SCF_Lab @LNF: Status and Prospects of Space Research/Test Activities

Dell'Agnello S.

INFN - Laboratori Nazionali ddi Frascati (Rome), Italy

for the LNF/SCF_Lab and INFN/SPRINGLETS Team

What Next LNF: Perspectives of Fundamental Physics at LNF

INFN-LNF, Frascati (RM), Italy - November 11, 2014

Outline

- SCF_Lab (2004-14)
- Precision Test of Fundamental Gravity
  - Lunar Laser Ranging: MoonLIGHT-2 Program
  - NASA-INFN Partnership for Solar System Research
  - Gravitational Redshift: Galileo satellites (*spare slides*)
- Intern. Space Station (ISS) as science platform
  - Laser Positioning Metrology for Copernicus
  - Laser Quantum Physics in Space
- Outlook

SCF_Lab (2004 -14)

- Fundamental gravity with LLR
  - MoonLIGH-2, INFN-**CSN2** (2013-18)
  - 1 **ASI** study (2006-7) and 1 **ASI** Phase A (2008)
  - 2 R&D projects for **NASA** LSSO (2007-8), NLSI (2009-12)
- R&D HW Experiments
  - 3 INFN-**CSN5**: ETRUSCO (2006-9), MoonLIGHT-ILN (2010-12), ETRUSCO-GMES (2013-15)
- Contracts with **Space Agencies** (ASI, ESA, ISRO) and Italian **Ministries** (Defense, MIUR, MAECI)
  - External funds: **> 4.2 M€**
  - For Space Flagships: Galileo, Copernicus, COSMO-SkyMed
- **NASA Partnership** Solar System Exploration Research

Affiliation of INFN to NASA/SSERVI

- SSERVI, **Solar System Exploration Research Virtual Institute**
  - Centrally managed by NASA-ARC, sservi.nasa.gov

- **Solar system Payloads of laser Retroreflectors of INfn for General reLativity, Exploration and planeTary Science**

- INFN: 1st Italian Partner of SSERVI
- Others: UK, Germany, Canada, Korea Netherlands, Israel, Saudi Arabia

NASA-SSERVI & INFN *formal statement (I)*

National Aeronautics and Space Administration – Istituto Nazionale di Fisica Nucleare
Solar System Exploration Research Virtual Institute Affiliate Member Cooperation

15 September 2014

The National Aeronautics and Space Administration (NASA) of the United States of America is pleased to recognize the Istituto Nazionale di Fisica Nucleare (INFN) of the Italian Republic as an Affiliate level partner with the NASA Solar System Exploration Research Virtual Institute (SSERVI). With this honor, NASA recognizes INFN as the formal representative of Italy's Solar System science community.

INFN's impressive proposal to SSERVI offers scientific and technological expertise to further the broad goals of Solar System science in many important ways, including INFN's unique expertise with Laser Retroreflector Arrays (LRAs). LRA technology and applications promise to provide great support for future exploration missions to the Moon, Mars, Phobos, Deimos, as well as other planets and their moons in the Solar System. The affiliation will allow INFN and SSERVI to collaborate to improve future scientific undertakings. In addition, INFN and SSERVI will work to further the SSERVI goal of supporting the next generation of space scientists.

NASA-SSERVI & INFN *formal statement (II)*

This affiliation covers scientific collaboration as specified in the charter for SSERVI. Certain additional activities such as, for example, joint U.S./Italy mission development, the exchange of export controlled information, or the creation of intellectual property, will need to be covered by separate, legally binding, international agreements.

With the establishment of INFN as a SSERVI Affiliate, the SSERVI Central Office will work with INFN to develop a public announcement as well as plan for future joint scientific undertakings, including establishment of systems to facilitate virtual collaboration. NASA and INFN look forward to fruitful scientific collaborations through this affiliation including the development of future mission concepts and would hope that future plans might lead to future agreements between the relevant United States of America and Italian Republic organizations.

NASA and INFN are confident that this partnership will result in more great scientific discoveries in Solar System science for both of our nations, as well as furthering the SSERVI goal of understanding the Moon, near-Earth objects, Phobos, Deimos, and their environments.

Gregory K. Schmidt
Deputy Director
Solar System Exploration Research Virtual Institute
NASA Ames Research Center

Fernando Ferroni
President
Istituto Nazionale di Fisica Nucleare

SPRINGLETS: INFN Research Teams

- **INFN-LNF / Laser Retroreflector SCF_Lab**: S. Dell'Agnello (PI), G. Delle Monache, R. Vittori, C. Cantone, A. Boni, G. Patrizi, C. Lops, L. Porcelli, M. Martini, E. Ciocci, S. Contessa, L. Filomena, M. Tibuzzi, P. Tuscano, C. Mondaini, R. March, G. Bellettini, R. Tauraso, F. Muto, L. Salvatori, N. Intaglietta, A. Stecchi, E. Bernieri, M. Maiello
- **INFN-LNF / DAΦNE-Light** (Synchrotron radiation facility - IR/VIS/UV/X): A. Balerna (PI), M. Cestelli-Guidi, E. Pace, R. Larciprete, A. Di Gaspare, R. Cimino
- **INFN-LNF / BTF** (particle Beam Test Facility): P. Valente (PI), B. Buonomo, L. Foggetta
- **ILRS & ASI-MLRO** (Matera Laser Ranging Observatory): G. Bianco
- **INFN & Univ. Padova** (Laser Quantum Communication and Encryption): P. Villoresi (PI), G. Vallone, M. Schiavon, M. Tomasin, P. Salvatori
- **INFN Roma 2 / LARASE** (LAser RAnged Satellite Experiment): D. M. Lucchesi (PI), R. Peron, M. Visco, G. Pucacco

US Collaborators

Satellite/Lunar Laser Ranging & Lasercomm community

- S. Merkowitz (GSFC), J. Mc Garry (GSFC), M. Pearlman (ILRS/CfA), J. Degnan, D. Smith (MIT, GSFC-retired)
- D. Currie (UMD, Apollo Veteran), T. Murphy (UCSD), J. Chandler (CfA), I. Shapiro (CfA), C. Neal (U. Notre-Dame), J. Williams (JPL)
- B. Abhijit (JPL), M. Wright (JPL), M. Hoffmann (GRC), D. Raible (GRC)

