MoonLIGHT-2 & SCF_Lab

Test of fundamental gravity with laser ranging and altimetry to Moon(s) and planets

Simone Dell'Agnello (INFN-LNF), D. Currie (U. of Maryland), et al
INFN (Italian National Institute for Nuclear Physics)
LNF (Frascati National Labs)

Quantum to Cosmos 6 (Q2C6)
Nice-Cemelenum-Nikaia, Oct. 17, 2013

SCF_Lab

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

A 5-Year Research Program on

High Accuracy Tests of General Relativity and New Gravity Theories,

Planetary Exploration, Geodesy, Positioning services

with Laser Retroreflectors on

Earth's Moon,
(Exo)Mars,
Europa and Encelado

"MoonLIGHT-2" experiment approved by INFN-CSN2

ASI: positive feedback; further on-going evaluation

Acknowledgments, International Partners

Acknowledgments:
ILRS lunar stations:
APOLLO (USA)
GRASSE/CERGA (Fra)
McDonald (USA)
Tahiti (USA)
MLRO (Ita)

Acknowledgments:
ASI, NASA,
INFN,
University of
Maryland,
NSF

International Collaborations

Univ. of Maryland at College Park - D. Currie
(LLRRA21: LLR Array for the 21 century; Apollo)

H-S Center for Astrophysics (CfA),
J. Chandler, I. Shapiro

Instituto Superior Tecnico Lisboa, Univ. Porto
O. Bertolami, J. Paramos

Univ. of California at San Diego (UCSD)
APOLLO lunar laser ranging station, T. Murphy

NASA-GSFC, S. Merkowitz, J. McGarry

International Communities

International Laser Ranging Service (ILRS)
NASA SSERVI (formerly NLSI), NASA-ARC
Commercial International Lunar Network (C-ILN)

Italian Collaborations

ASI - Centro di Geodesia Spaziale (CGS), G. Bianco
Ministry of Defense, R. Vittori

INFN, SCF_Lab Team

INFN-LNF (~16 FTE)

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

SCF_Lab located right next to
ESA-ESRIN
Frascati (Rome), Italy

Students

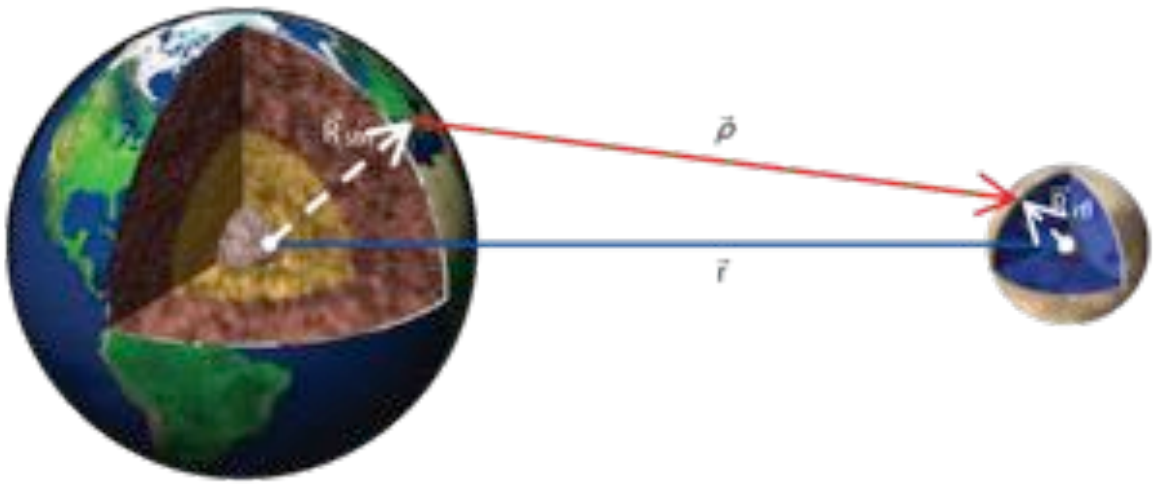
F. Piergentili, G. Capotorto,
M. Marra, N. Castel-Branco,
D. McElfresh, R, Heller,
G. Hosseinzadeh

Several INFN-LNF Technical Support Services
(part of Research, Accelerator and Technical Divisions)

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/Lunokhod, MEX, Astrobotic, C-ILN/GLXP, SELENE-2, Chandrayaan-2, LGN landers/rovers

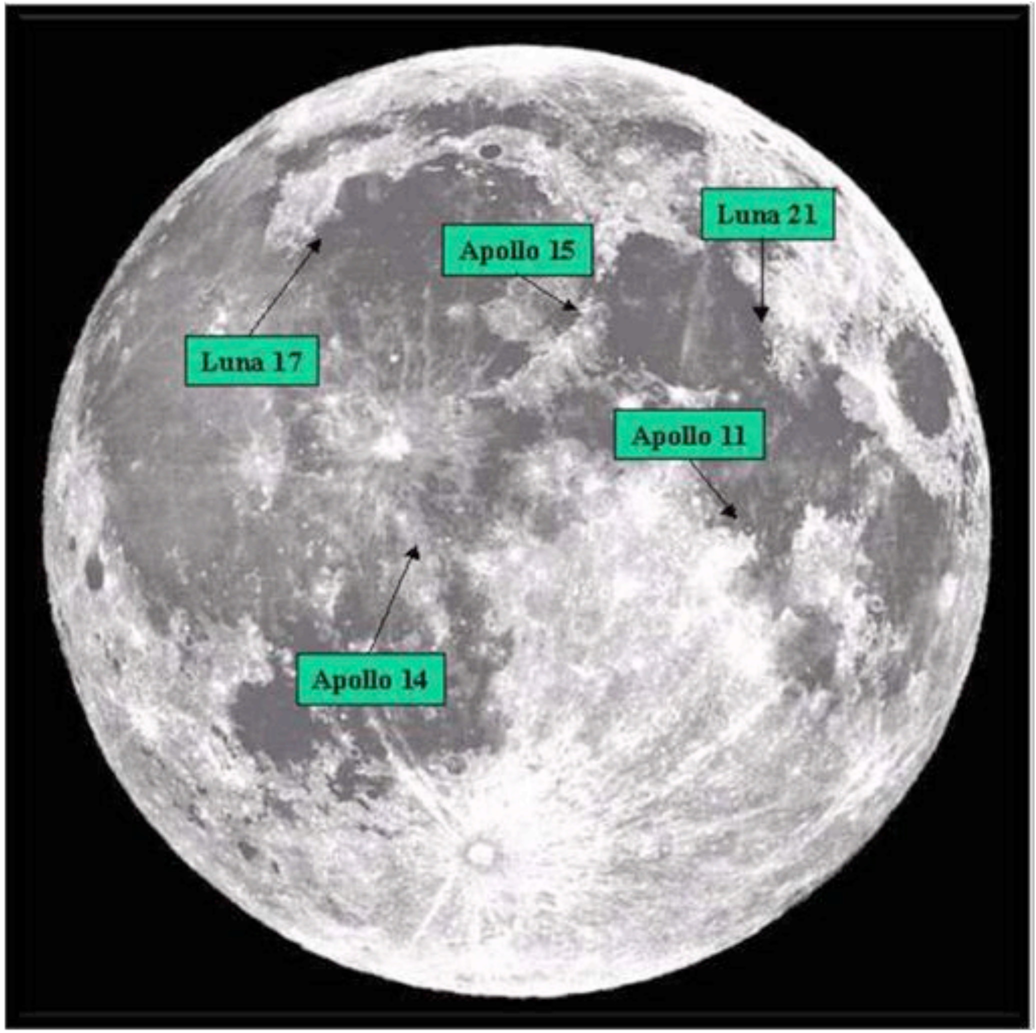
ITRF/IMRF: International Terrestrial/Moon Reference Frame

Apollo/Lunokhod Lunar Laser Ranging (LLR)

Laser retroreflector Arrays (LRAs) of CCRs

SLR (Satellite Laser Ranging) and LLR are time-of-flight measurements of short laser pulses to Cube Corner laser Retroreflectors (CCRs)

SLR defines the geocenter and, with VLBI, **the scale of length** of the International Terrestrial Reference System (ITRS)

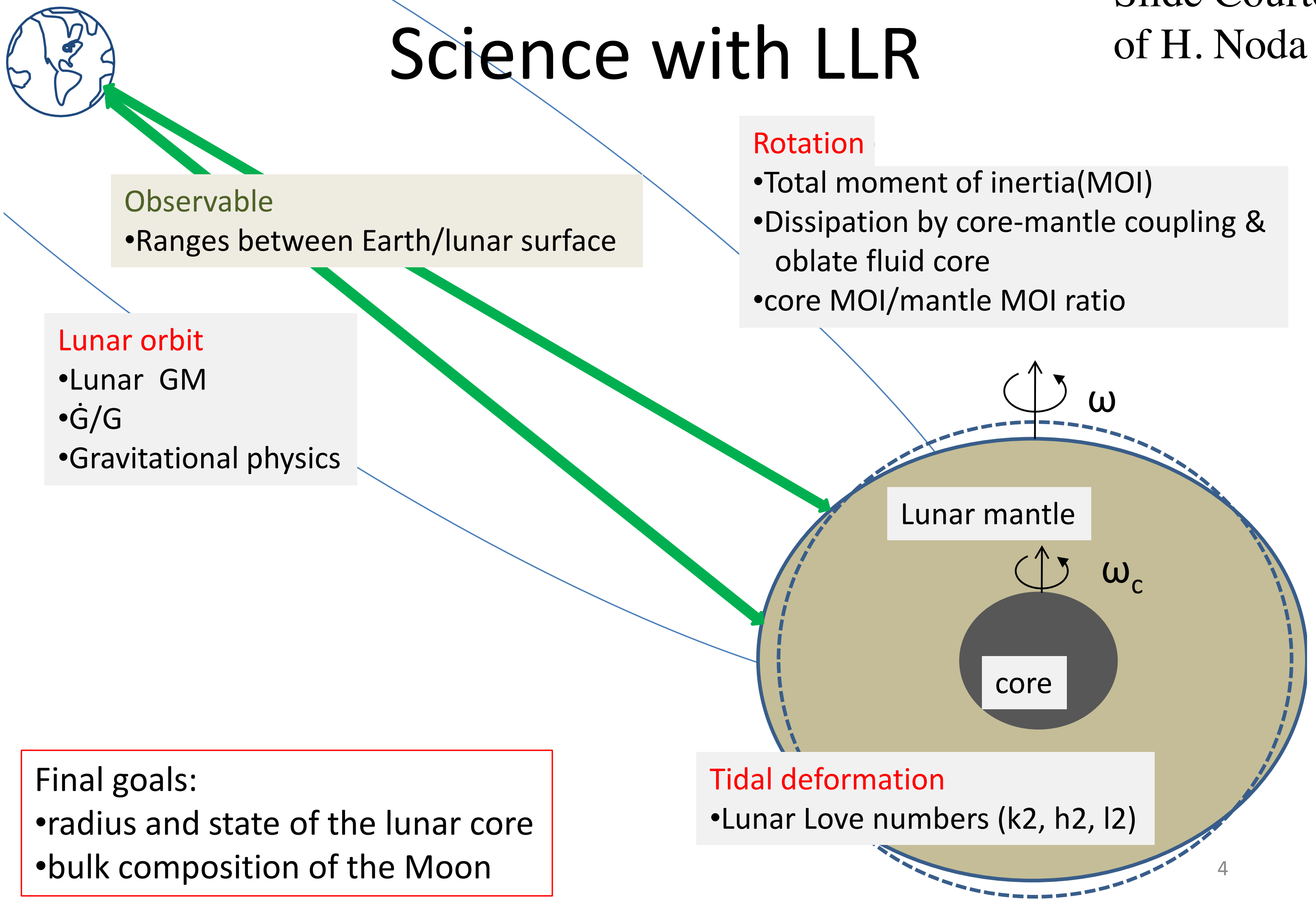


SLR (Satellite Laser Ranging)

