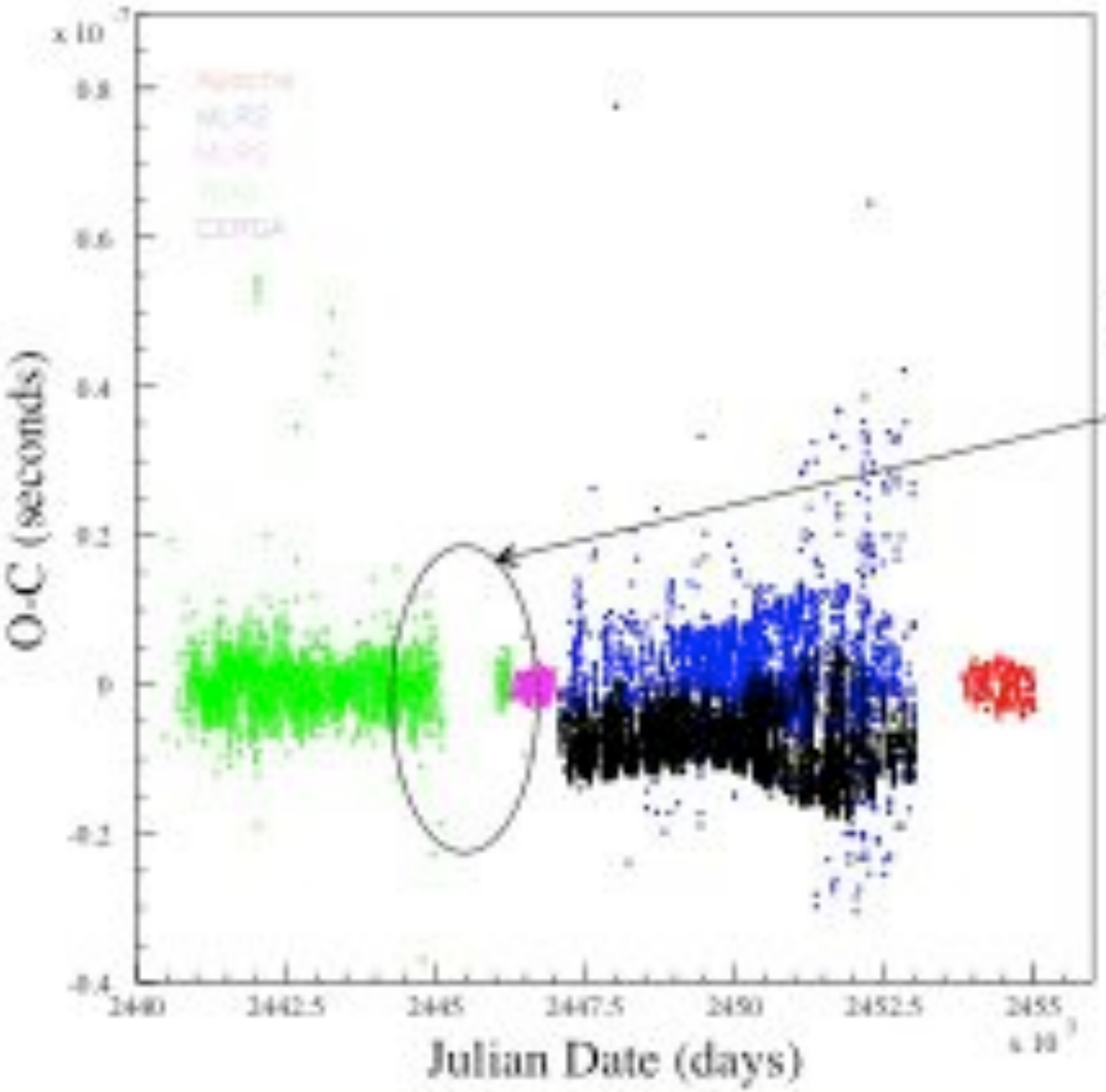
- Subtracting UW from LLR results one gets the SEP test:

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

- **Assuming Nordtvedt effect: limit PPN parameter β at 10^{-4}**

SEP can only be tested LLR

LLR Time-of-Flight residuals with PEP



Data by station from 1980s to 2009

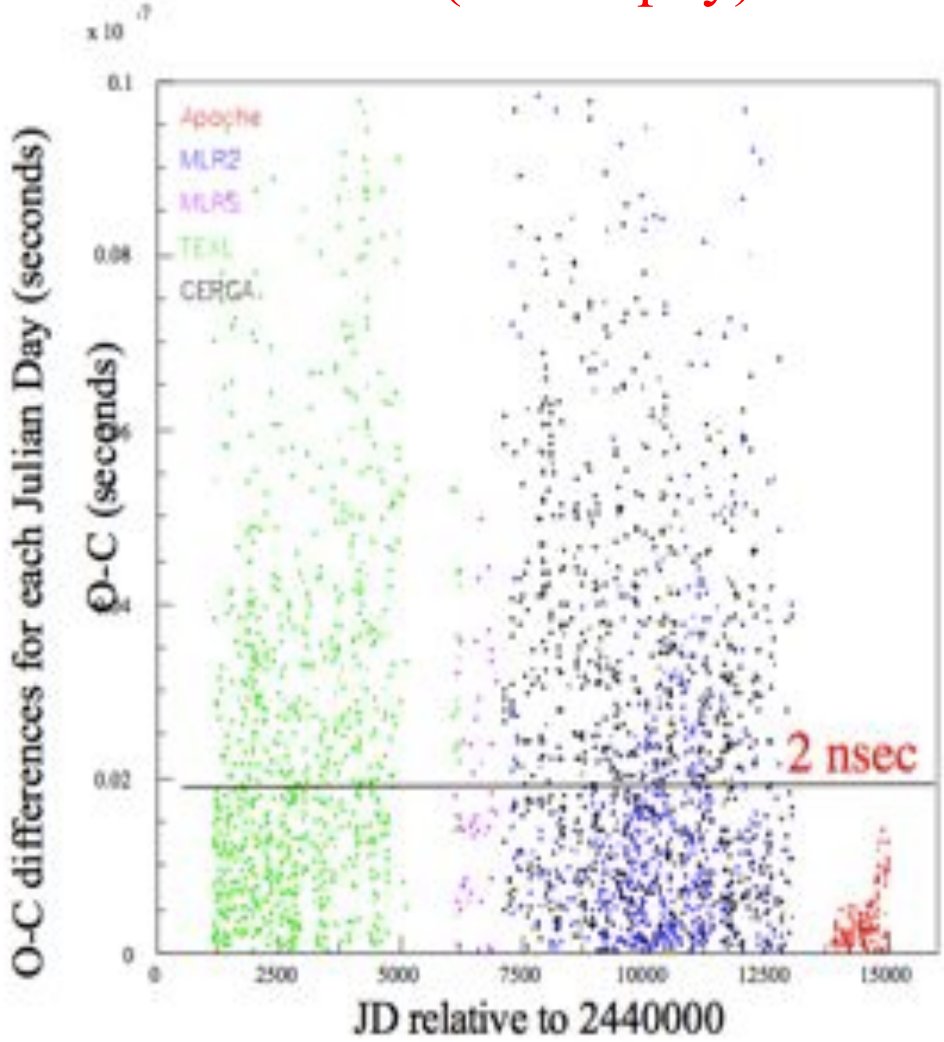
Red: dedicated APOLLO station, optimized performance

Rotation/Librations: well measured by LNF

1980s to 2009 Red: dedicated APOLLO station (T. Murphy)

We study the quantity ||max(O-C)|-|min(O-C)|| for days where multiple measurements were recorded for Apollo 11, 14 and 15.