Planetary Science/Exploration community (PIs of SSERVI-funded projects)

- **W. Farrell**, NASA Goddard MD
- **T. Glotch**, Stony Brook University NY
- **J. Heldmann**, NASA Ames CA
- **M. Horanyi**, University of Colorado in Boulder CO
- **D. Kring**, Lunar and Planetary Institute in Houston TX
- **C. Pieters**, Brown University in Providence RI
- **W. Bottke**, Southwest Research Institute in Boulder CO
- **D. Britt**, University of Central Florida in Orlando FL
- **B. Bussey**, Johns Hopkins University APL in Laurel MD

Satellite/Lunar Laser Ranging (SLR/LLR)

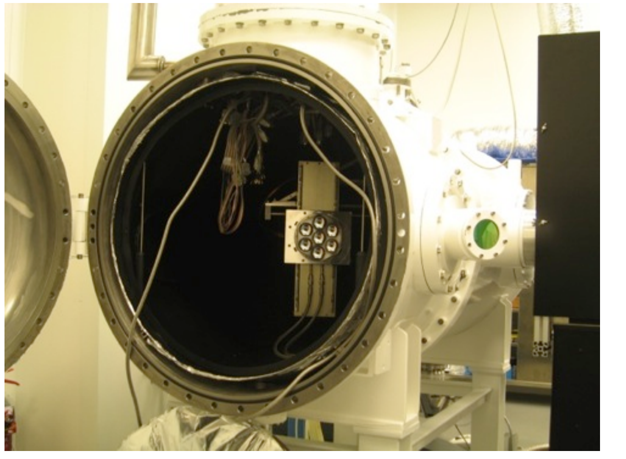
- Time of Flight (ToF) of short laser pulses
- International Laser Ranging Service (ILRS). New:
  - **SCF_Lab** (CSN2/5) is Associate Analysis Center for LLR
  - **LARASE** (CSN2) is Associate Analysis Center for SLR
- **1st SLR to cube corner retroreflectors (CCRs) 50 years AGO,** October 31, 1964 from NASA-GSFC, by H. Plotkin et al

INFN-NASA/SSERVI Affiliation goals

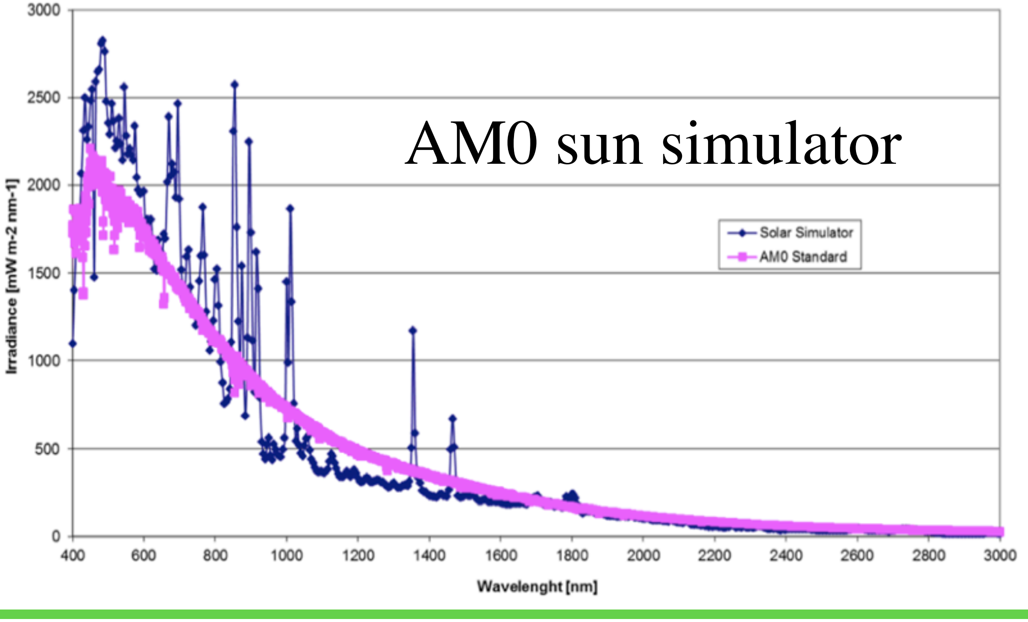
- Jointly study and develop technologies for LRAs, their characterization and their applications to laser ranging, laser altimetry and lasercomm within missions in the Solar System
- Allow INFN and NASA to jointly exchange information
- Involvement also of DAΦNE-Light, BTF, MS_Lab as LNF "Internal Special Facilities", with unique expertise in calibration, characterization and test of payloads, detectors with low-energy radiation, photons, electrons, positrons, neutrons

SCF_Lab: reflector characterization

2 Optical Ground Support Equipment (OGSE)



- SCF (top); SCF-G (bottom right) for Galileo
  - Two AM0 sun simulators, IR thermometry
  - Very detailed optical testing
  - J. Adv. Space Res. 47 (2011) 822–842
- Next, I: seeking ISO-17205 (space certification)
- Next, II: active optical payload/microsat for ISS (with INFN/U. Pd, ASI)