Not only GR: Selenodesy with LLR

Slide Courtesy of H. Noda

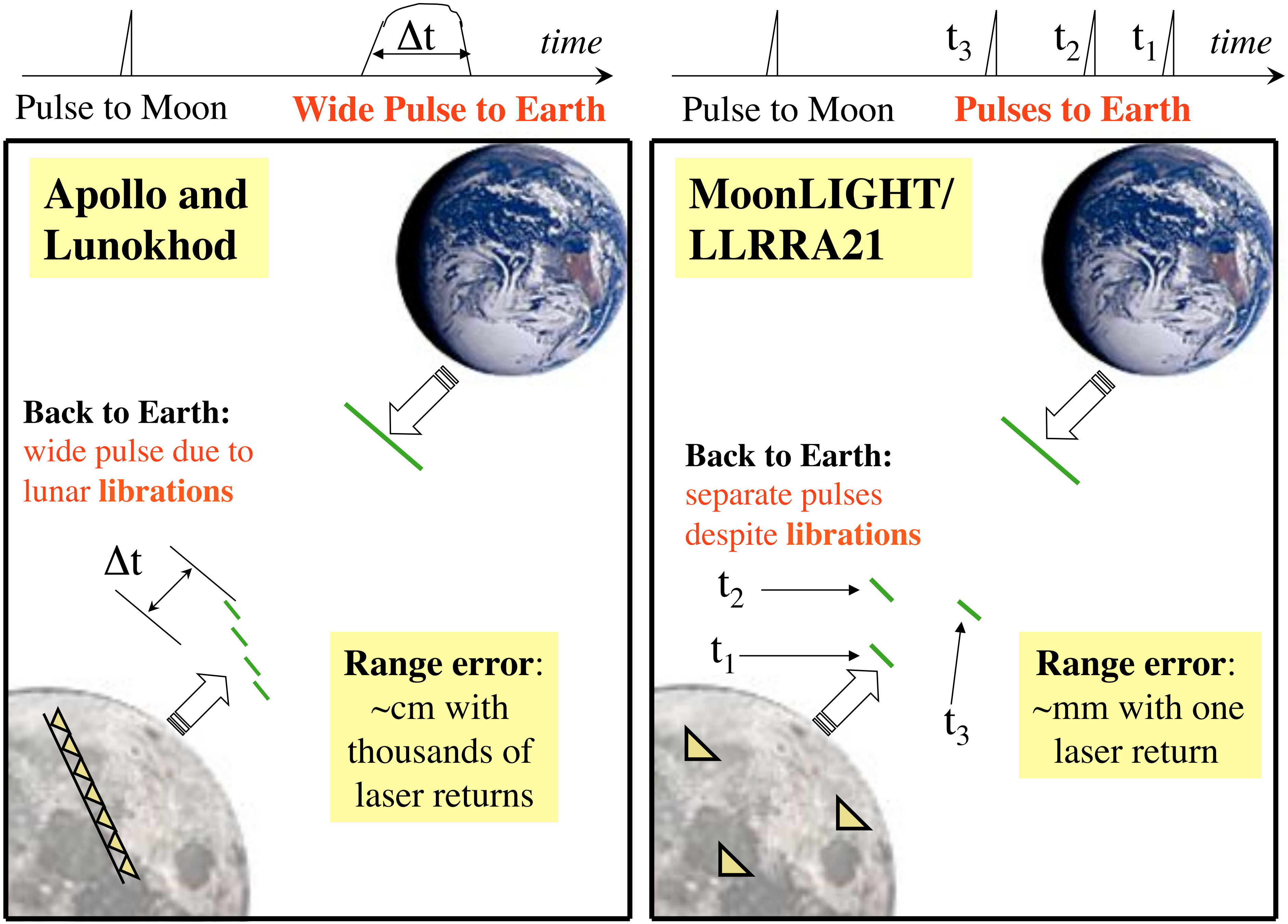
Science with LLR



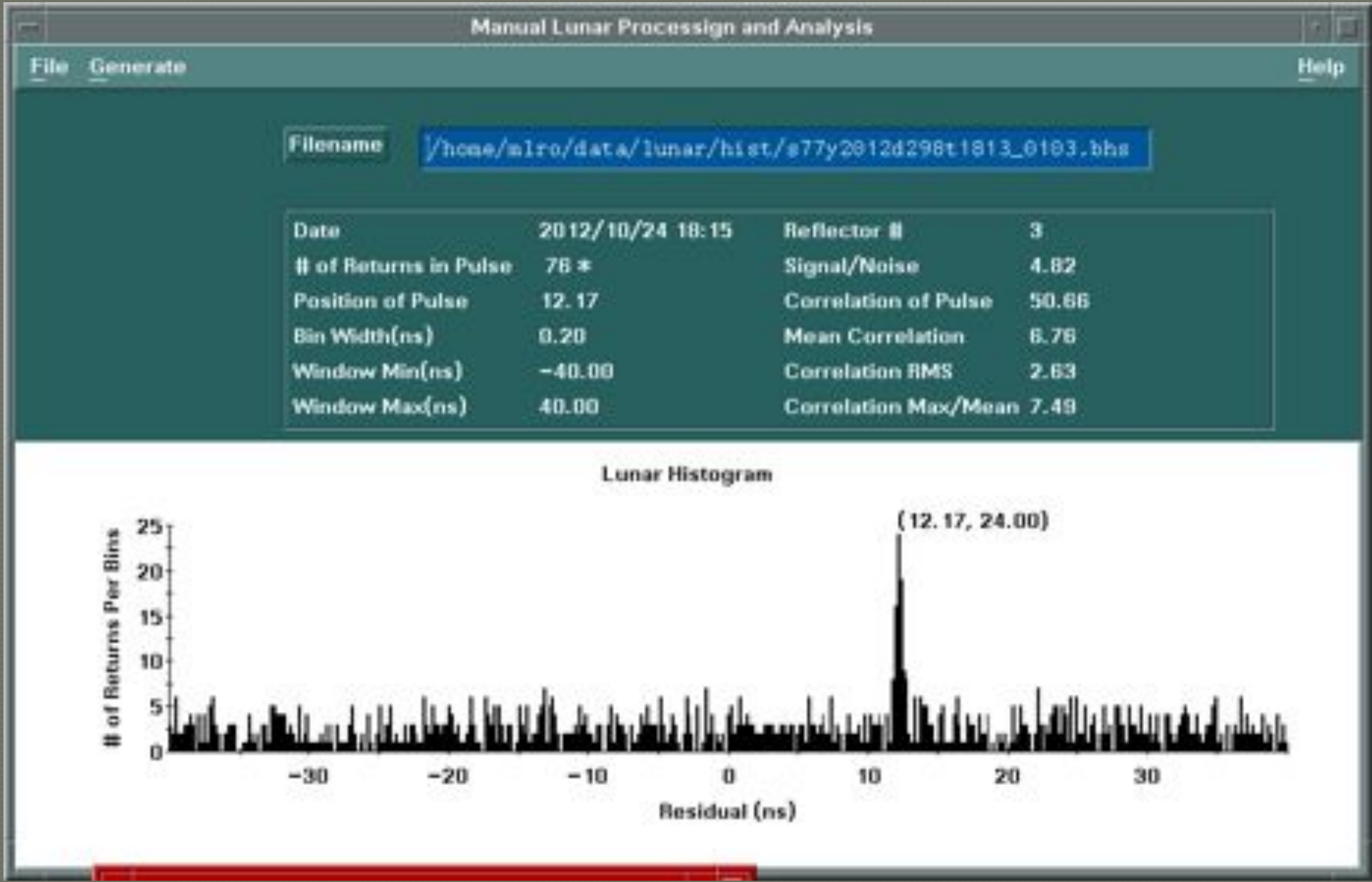
Final goals:
- radius and state of the lunar core
- bulk composition of the Moon

Main Activities and Goals

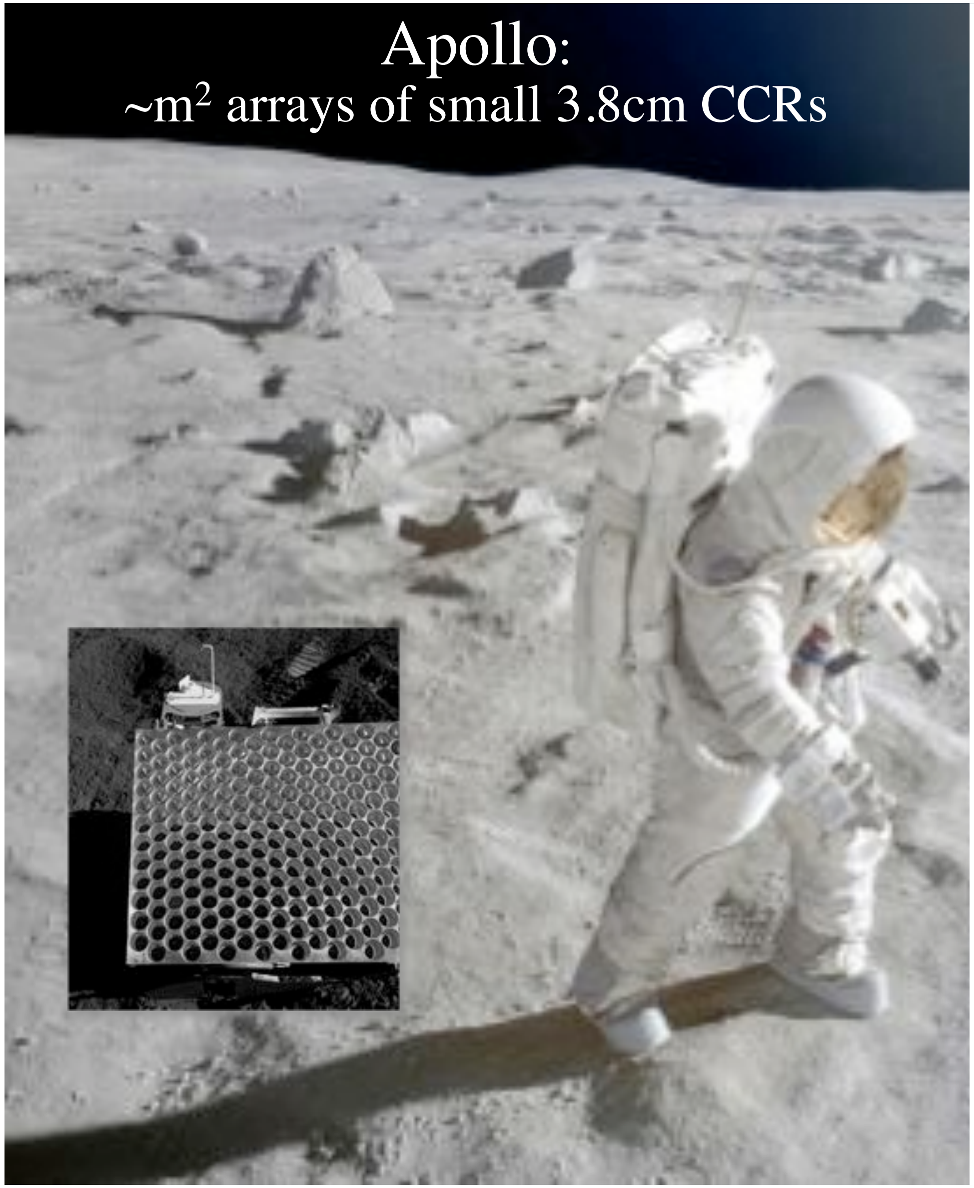
- Moon / (Exo)Mars missions, as unitary program
- Improved GR test with LLR data from **Apollo & Lunokhod reflectors**
- Improved GR test (up to x100), improved Selenodesy (lunar interior) – **MoonLIGHT**
- Enabling technology for Gravity, Planetary Exploration and Geodesy of other moons & planets - **INRRI**
- **All above with:**
  - SCF_Lab thermal-vacuum-optical-orbital testing and modeling With U. of Maryland (Doug Currie)
  - GR analysis. With CfA's Planetary Ephemeris Program (USA)
  - f1(R)+f_2(R), Solar System limits with Lisbon/Porto Univ's


Δt
time
Pulse to Moon
Wide Pulse to Earth
Apollo and Lunokhod
Back to Earth:
wide pulse due to lunar librations
Δt
Range error: ~cm with thousands of laser returns
t3
t2
t1
time
Pulse to Moon
Pulses to Earth
MoonLIGHT/ LLRRA21
Back to Earth:
separate pulses despite librations
t2
t1
t3
Range error: ~mm with one laser return

ASI-MLRO: LLR to Apollo 15



Apollo vs. MoonLIGHT (cartoon, no to scale)