This difference is small, showing that the relative Earth rotations and lunar librations are well modeled by PEP



Test of geodetic precession $\mathbf{K_{GP}}$ with LLR

- 5th test of General Relativity
- First measured at **2% accuracy** in 1988 by Shapiro et al

- CfA+LNF current accuracy with PEP, Apollo arrays and APOLLO laser station: **1%**
  - M. Martini et al, Planetary and Space Science 74 (2012) 276–282

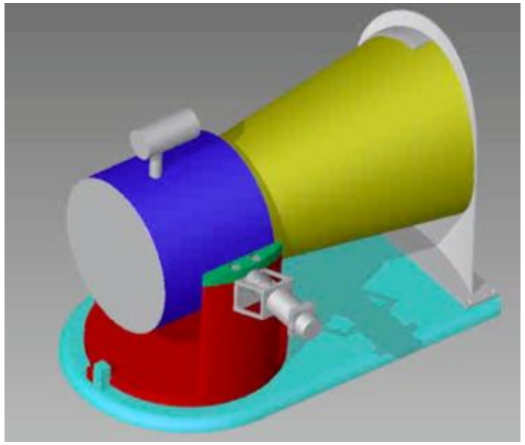
- Comparable with accuracy by JPL **=0.64%**
  - J. G. Williams et al, PRL 93, 261101 (2004)

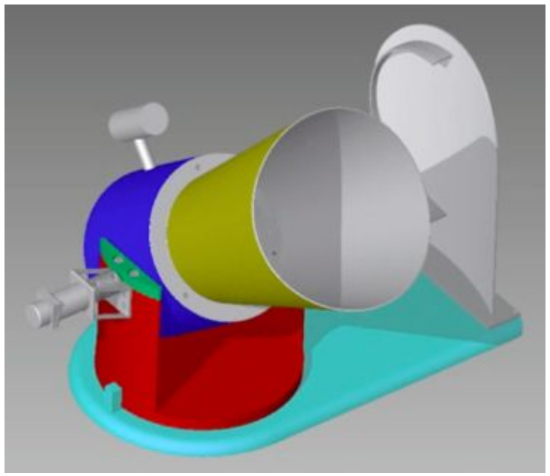
- Gravity Probe B final result on GP, accuracy: **=0.28%**
  - C.W. F. Everitt et al, PRL 106, 221101 (2011)

MoonLIGHT Pointing System (MPS)