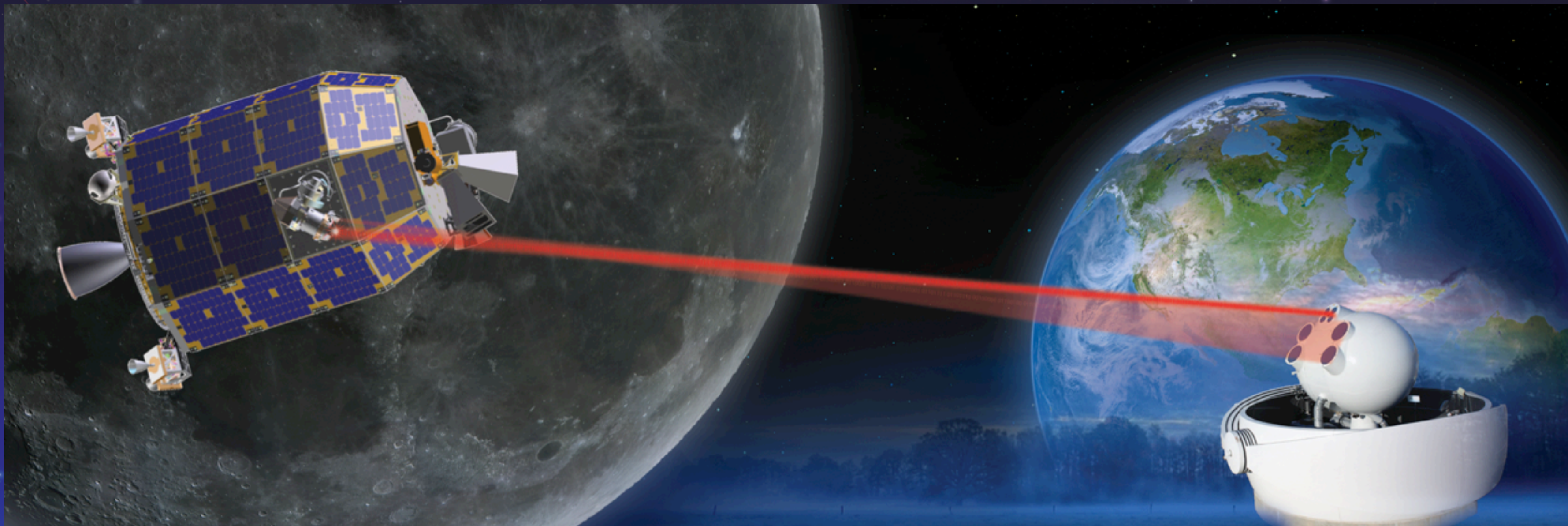
SCF-Test: Retroreflector characterization

- 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 ($\boldsymbol{\tau_{CCR}}$)
  - **Optical response**
    - Far Field Diffraction Pattern (FFDP)
    - Wavefront Fizeau Interferometer (WFI), vibe-insensitive
- Invariant lidar Optical Cross Section, OCS, in air/isothermal conditions

Moon: a test body for General Relativity

- Next-generation **single, large reflector** "MoonLIGHT", laser ranged by Earth
  - D. Currie, Univ. of Maryland
  - Italian Teams: INFN-LNF, ASI, INFN/Univ. Padua
- Orbit sw: PEP by CfA, installed and run @SCF_Lab
- **Microreflector**, "INRRI" laser ranged by orbiters
  - Planetary geodesy and georeferencing rovers and landers
  - Motivated by success of Lunar Laser Communications Demo (LLCD) on LADEE
    - Earth-Moon laser ToF @ ~100-200 psec accuracy

NASA's First, Historic Lasercom Mission

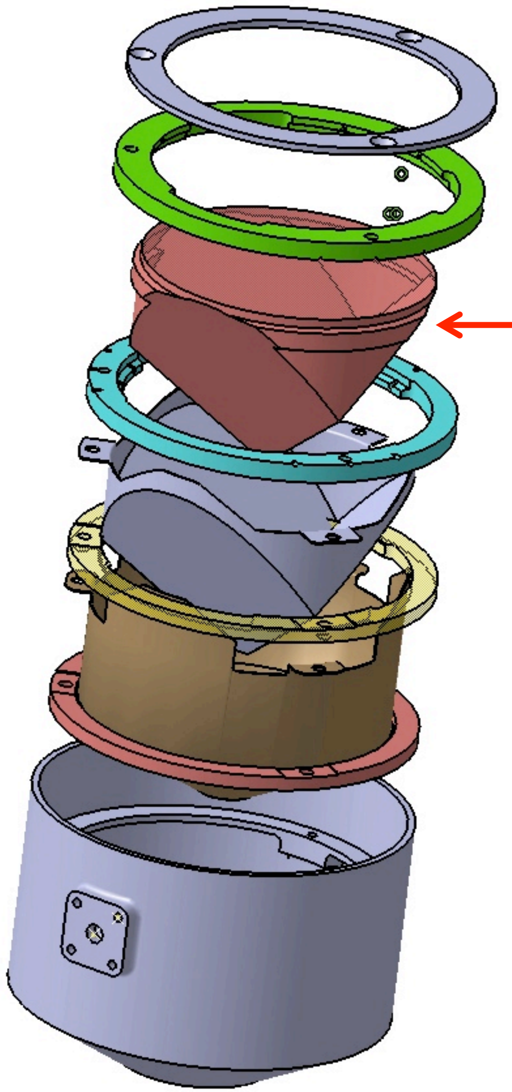


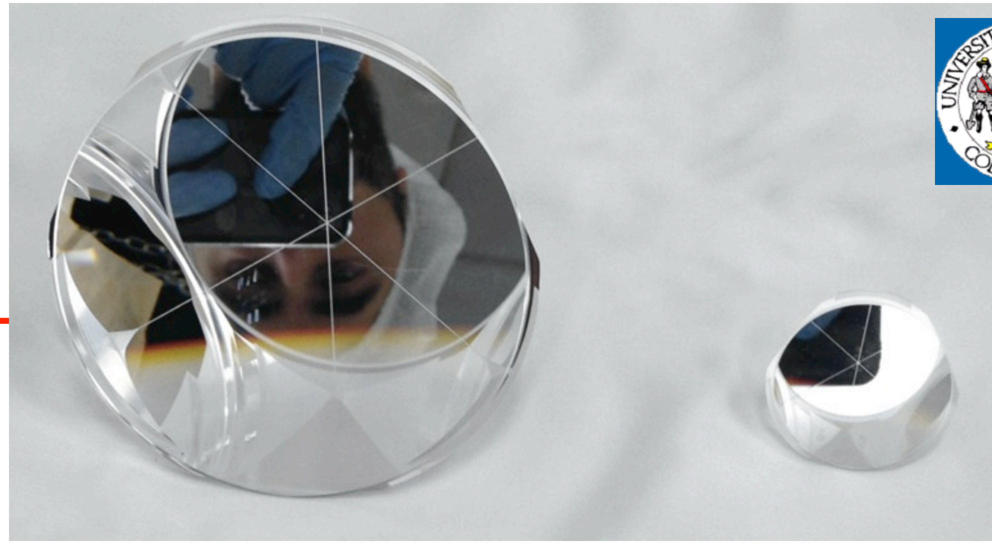
The Lunar Laser Communication Demonstration (LLCD), Flown to the Moon in September 2013