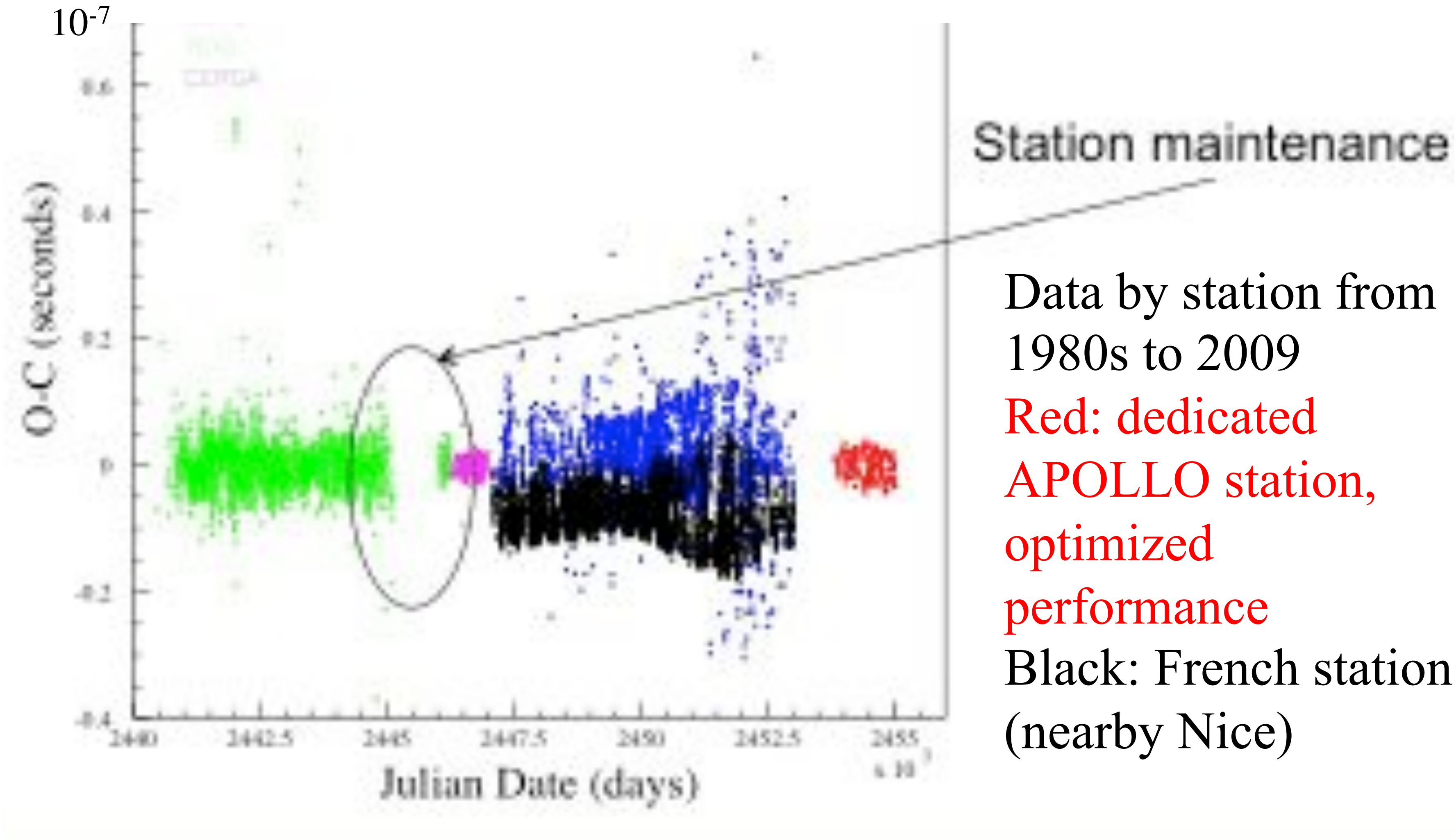


Precision tests of General Relativity with Lunar Laser Ranging (LLR)

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

* J. G. Williams et al, PRL 93, 261101 (2004), based on 35 years of LLR data

LLR Time-of-Flight residuals with CfA's Planetary Ephemeris Program (PEP)



Data by station from 1980s to 2009

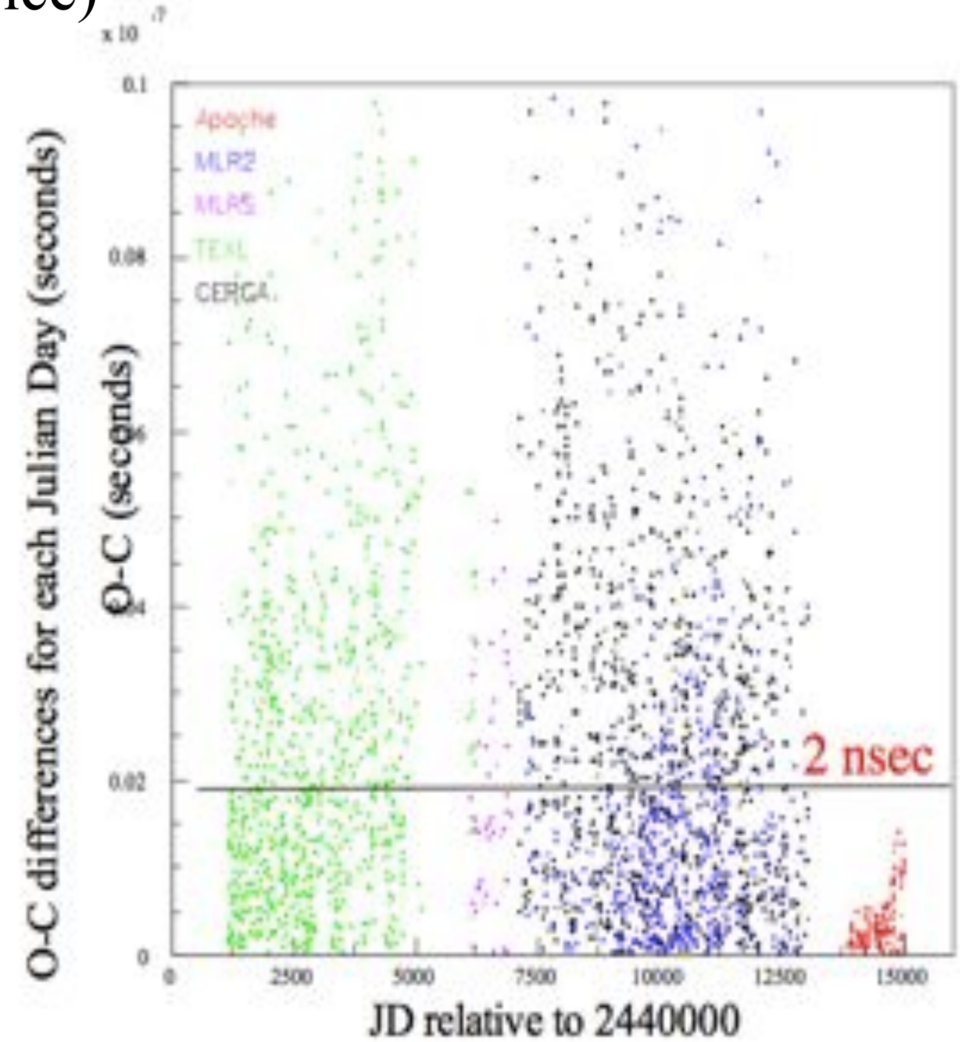
Red: dedicated APOLLO station, optimized performance

Black: French station (nearby Nice)

Rotations/Librations: well measured by LNF

1980s to 2009 Red: dedicated APOLLO station (T. Murphy)
Black: French station (nearby Nice)

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

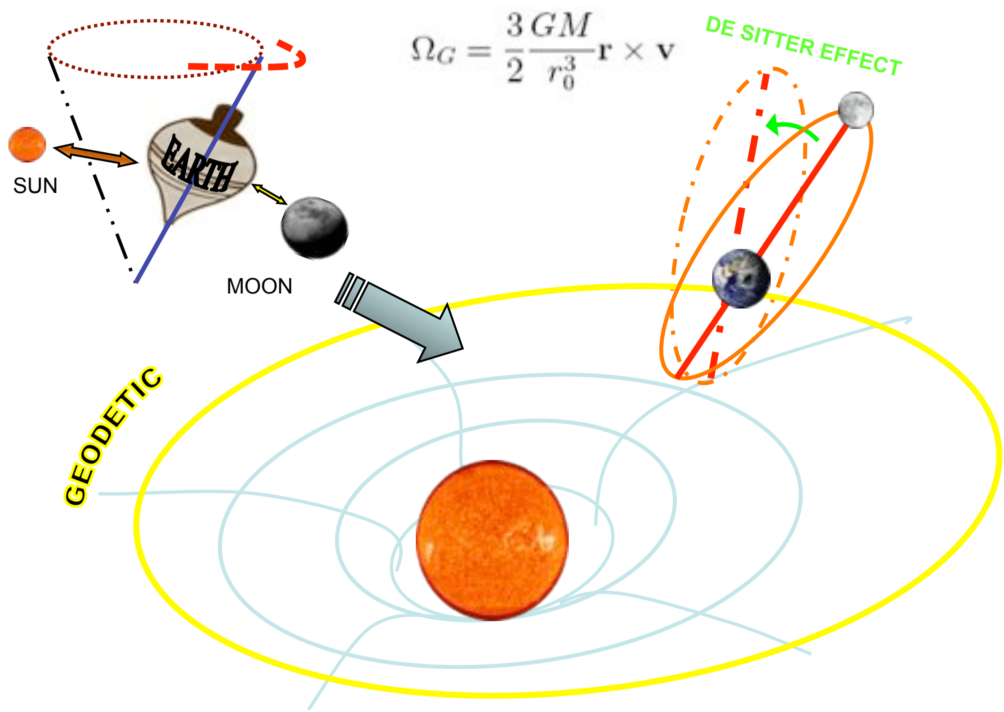


GR test benchmark: geodetic precession

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 (the Sun) is

~ 3 m/(lunar orbit) ~ 2”/century



Relative deviation of geodetic precession from GR value:

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

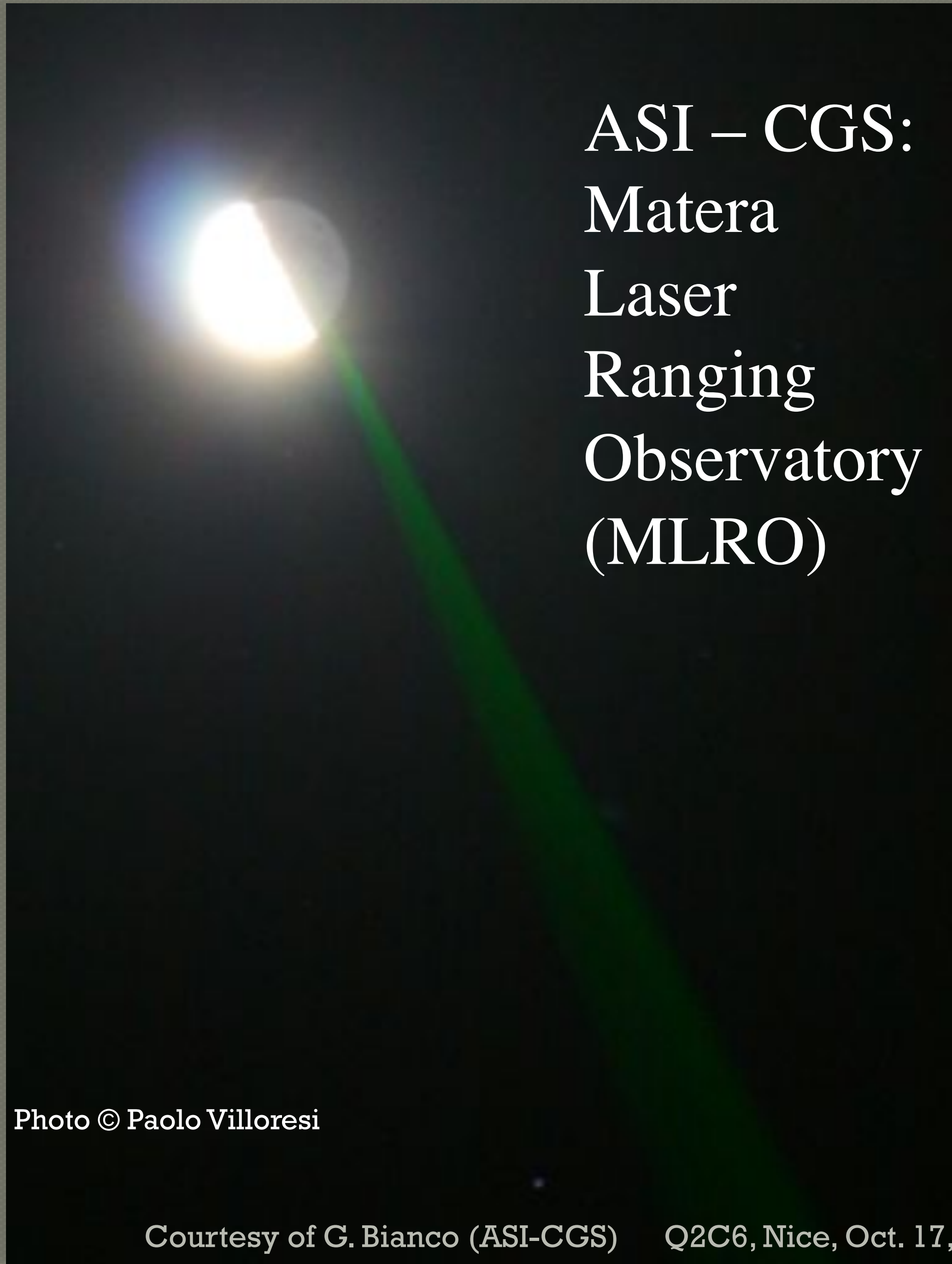
Ω_G = geodetic precession
r_0 = circular orbit radius
$\mathbf{v}$ = gyroscope velocity
r = position vector
G = gravitational constant
M = central body mass