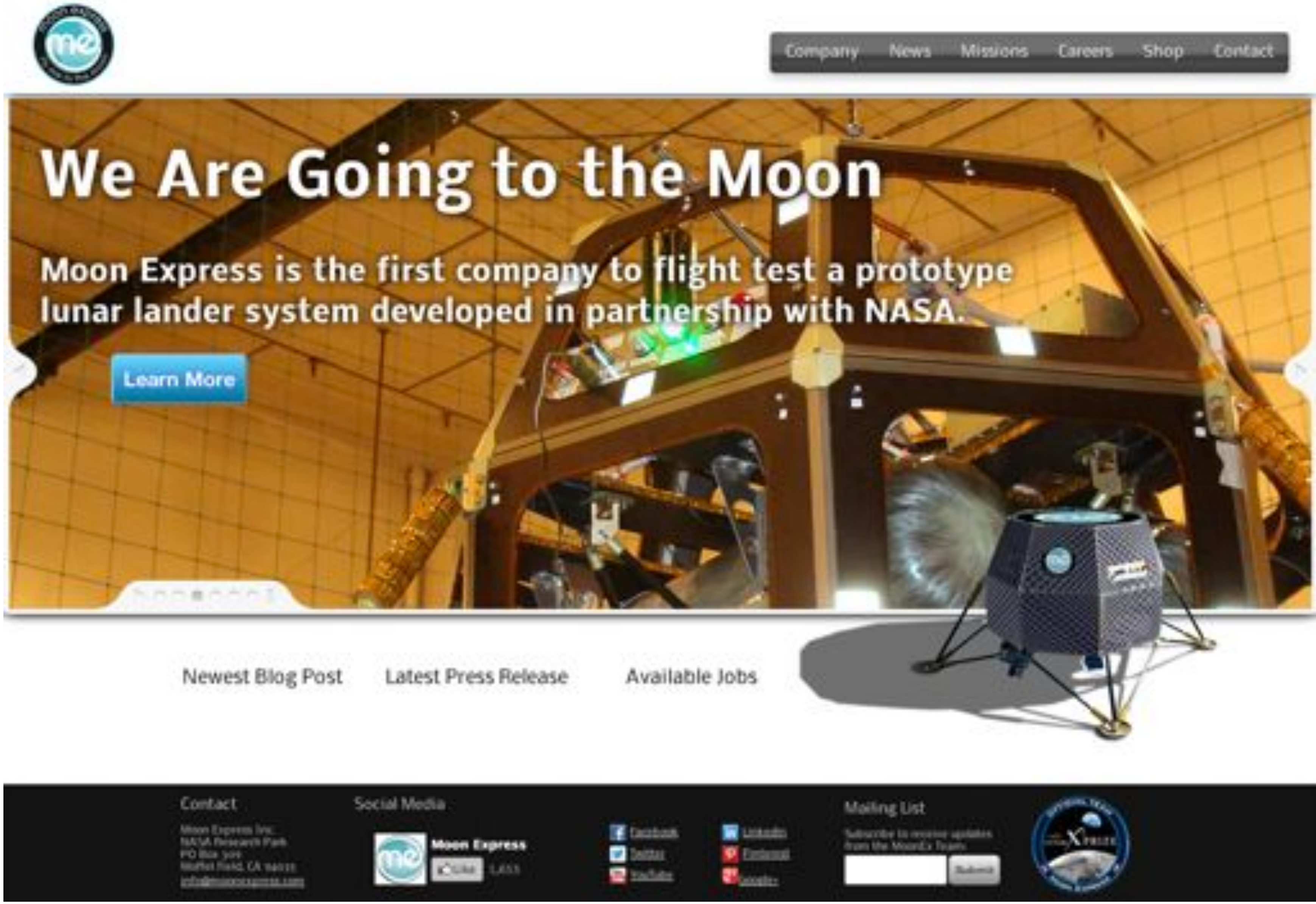
Two motors + CCD (to locate Earth and point it after landing)
Stowage screen (for dust protection during landing); **~1.3 kg**

- Pointing requirement: about +/- 2°
- MoonLIGHT Needs an Automatic Pointing System
- Needs Only a Start Pulse
- Operational Sequence (at equator site)
  - Point to Zenith
  - Take a Camera Exposure
  - Fit Earth Image (On-Board)
  - If Missing -Search off Zenith
- Lock Brakes