NASA GSFC, MIT Lincoln Laboratory, NASA JPL, ESA

MoonLIGHT (INFN-CSN2/CSN5)

(Moon Laser Instrumentation for General relativity High accuracy Tests)



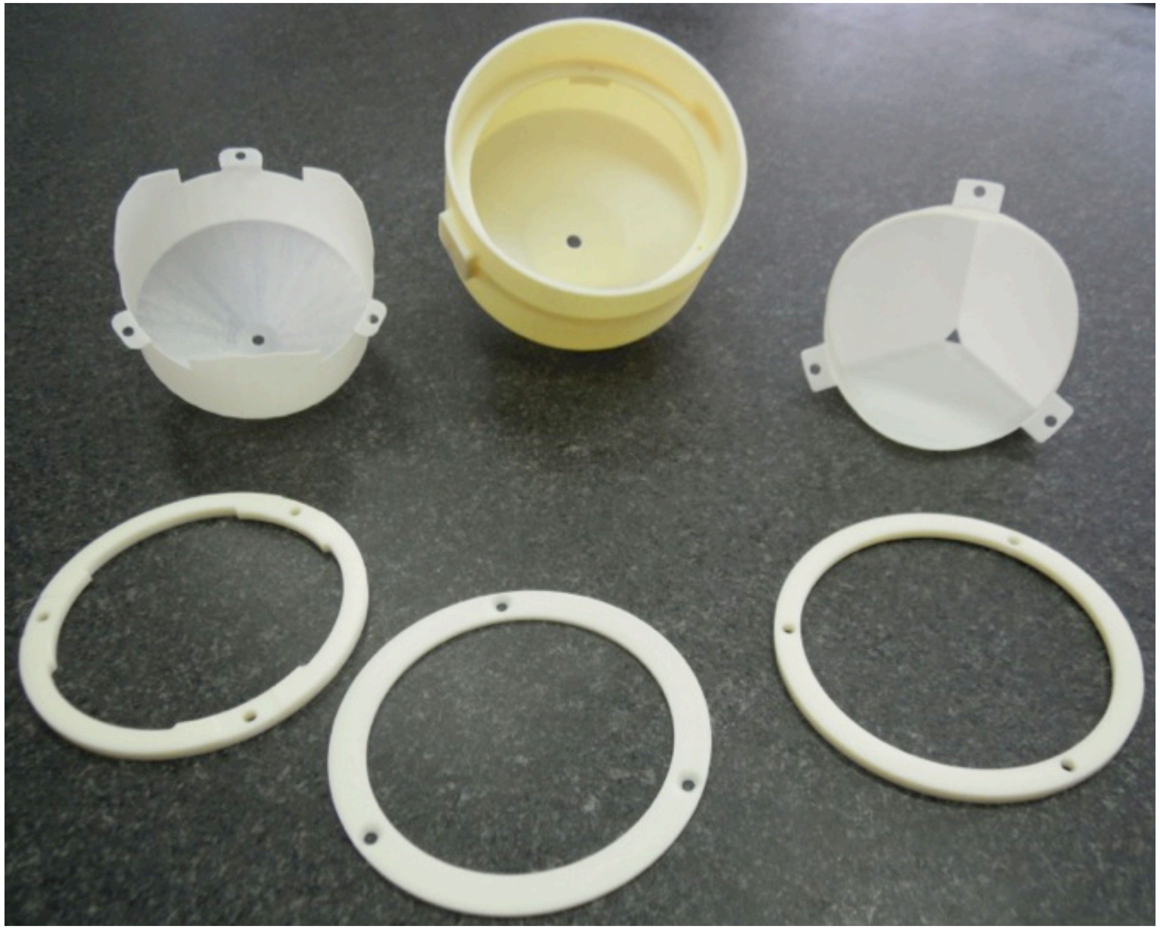


MoonLIGHT vs. Apollo:

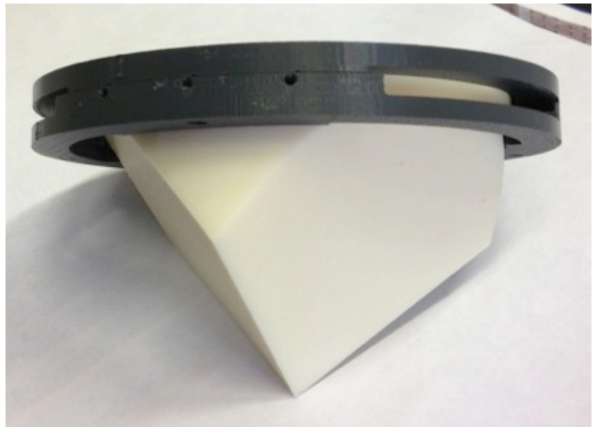
- Suprasil 311 vs. Suprasil 1
- Optical specs wave/10 RMS vs. wave/4
- Single reflector 100 mm vs. array of 100-300 reflectors of 38 mm
- Laser return better than Apollo 15 (brightest reflector array) due to A15 degradation, likely due to dust deposit