LLR test of geodetic precession $\mathbf{K_{GP}}$

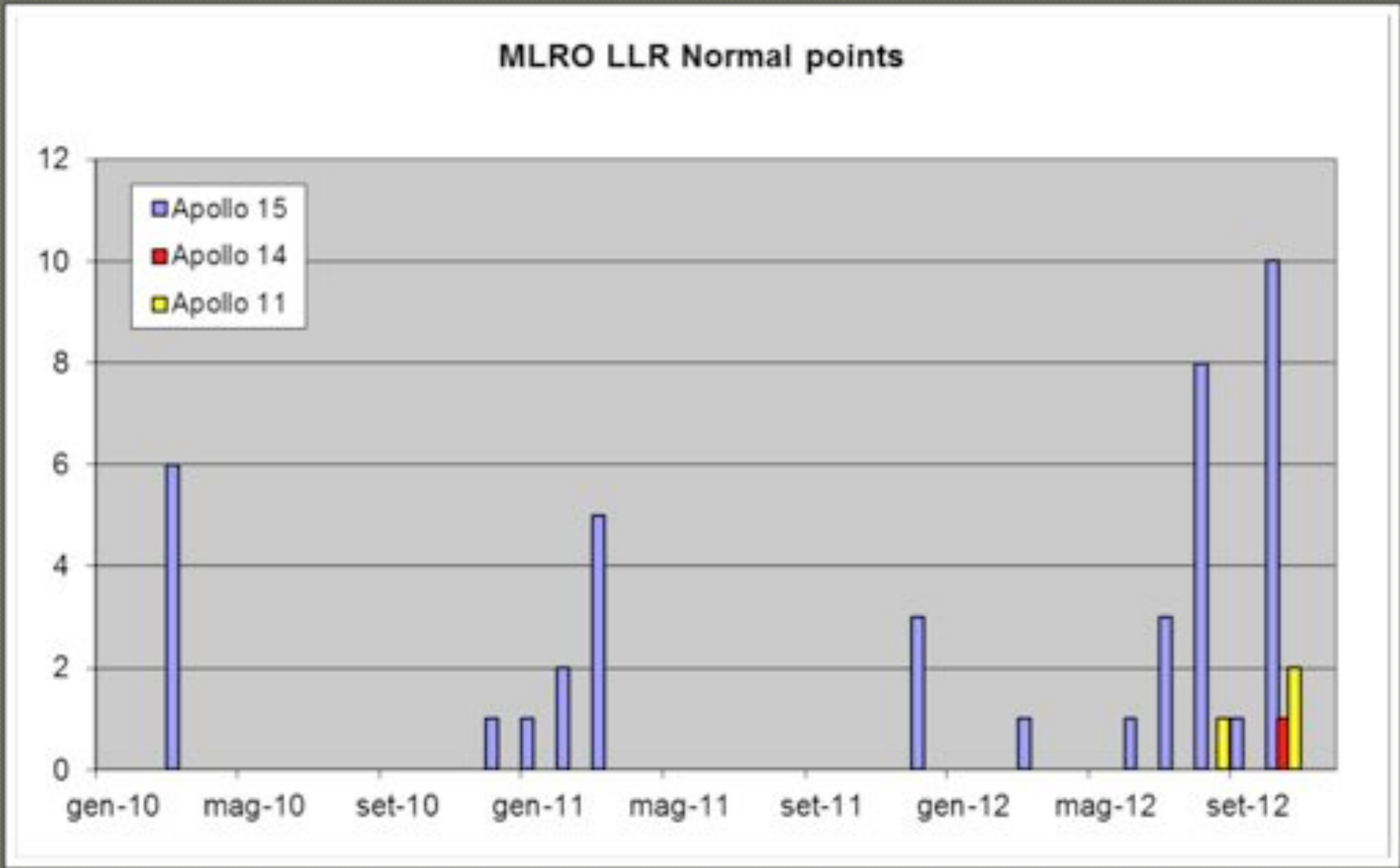
- First measured at **2% accuracy** in 1988 by Shapiro et al
- Our current accuracy with PEP, Apollo arrays: **~1%**
  - M. Martini et al, Planetary & Space Science 74 (2012) 276–282
- Comparable with accuracy by JPL **=0.64%**
  - J. G. Williams et al, PRL 93, 261101 (2004)
- Gravity Probe B final result on GP, accuracy: **=0.28%**
  - C.W. F. Everitt et al, PRL 106, 221101 (2011)
- **With MoonLIGHTs (and Apollo/Lunokhod):**
  - **Keep improving, up to x100**

ASI-Matera Laser Ranging Observatory (MLRO)

Courtesy of G. Bianco (ASI-CGS)



Courtesy of G. Bianco (ASI-CGS)



1 NP every ~10 min
in good conditions

Current test of 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}**

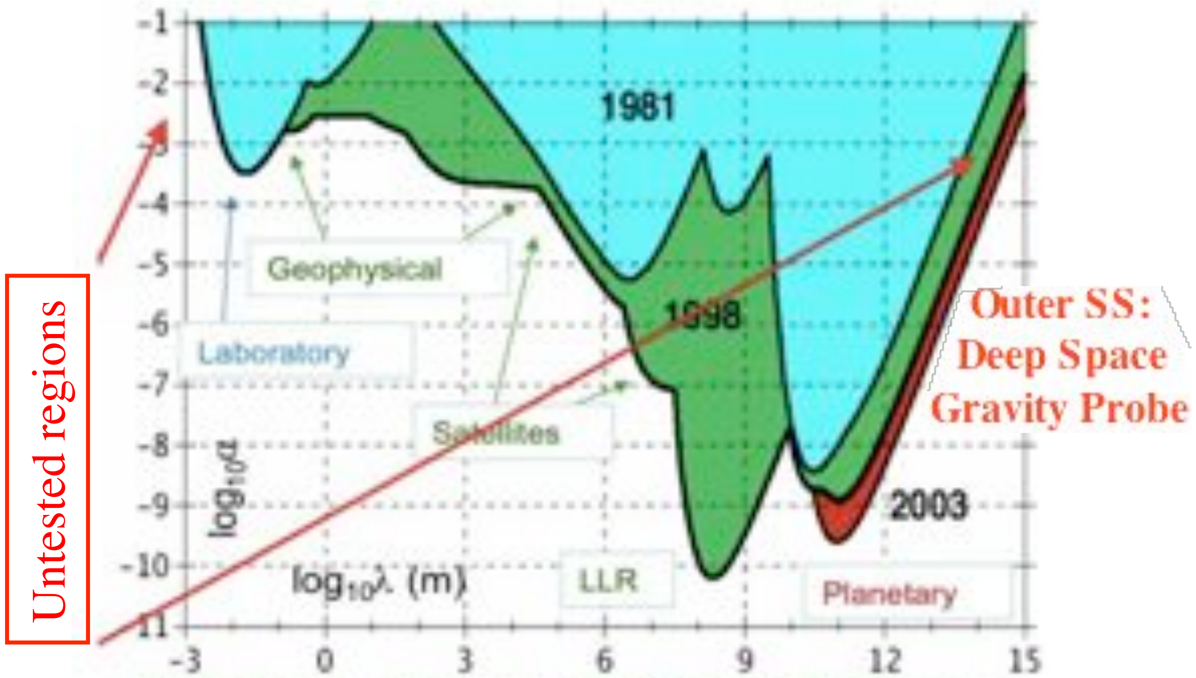
Limits on $1/r^2$ deviations in the Solar System

MoonLIGHT designed to provide accuracy of 100μm or better on space segment (the CCR), if deployed by drilling the regolith

If other error sources on LLR will improve with time at the same level, then MoonLIGHT CCRs will improve limits on α from ~10^{-10} to ~10^{-12} at scales λ ~ 384000 km (~ 4×10^{8} meters)

Limits on additional Yukawa potential:

α × (Newtonian-gravity) × $e^{-r/\lambda}$



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

“f1(R) + f2(R)” Gravity, Solar System Constraints

PRD 88, 064019 (2013)

Solar System constraints to nonminimally coupled gravity

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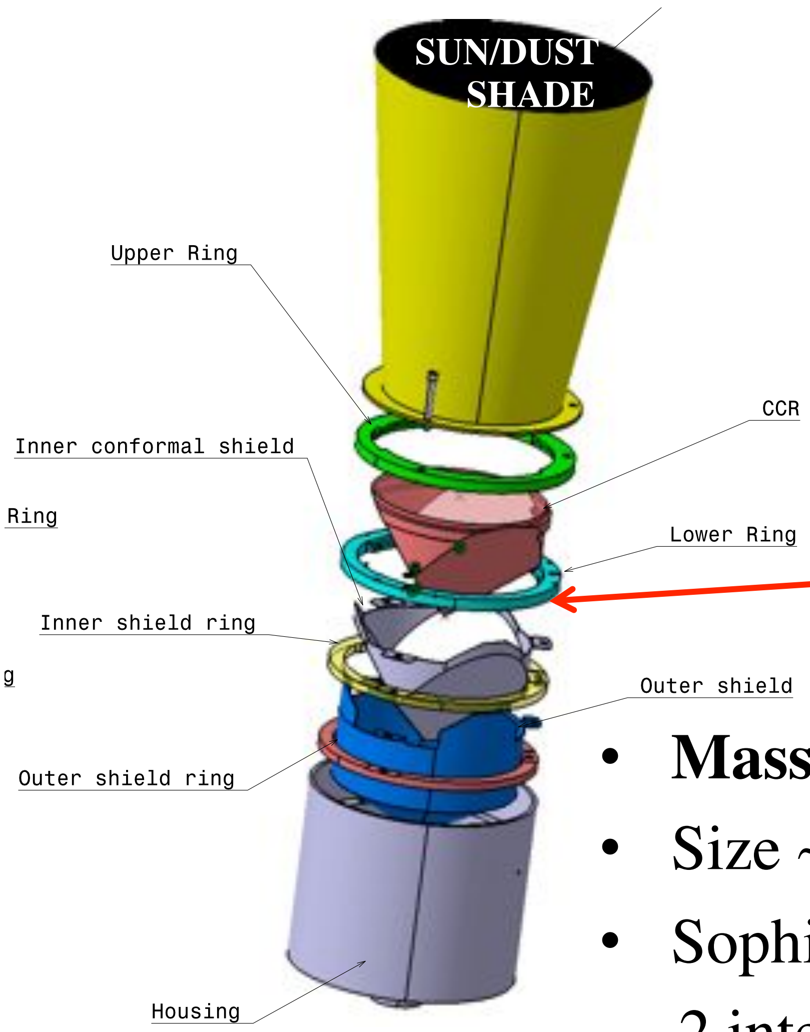
(Dated: June 6, 2013)

“f1(R) + f2(R)” studying possible NMC contributions to Yukawa Potential

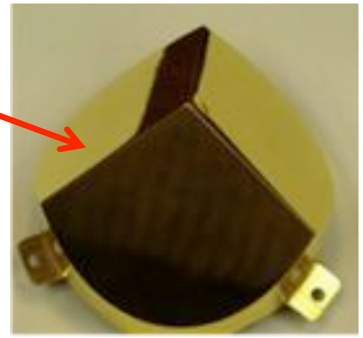
R.M. is partially supported by INFN (Istituto Nazionale di Fisica Nucleare, Italy), as part of the MoonLIGHT-2 experiment in the framework of the research activities of the Commissione Scientifica Nazionale n. 2 (CSN2).

We extend the analysis of Chiba, Smith and Erickcek [1] of Solar System constraints on $f(R)$ gravity to a class of nonminimally coupled (NMC) theories of gravity. These generalize $f(R)$ theories by replacing the action functional of General Relativity (GR) with a more general form involving two functions $f^1(R)$ and $f^2(R)$ of the Ricci scalar curvature R. While the function $f^1(R)$ is a nonlinear term in the action, analogous to $f(R)$ gravity, the function $f^2(R)$ yields a NMC between the matter Lagrangian density $\mathcal{L}_m$ and the scalar curvature. The developed method allows for obtaining constraints on the admissible classes of functions $f^1(R)$ and $f^2(R)$, by requiring that predictions of NMC gravity are compatible with Solar System tests of gravity. We apply this method to a NMC model which accounts for the observed accelerated expansion of the Universe.