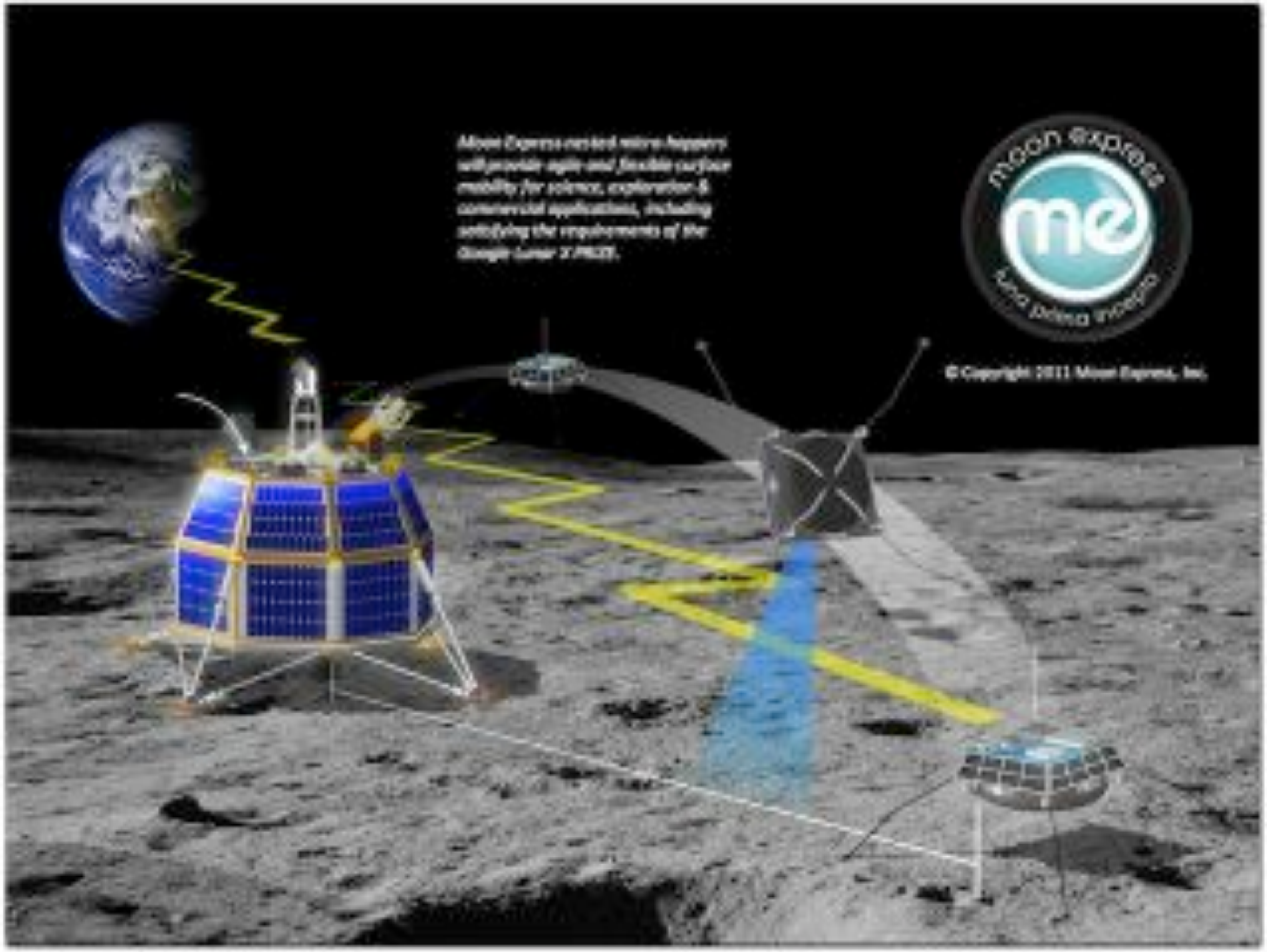




Moon Express-1 Mission to the Moon



Moon Express-1 Mission Concept

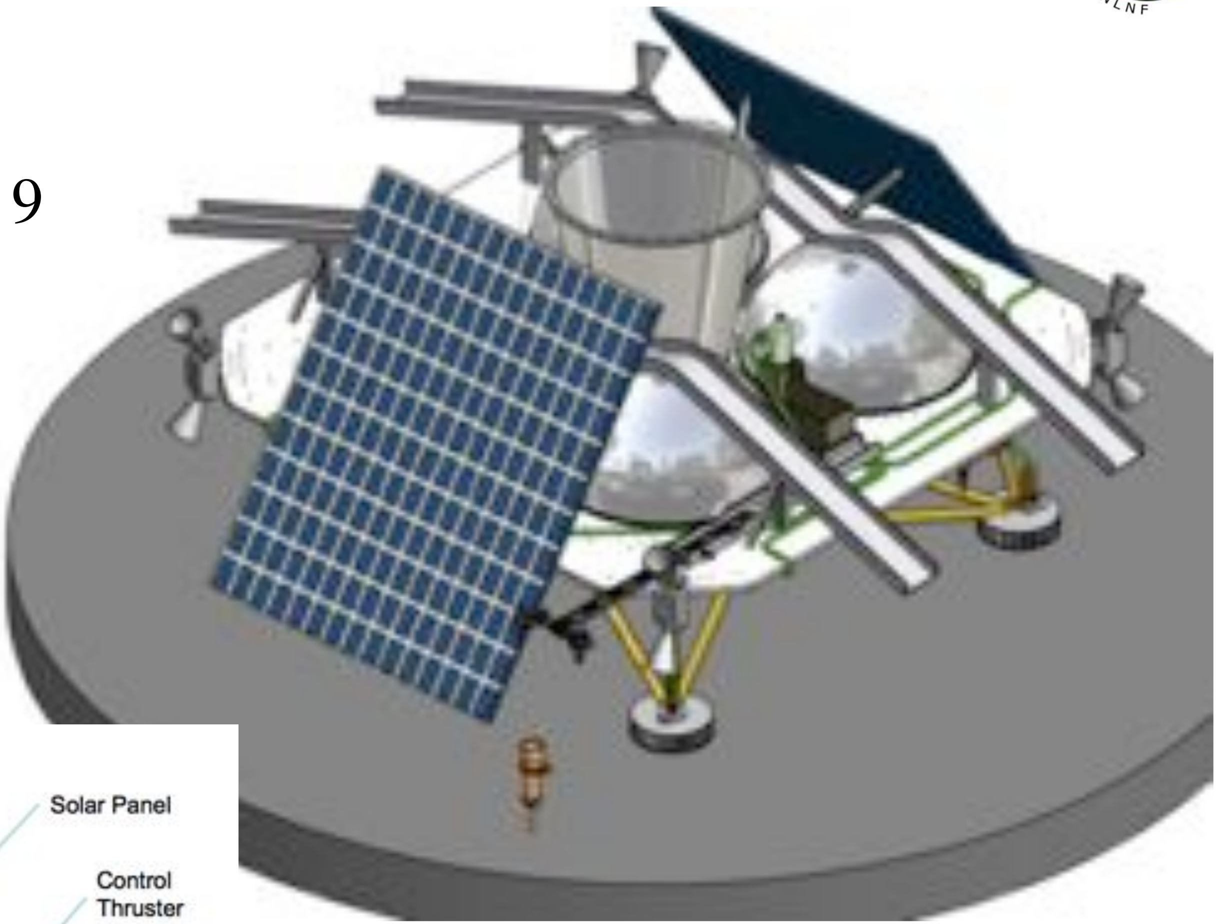


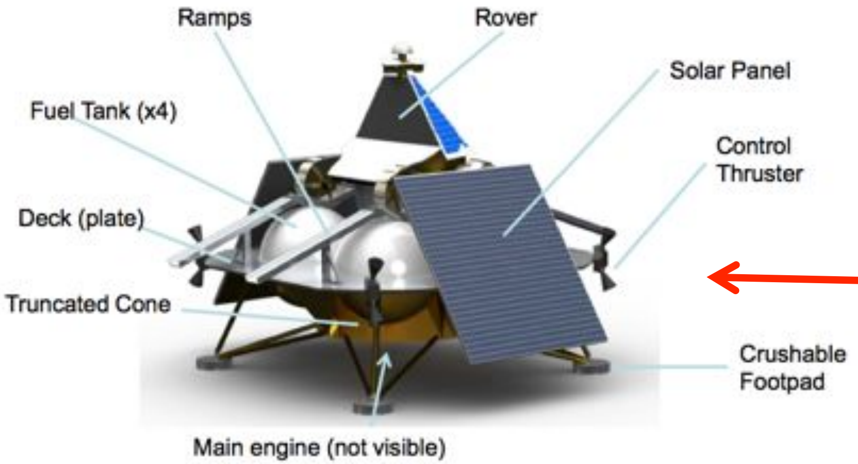
MoonLIGHT on MEX-1 top deck

Launch by Dec 2105

Astrobotic Landing Mission to the Moon

'Griffin' lander. Launch
by Space X with Falcon 9
On October 2015





From
Payload User Guide 3.0

Acronyms and definitions

1. AM0: Air Mass Zero
2. ASI: Agenzia Spaziale Italiana
3. BT: Break Through
4. CCR: Cube Corner Retroreflector
5. EO = Earth Observation
6. ESA: European Space Agency
7. ETRUSCO: Extra Terrestrial Ranging to Unified Satellite Constellation
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. TIR: Total Internal Reflection
26. WI: Wavefront Interferogram

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