MoonLIGHT 3D-printed model built in Italy

Full retroreflector package
∅ ~ 130 mm × h ~100 mm



Retroreflector:
∅ = 100 mm



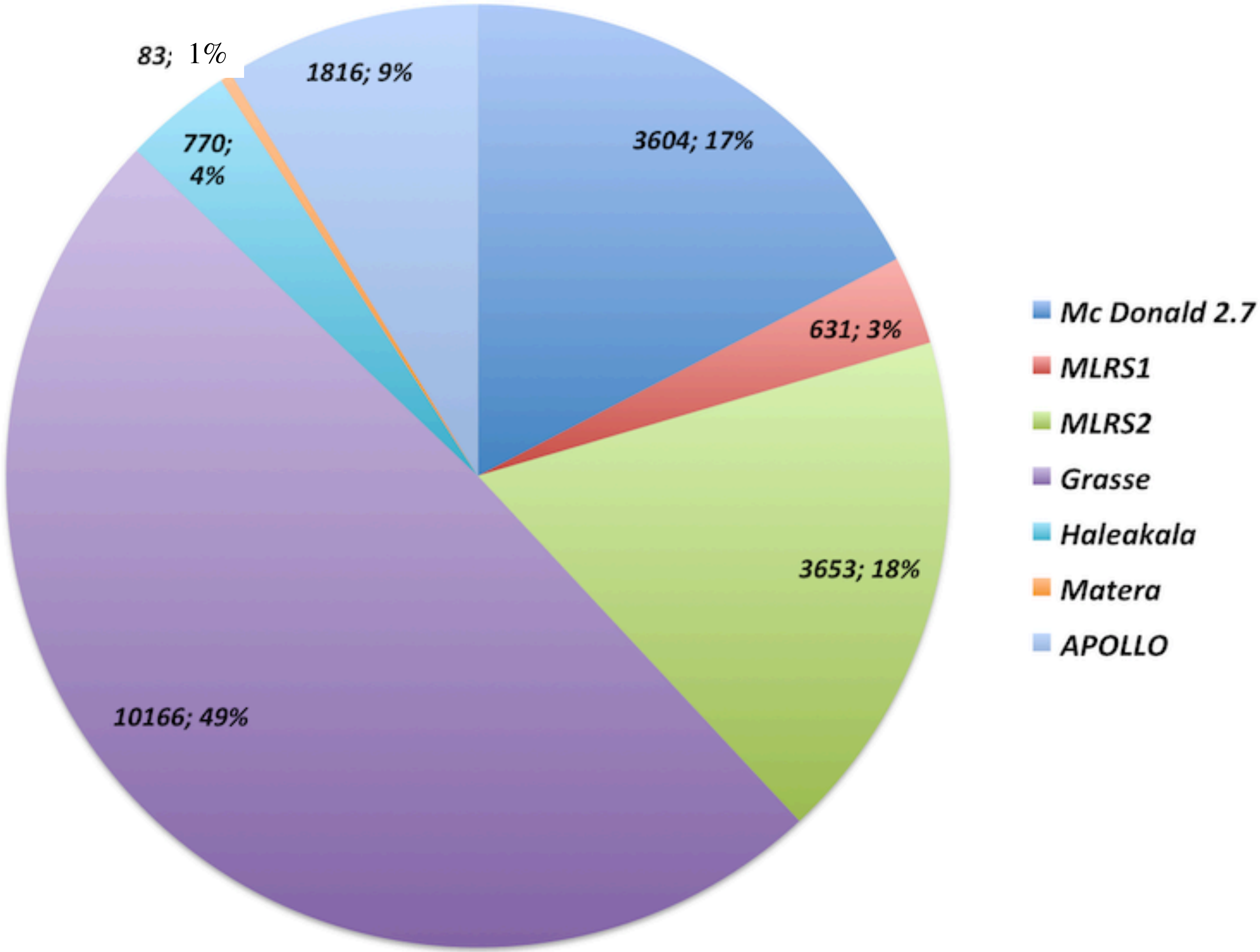
Science with Lunar Laser Ranging

- **General Relativity**: precisions tests, improvement potentially up to ×100 in the long term with 3 MoonLIGHTs in 'best' sites: N/S poles, E/W limbs
- **Selenodesy**: measurement of deep interior; first evidence of molten lunar core
- **Exploration**: precise positioning of landing site, hopping and roving

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

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

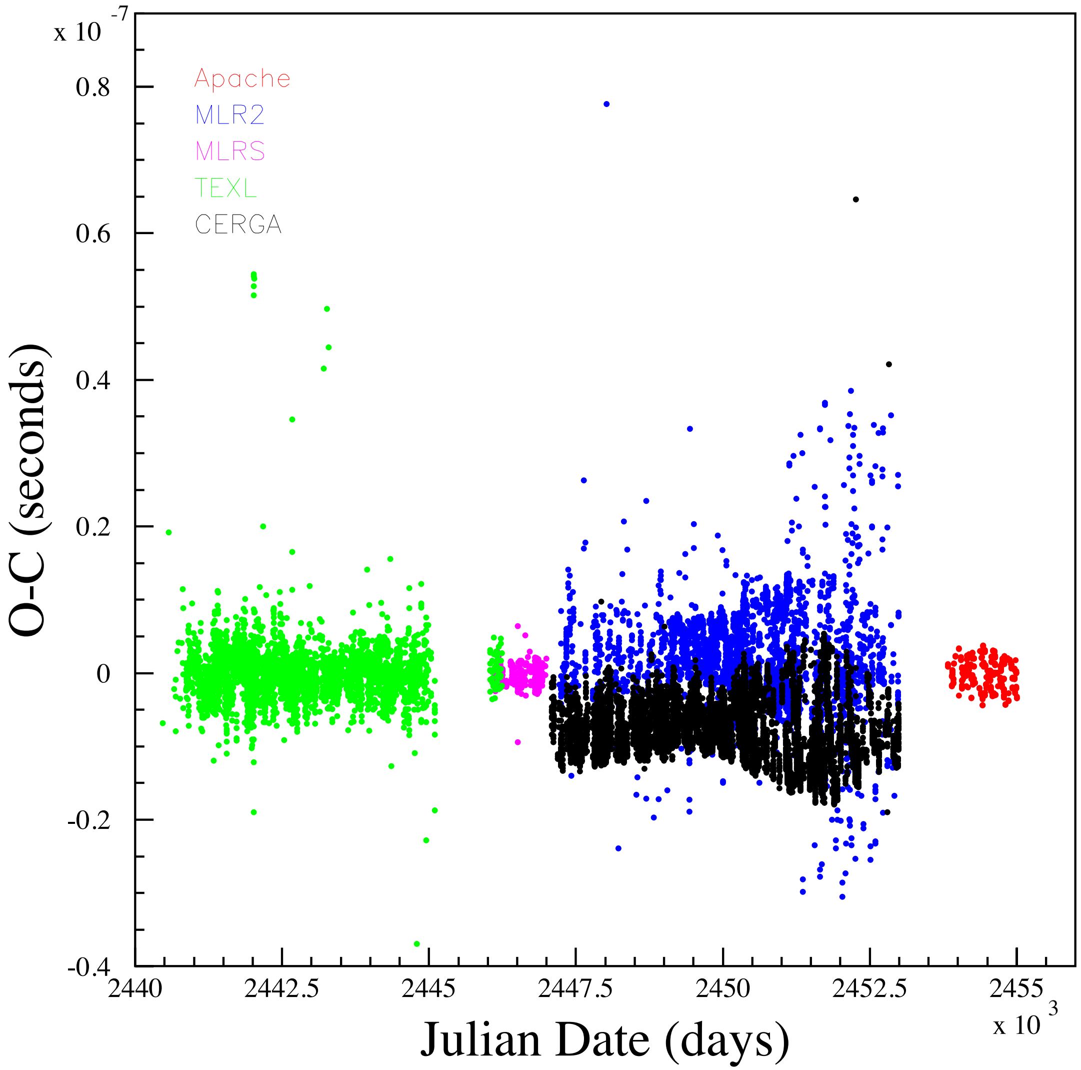
Data Analysis: LLR Normal Points



CfA & LNF Lunar orbit analysis with PEP

Observed-Computed (O-C) Residuals reconstructed with Planetary Ephemeris Program (PEP)