MoonLIGHT cube corner reflector (CCR)



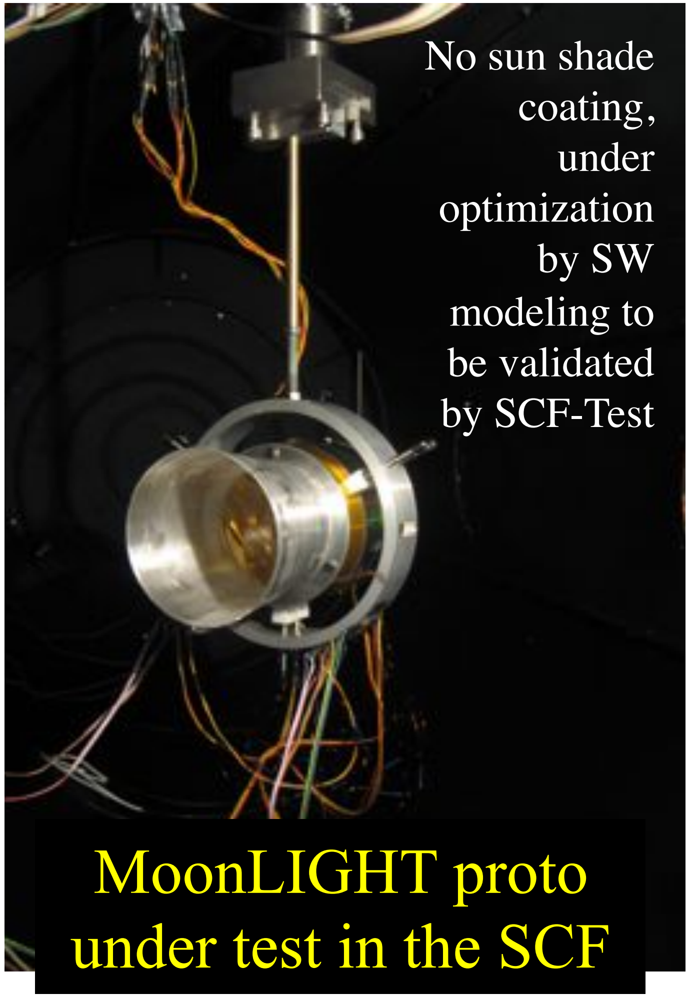
INNER CONFORMAL THERMAL SHIELD (Au-Ag coated)



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

Performance: MoonLIGHT vs. Apollo

- MoonLIGHT nominal optical response ~1/2 x Apollo 11
- HOWEVER: due to dust degradation of Apollo after 40+ years, MoonLIGHT laser return initially ~as good as Apollo 15 !!
- Stations improved x200, LLR error now limited by Apollo arrays
- LLR accuracy and data volume up to x100 better than Apollo

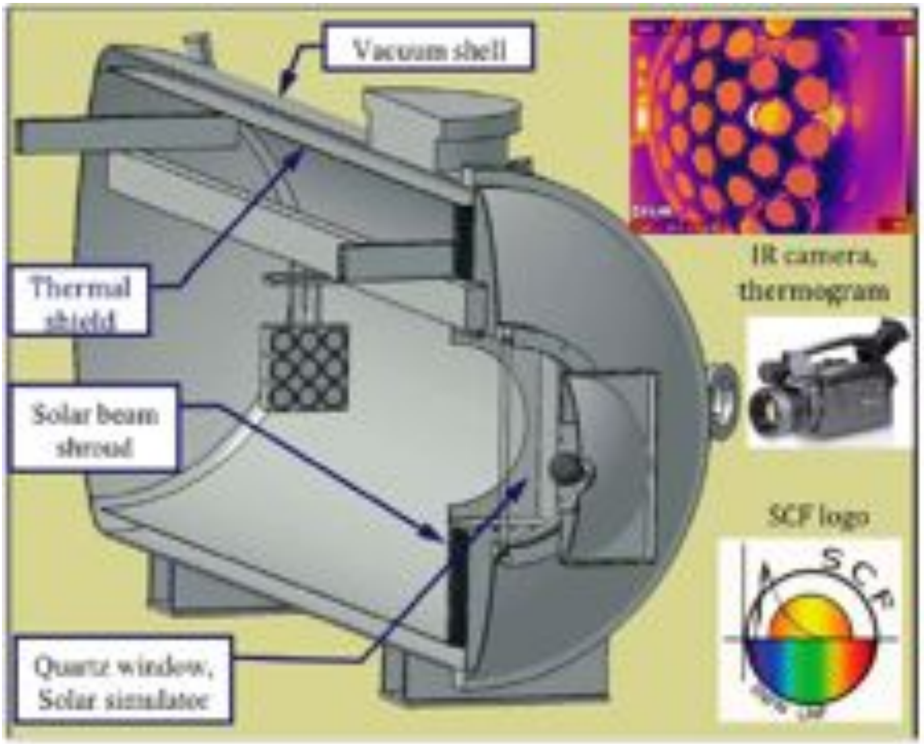


SCF_Lab

Satellite/Lunar/GNSS laser ranging and altimetry
Characterization **F**acility **Lab**oratory

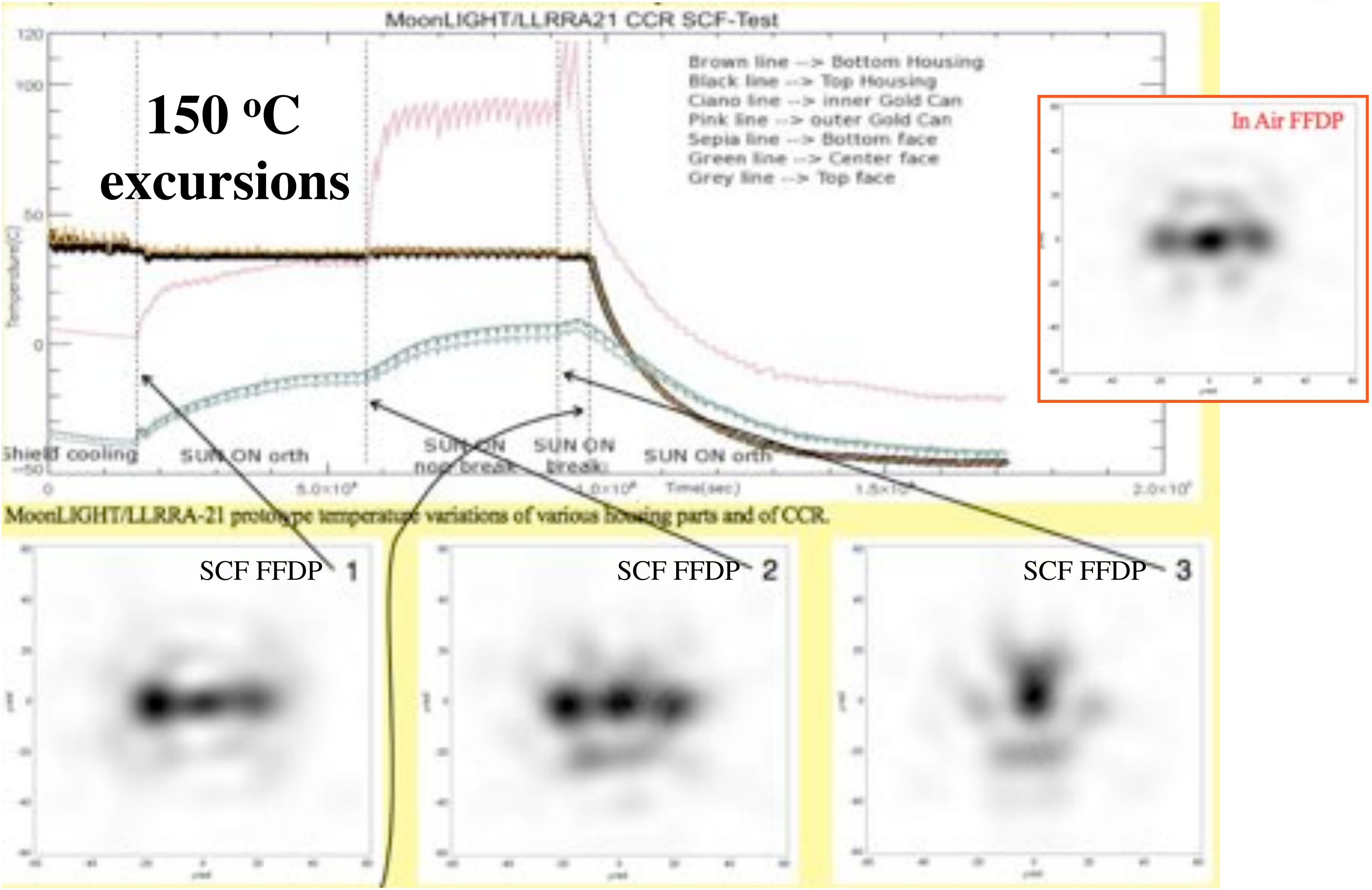
Two unique OGSEs (Optical Ground Support Equipments)
facilities in ISO 7 clean room, two sun simulators, IR thermometry

SCF for SLR/LLR/Altimetry



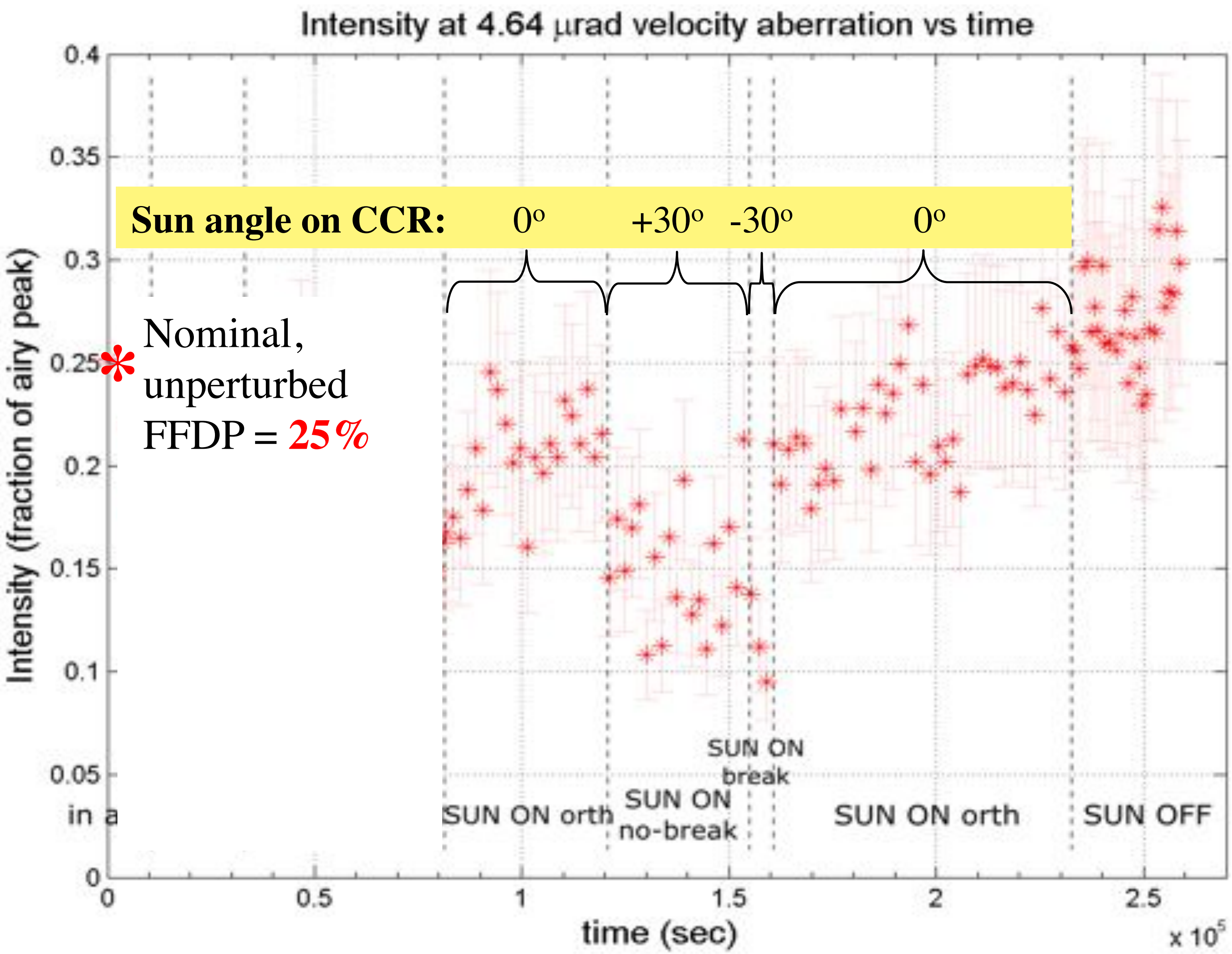
SCF-G for GNSS

SCF: CCR Temperatures & optical FFDP (no sunshade)



SCF: Optical performance (no sunshade)