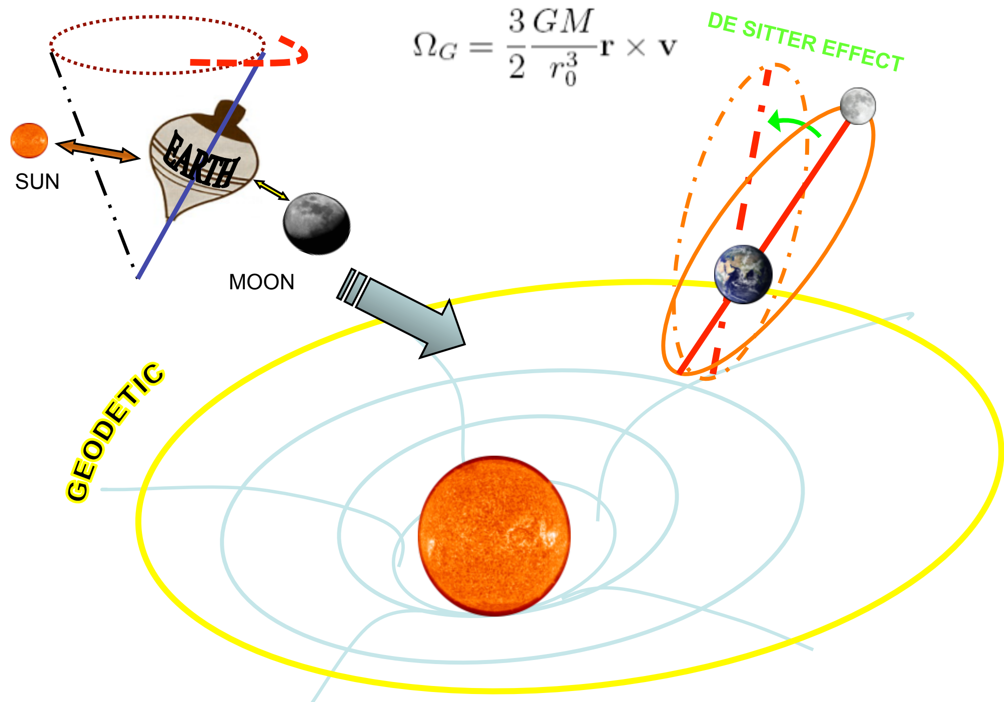
PEP developed since 1970 by Center for Astrophysics (CfA), by I. Shapiro, J. Chandler



LLR measurement of geodetic precession

- 3-body effect predicted by GR: precession of the Earth-Moon gyroscope moving in the field of the Sun ~ (3.00± 0.02)m/orbit
  - K_{GP}: relative deviation from GR value
- Our result with PEP

$$K_{GP} = (4.3 \pm 8.6) \times 10^{-3}$$



- Result by JPL:

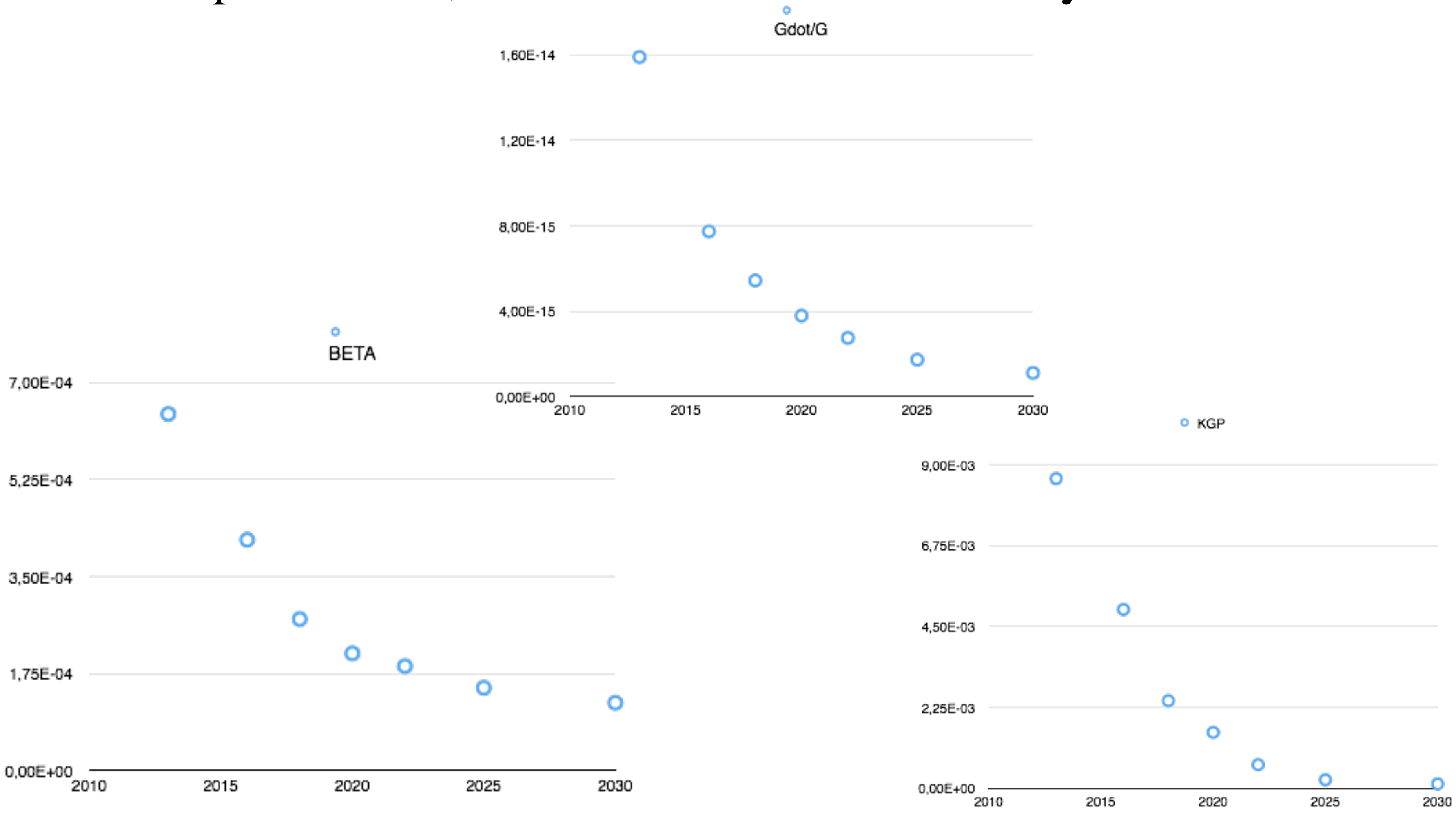
$$K_{GP} = (-1.9 \pm 6.4) \times 10^{-3}$$