Optical FFDP

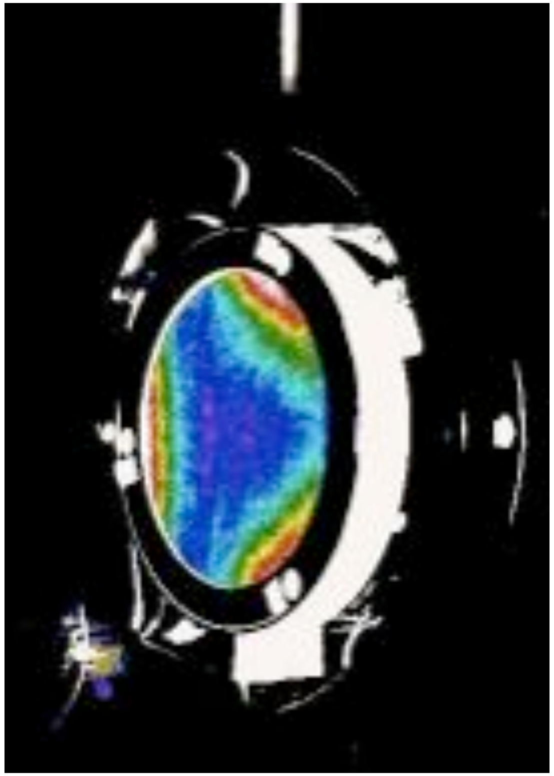


SCF: thermal testing & modeling

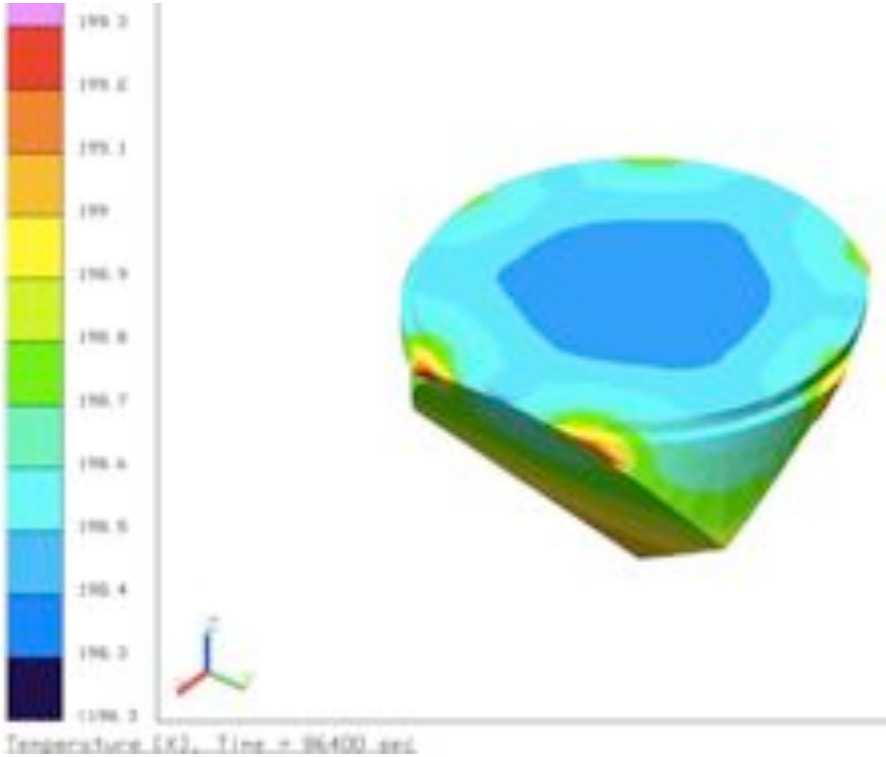
We measure/model subtle thermal effects, and optimize thermal conductance of retroreflector mounting

SCF-Test: IR imaging

IR Heat Flow Due to CCR Tab Supports

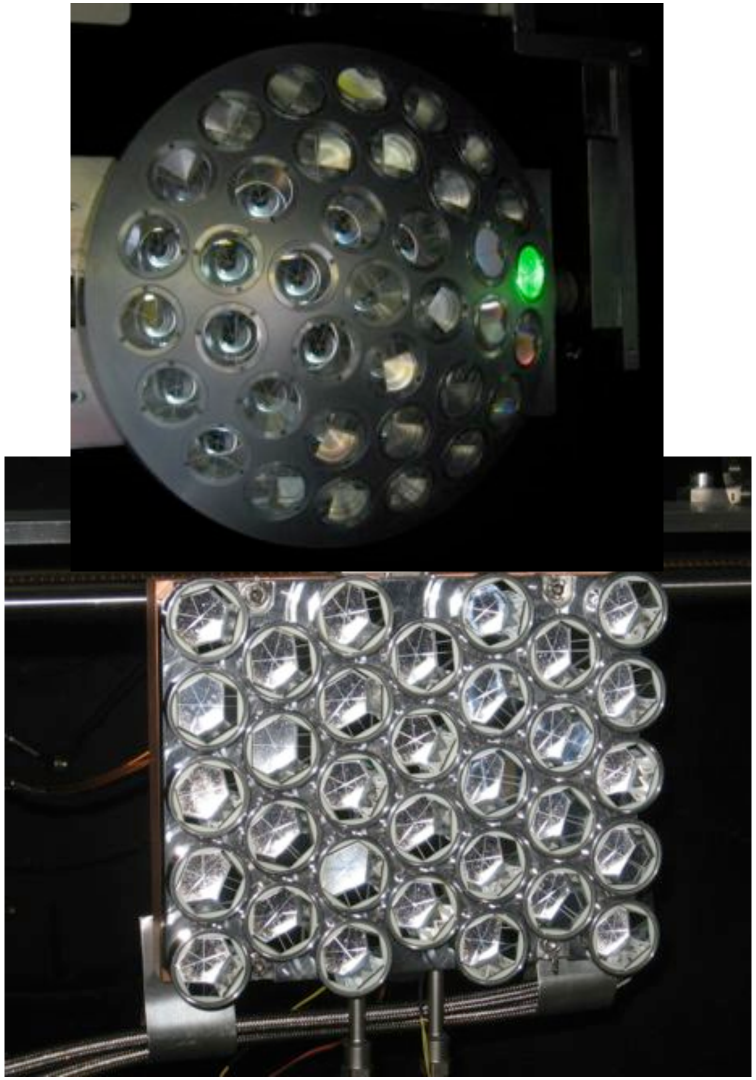


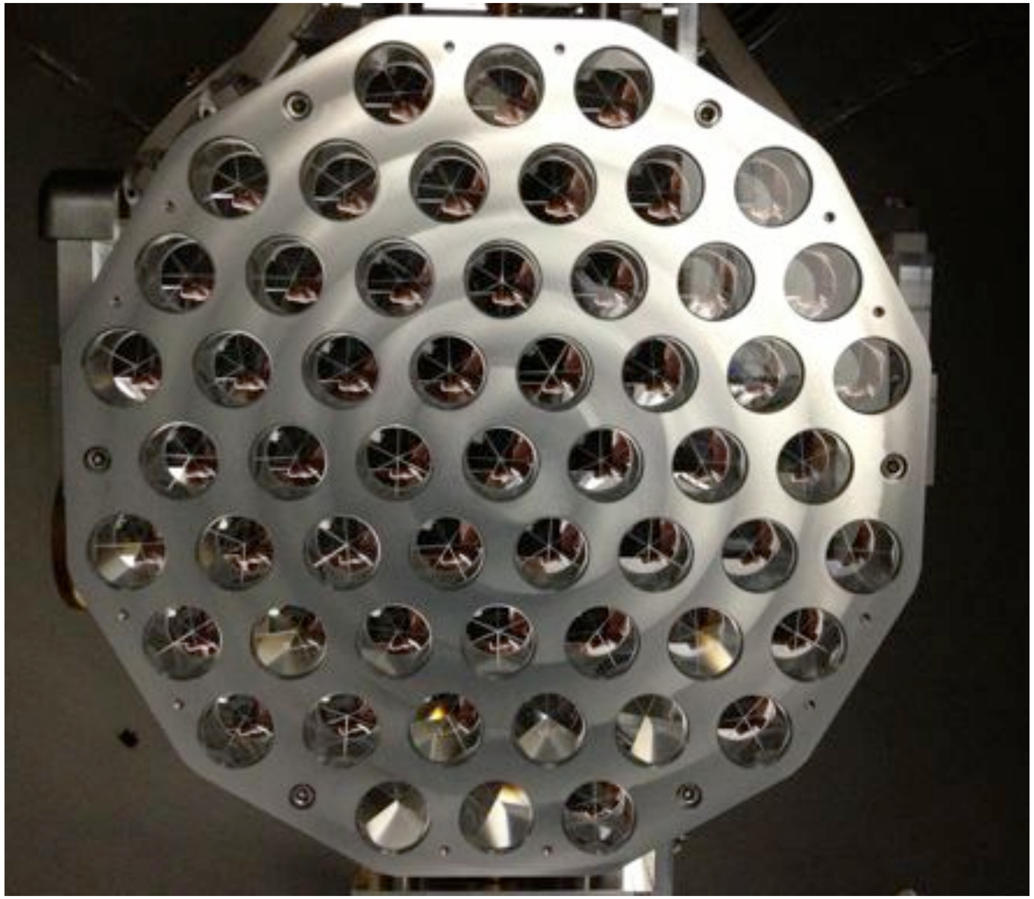
Thermal modeling: CCR at noon at Moon equator



Other SCF-Tested retroreflector arrays:

LAGEOS model by GSFC, GPS flight model by Maryland, modern GNSS array for Galileo/GPS3 by INFN-ASI





We also did industrial optical acceptance test of LARES (<u>in-air nominal specs, NO SCF-TEST!</u>)

MAJOR INHERITANCE. And more.

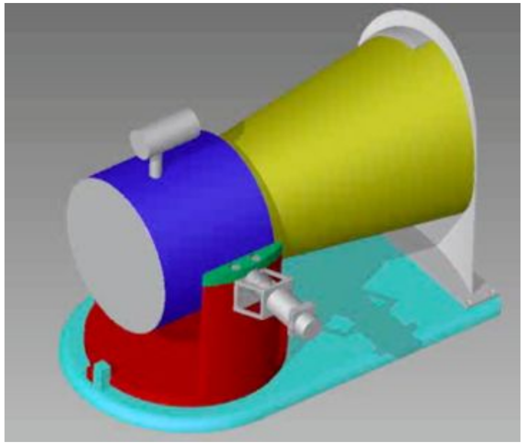
- **MoonLIGHT**:
- Inherits from longest-lived man-made payload: Apollo
  - Scaled-up version of Apollo CCR and its *pristine* mounting scheme
- More compact and light than Apollo
- More insensitive to dust than Apollo
- Further thermal optimizations (sunshade, …)
- But with robotic positioning system

- **INRRI**: inherits from NASA’s Phoenix Mars lander

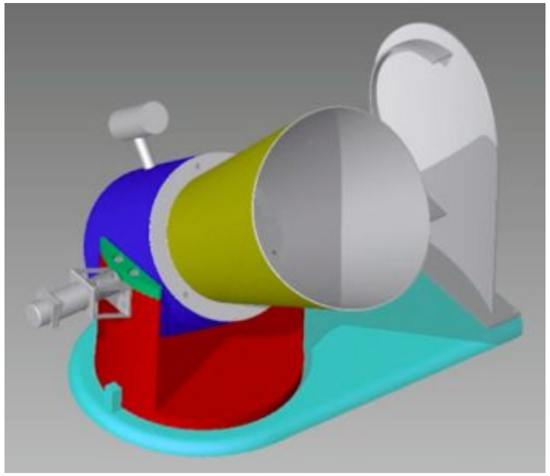
- Characterized & qualified @SCF_Lab & SERMS (which did qualifications for AMS-02 astroparticle detector now on ISS)

MoonLIGHT Pointing System

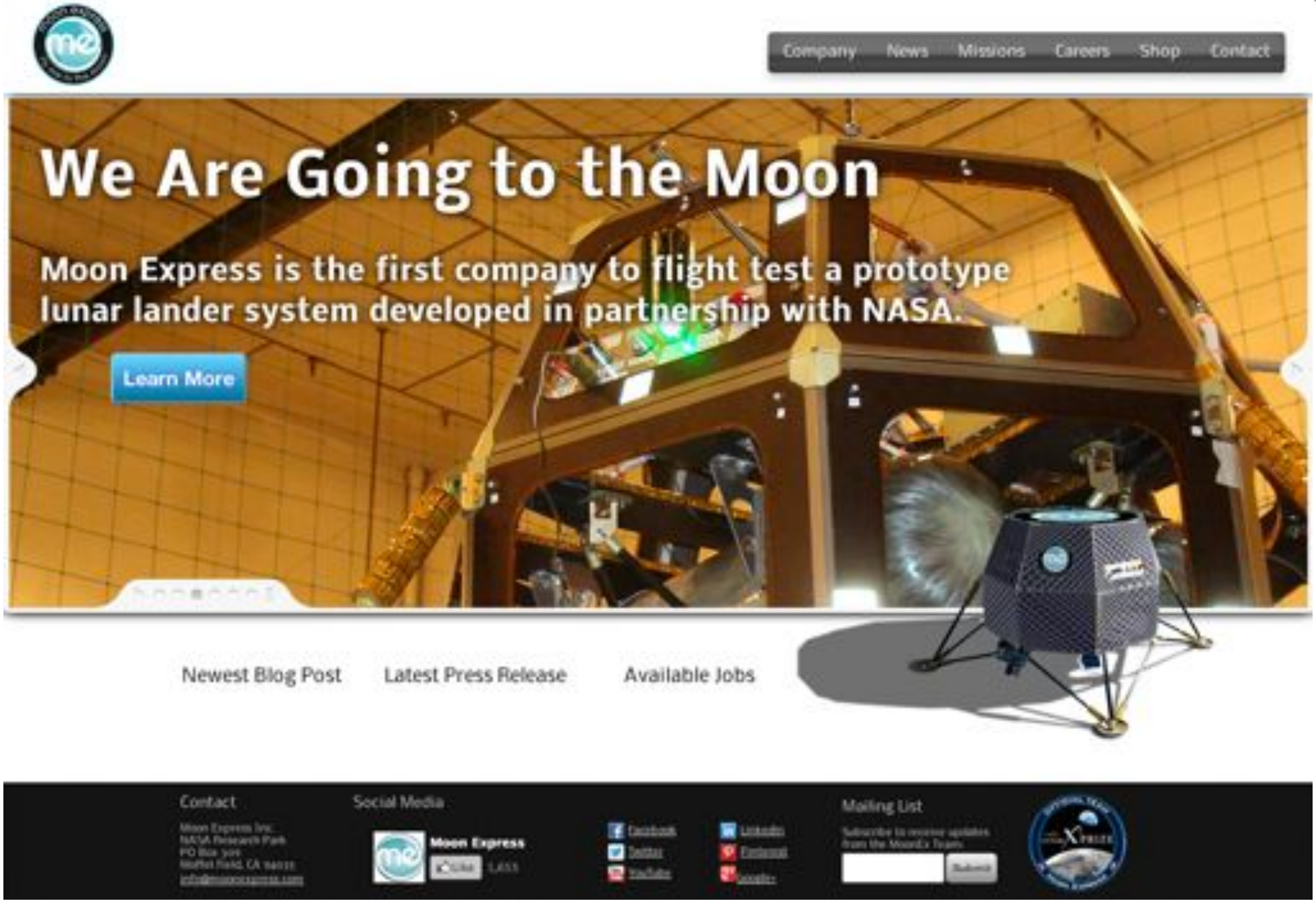
Two motors + CCD (to locate/point Earth)
Stowage screen (dust protection at landing)
~1.3 kg



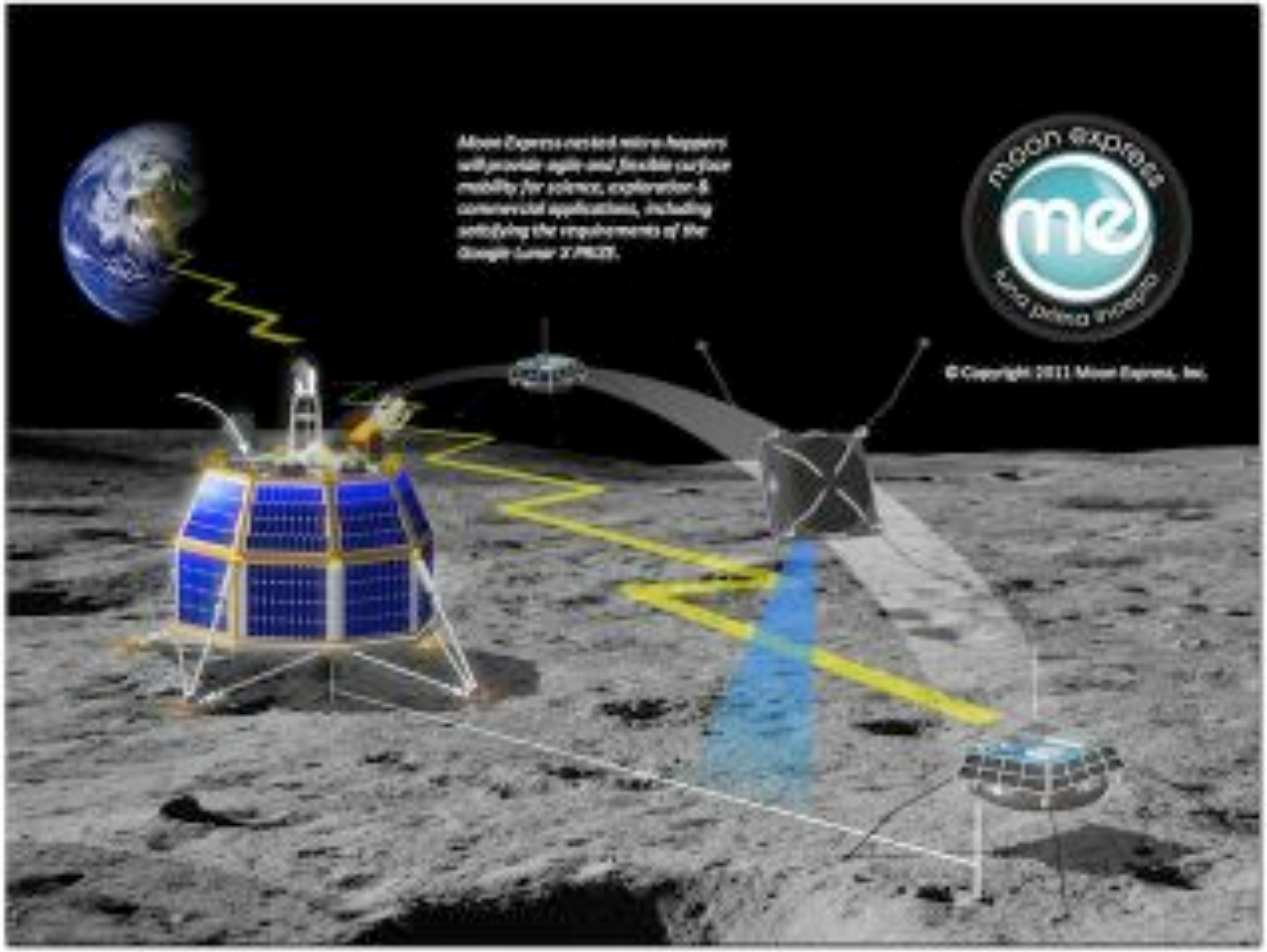
- By Scuola Superiore Sant'Anna (Pisa, Italy)
  - Led by Calogero Oddo
- Pointing: about ± 2°
- Automatic System
- Only a Start Pulse
- Sequence (at equator site)
  - Point to Zenith
  - Take a Camera Exposure
  - Fit Earth Image (On-Board)
  - If Missing -Search off Zenith
- Lock Brakes



Moon Express-1 Mission to the Moon



Moon Express-1 Mission Concept



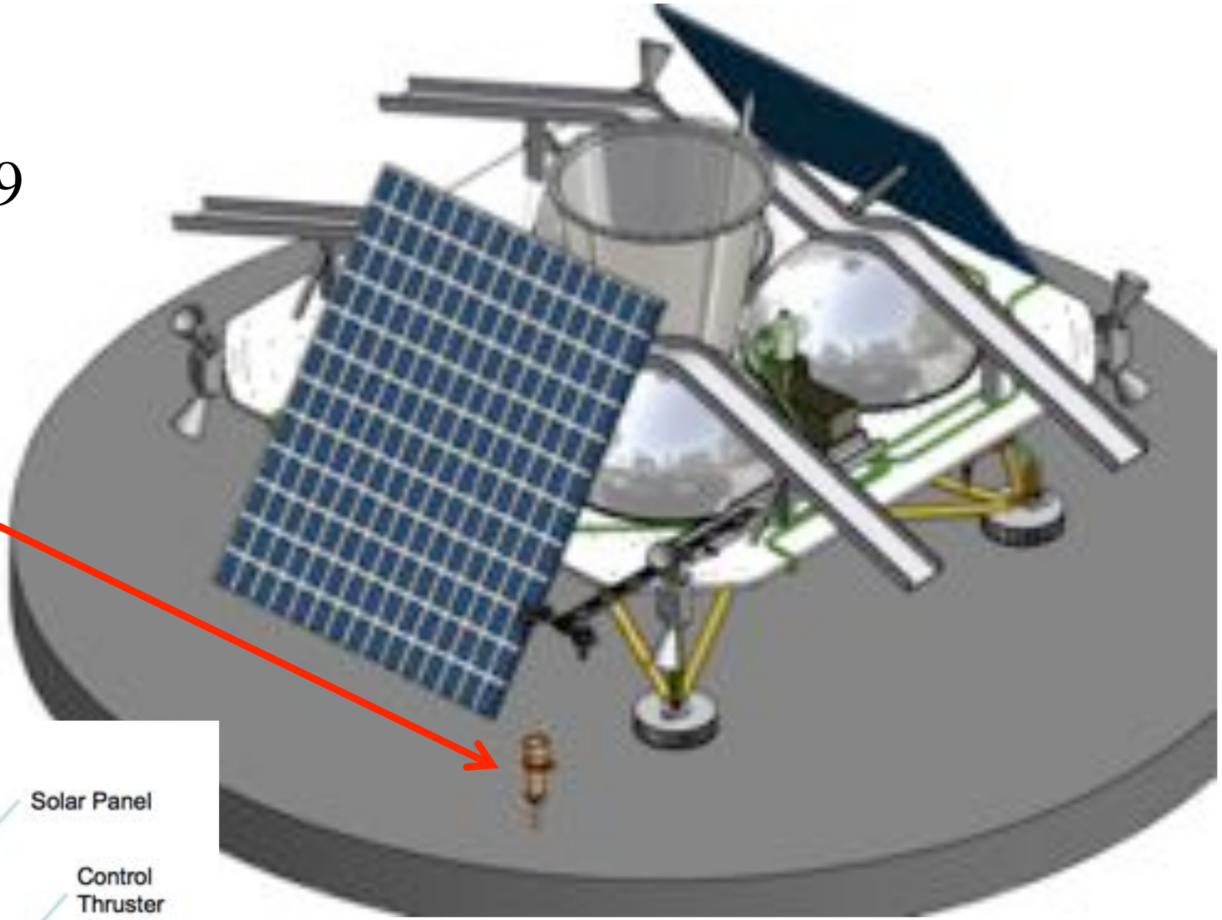
MoonLIGHT on MEX-1 top deck

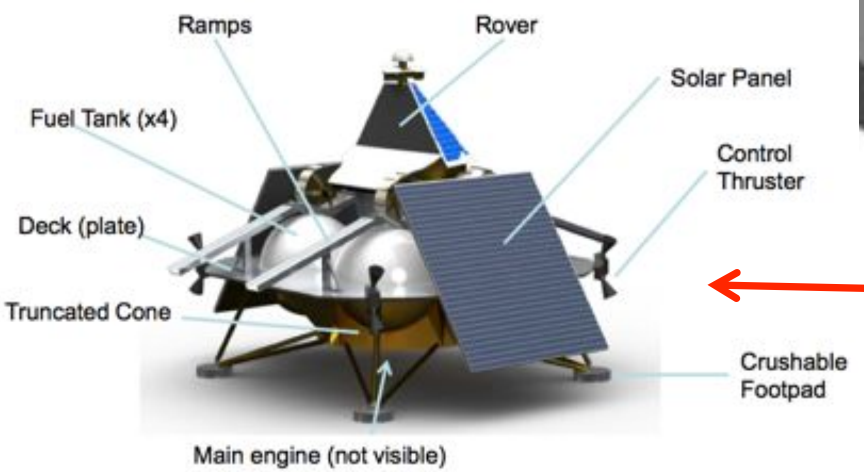
Moon Express-1: NASA $30M contract

Astrobotic Landing-Roving Mission to the Moon

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

Deployment on regolith or on lander





From
Payload User Guide 3.0

RFI on NASA-Industry (astrobotic) Partnership: July 2, 2013

A--REQUEST FOR INFORMATION ON POTENTIAL NASA PARTNERSHIPS FOR INDUSTRY-LEDDEVELOPMENT OF ROBOTIC LUNAR LANDERS

Solicitation Number: NNH13ZCQ002L
Agency: National Aeronautics and Space Administration
Office: Headquarters
Location: Office of Procurement (HQ)

Notice Details | Packages | Interested Vendors List   Print   Link

Original Synopsis
Jul 02, 2013
11:00 am

Return To Opportunities List | Watch This Opportunity | Add Me To Interested Vendors

Solicitation Number: NNH13ZCQ002L

Notice Type: Sources Sought

Synopsis:
Added: Jul 02, 2013 11:00 am
REQUEST FOR INFORMATION (RFI): THIS IS *NOT* A REQUEST FOR PROPOSAL, QUOTATION, OR INVITATION TO BID NOTICE. The National Aeronautics and Space Administration (NASA) is continually looking for ways to help advance the development of commercial space products and services. With the recent influx of U.S. private-sector companies interested in space exploration and utilization, NASA is seeking to better understand U.S. industrys interests in a myriad of exploration activities, including the private development of robotic lander capabilities for the lunar surface. To that end, NASAs Advanced Exploration Systems Division in the Human Exploration and Operations Mission Directorate is seeking input through this Request for Information (RFI) that focuses on an industry-developed robotic lander that can be integrated with a launch vehicle for the purposes of supporting commercial (and potentially future NASA) missions. An industry-NASA partnership would: Transfer and