- Goals: 0.5% accuracy with current data
- PEP simulations of improvement with our new reflectors

Simulations with PEP: Gdot/G, β, K_{GP}

Current arrays, plus 3 GLXP sites

No site at poles/limbs, most favorable sites chosen by Russia & China



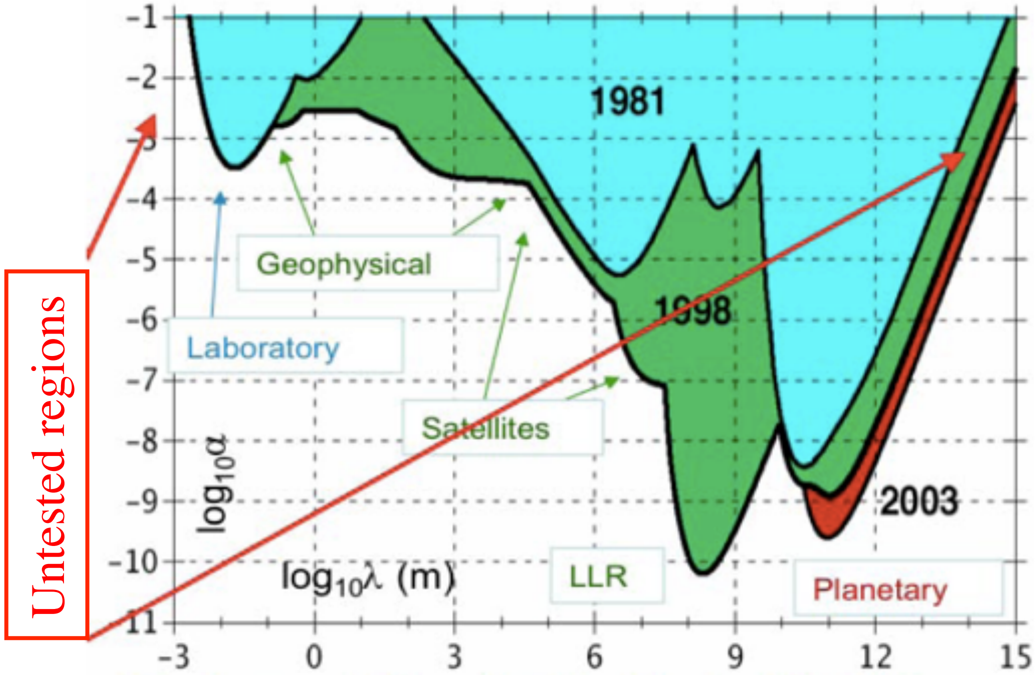
Limits on $1/r^2$ deviations with LLR: up to $\alpha < 10^{-12}$

MoonLIGHT designed to provide accuracy <1mm or better on space segment (the CCR)

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

Limits on Yukawa potential:

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



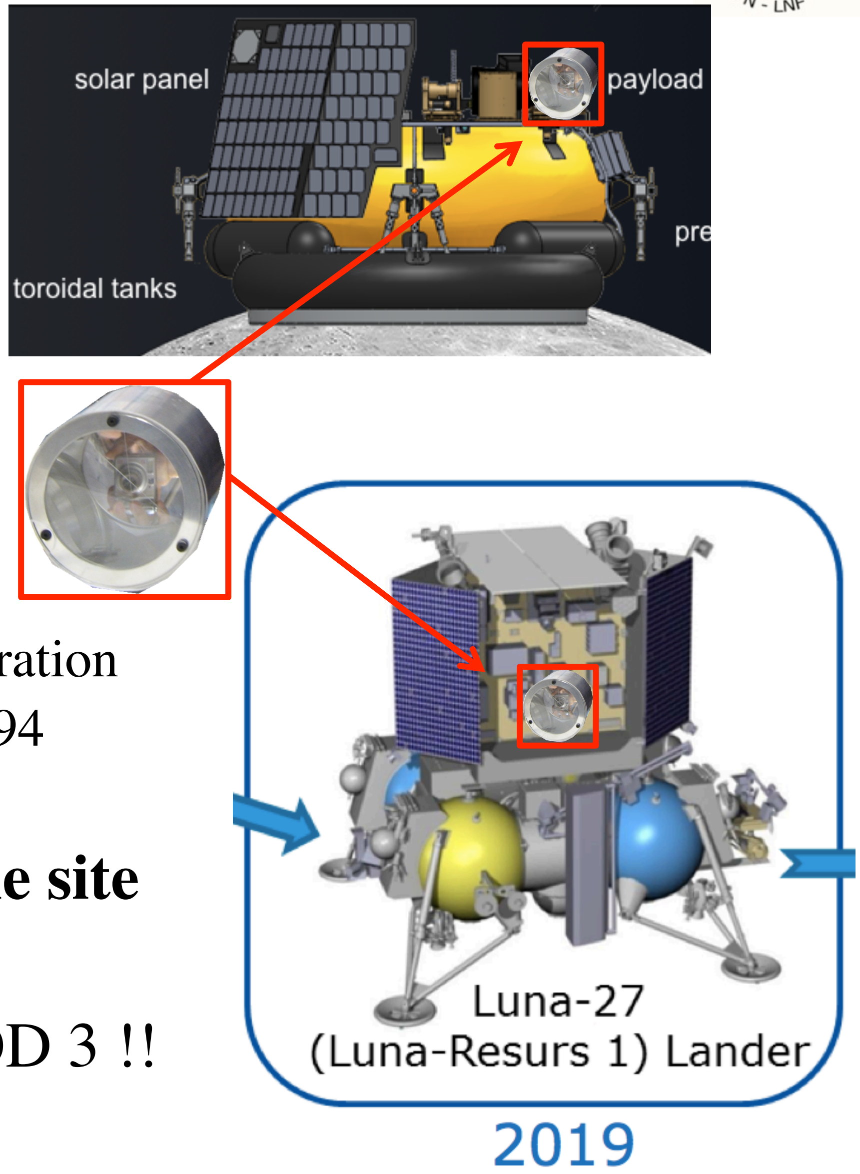
Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