GENERAL INFORMATION

Notice Type:
Sources Sought

Posted Date:
July 2, 2013

Response Date:
August 2, 2013

Archiving Policy:
Automatic, on specified date

Archive Date:
July 2, 2014

Original Set Aside:
N/A

Set Aside:
N/A

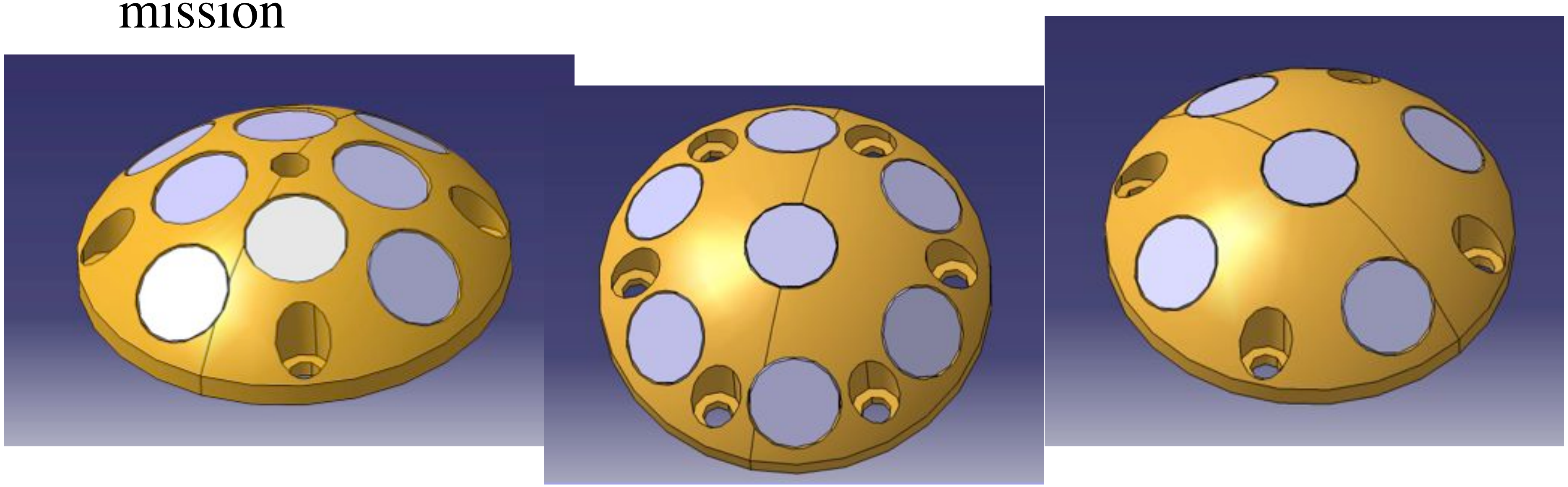
Classification Code:
A -- Research & Development

NAICS Code:
336 -- Transportation Equipment Manufacturing/336414 -- Guided Missile and Space Vehicle Manufacturing

Small LRA, ~25 gr, ~60 mm×20 mm, passive, no pointing

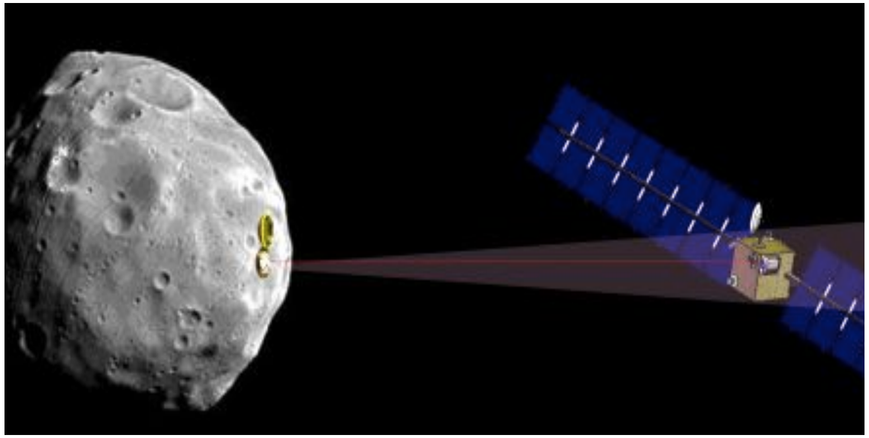
INRRI

- **IN**strument for landing-**R**oving laser ranging and altimetry **R**etroreflector **I**nvestigations
- Perfect for Lander, Rovers on moons and (Exo)Mars 2018
- ExoMars is strategic, cornerstone, approved, ESA-Roskosmos mission

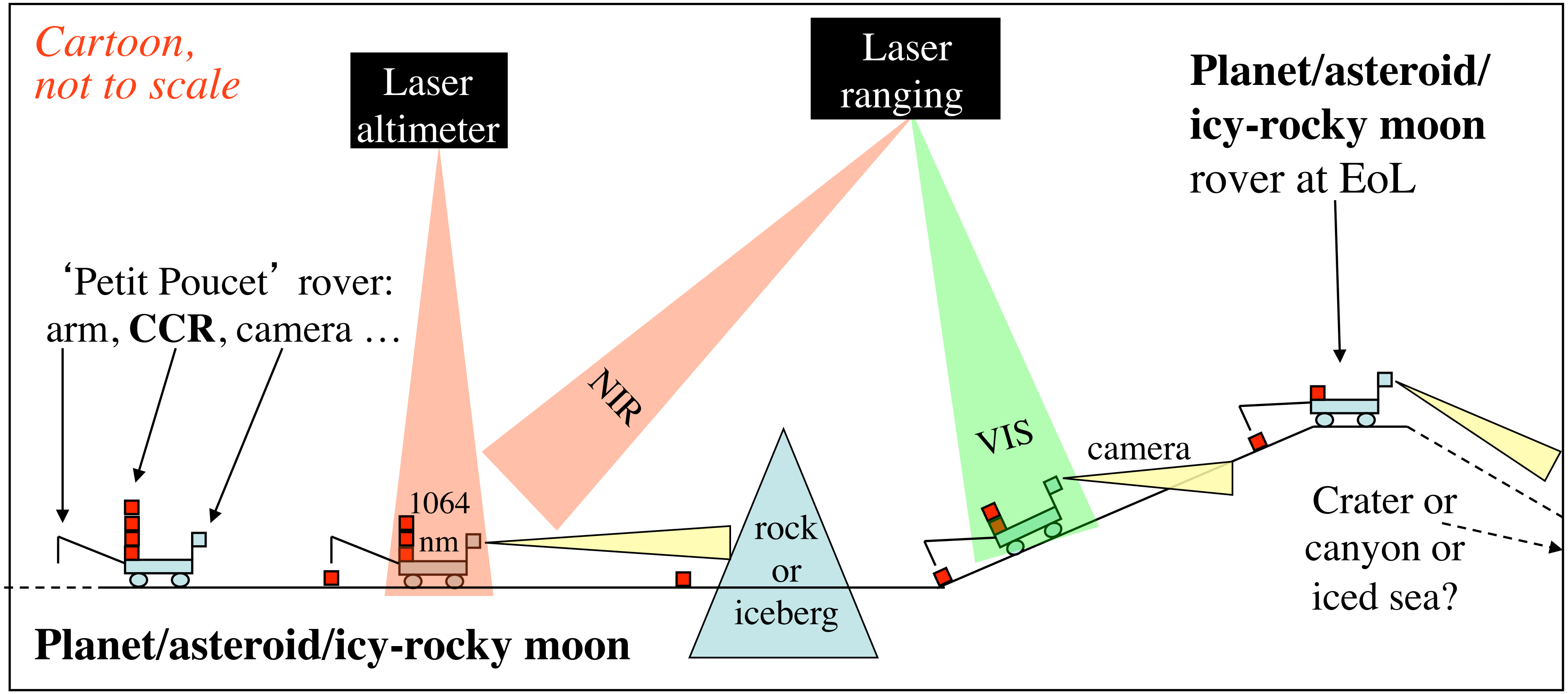


INRRI on ExoMars & other moons' Rovers

- Laser-positioned by Orbiter during exploration
- Orbiter radio-positioned by Earth
- Curiosity, Opportunity, Spirit do not have reflectors
  - INRRI on ExoMars 2018 rover may be a 'first'
- Beyond INRRI: new-generation gravity mission
  - **GETEMME**: **G**ravity, **E**instein's **T**heory, and **E**xploration of **M**artian **M**oons' **E**nvironment (ESA Cosmic Visions)
  - Orbiter deploys two reflector arrays on Phobos and Deimos
  - Orbiter laser-ranged by Earth
  - Orbiter laser-ranges arrays



INRRIs at Moon, Mars, Jupiter/Saturn moons



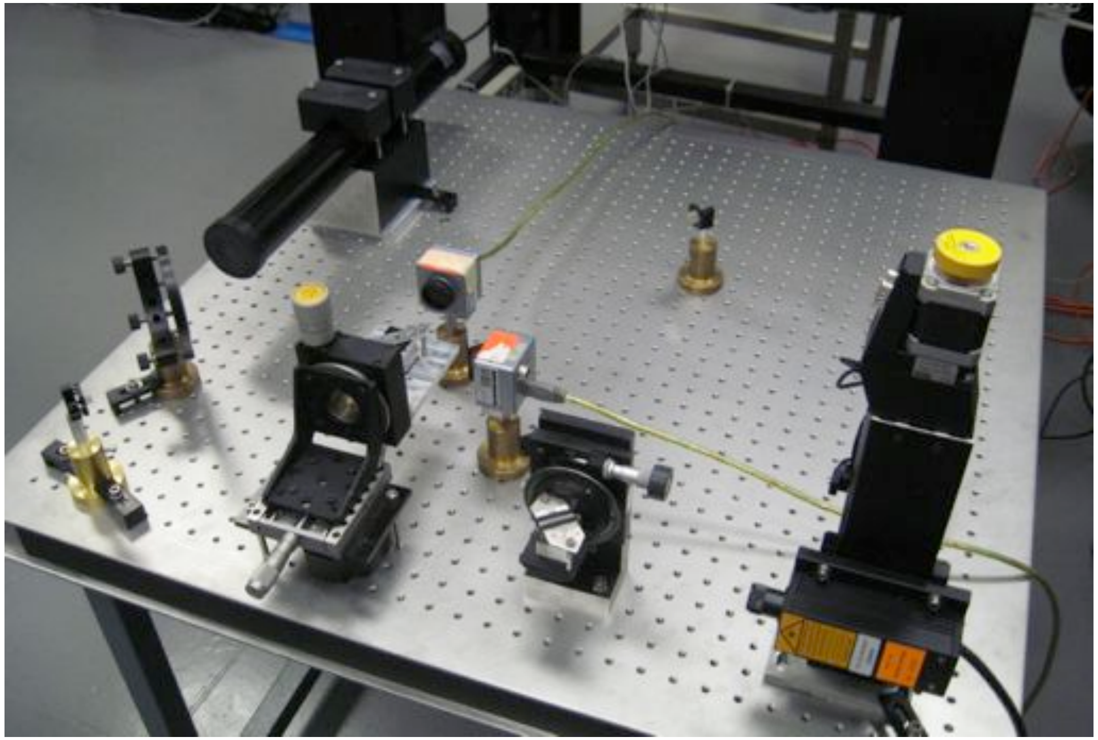
- Selenolocate rover activity from orbiters thanks to CCR (reflector):
  - Laser altimetry at nadir (LRO-like) to rovers at poles of moons
  - Laser ranging with pointing capability to CCRs anywhere (GETEMME-like)
- **Deploy CCR networks**! Also on far side of Earth's Moon

ExoMars 2018

New tool: SCF-Test/Revision-IR

Space characterization of retroreflectors for laser ranging/altimetry at 1064 nm from orbiter of Moon (like **LRO**), Mars-Phobos-Deimos (**GETEMME**, ESA Cosmic Visions), icy/rocky moons of Jupiter and Saturn (future Europa and Encelado landers). Enabling technology for:

fundamental gravity, planetary science, space exploration



Mission opportunities [MoonLIGHT/INRRI]

- **Moon, Commercial** (SpaceX Falcon 9) payload & data services competing in $30M Google Lunar X Prize:
  - **Moon Express-1 [M+I]: end 2105; lander deployment**
  - **Astrobotic [M+I]: October 2015; lander or drilling depl.**
- **Mars**
  - ExoMars 2018 [**I**], **2018; rover deployment**
- **Moon, Space Agency launches**
  - SELENE-2 (JAXA), [**M+I**], **2017**; <u>scientific agreement signed</u>
  - Chandrayaan-2 Lunar Lander (ISRO) [**I**], **2017**; <u>negotiating</u>
  - LGN (NASA) [**3*M+I**]: **2018**; <u>solid collaboration but TBD</u>

US-Italy LLR Team, 2010 photo

- We developed: new-generation LLR retroreflector and SCF_Lab
- New 2013 partners: Sant'Anna, IST Lisbon/Univ. Porto, aeroTecno
- Continuing: legacy of Apollo program and 50 years of fruitful US-Italy collaboration in space. Let's just go back to the Moon …

Conclusions & Highlights

- 5-year laser ranging program on Moon, (Exo)Mars, other moons
  - Missions: **Moon Express, Astrobotic, ExoMars 2108**
- World-unique capabilities (Apollo-Veteran D. Currie & SCF_Lab)

Led by D. Currie (USA), S. Dell'Agnello (Ita)

INFN-LNF, U. Maryland, Scuola Superiore Sant'Anna,

ASI

NASA-GSFC/ARC, CfA, UCSD, Lisbon/Porto Univ's, aeroTecno