General Relativity, New Gravity Physics

- LLR test of general relativity (GR: PPN β, Gdot/G, geodetic precession, …)
  - Planet and Space Sci 74 (2012), *Martini, Dell'Agnello et al*
  - Nucl Phys B 243–244 (2013) 218–228, *Currie, Dell'Agnello et al*
- LLR / SLR constraints to general relativity with Spacetime Torsion
  - PRD **83**, 104008 (2011), *March, Bellettini, Tauraso, Dell'Agnello*
  - GERG (2011) 43:3099–3126, *March, Bellettini, Tauraso, Dell'Agnello*
- Solar System constraints to Non-Minimally Coupled Gravity
  - PRD 88, 064019 (2013), *Bertolami, March, Páramos*
  - Physics Letters B 735 (2014) 25–32, *Castel-Branco, Páramos, March*
- LAGEOS II pericenter GR precession, non-Newtonian gravity
  - PRL 105, 231103 (2010), PRD 89, 082002 (2014), *Lucchesi, Peron*

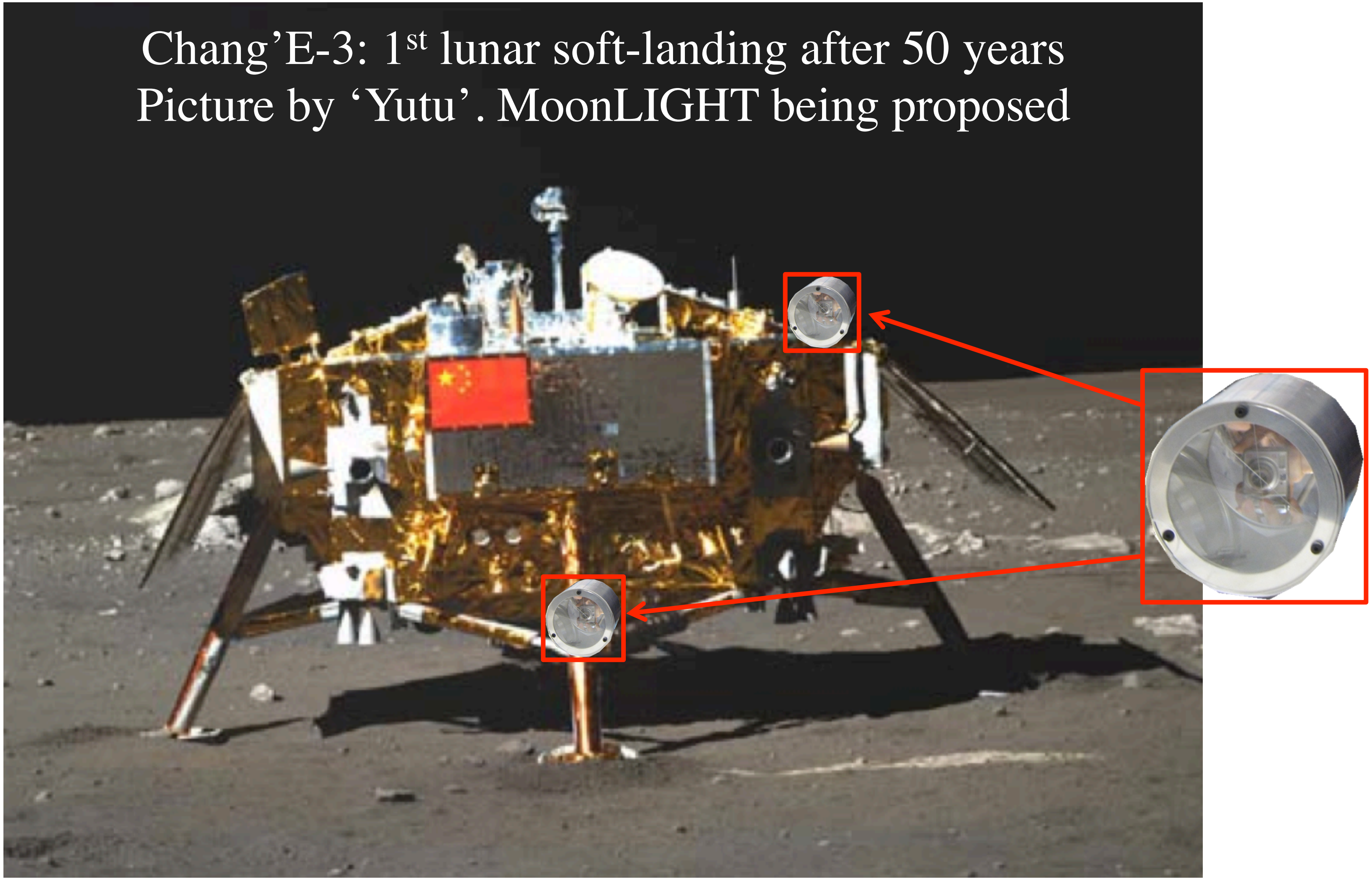
MoonLIGHT/INRRI lunar opportunities

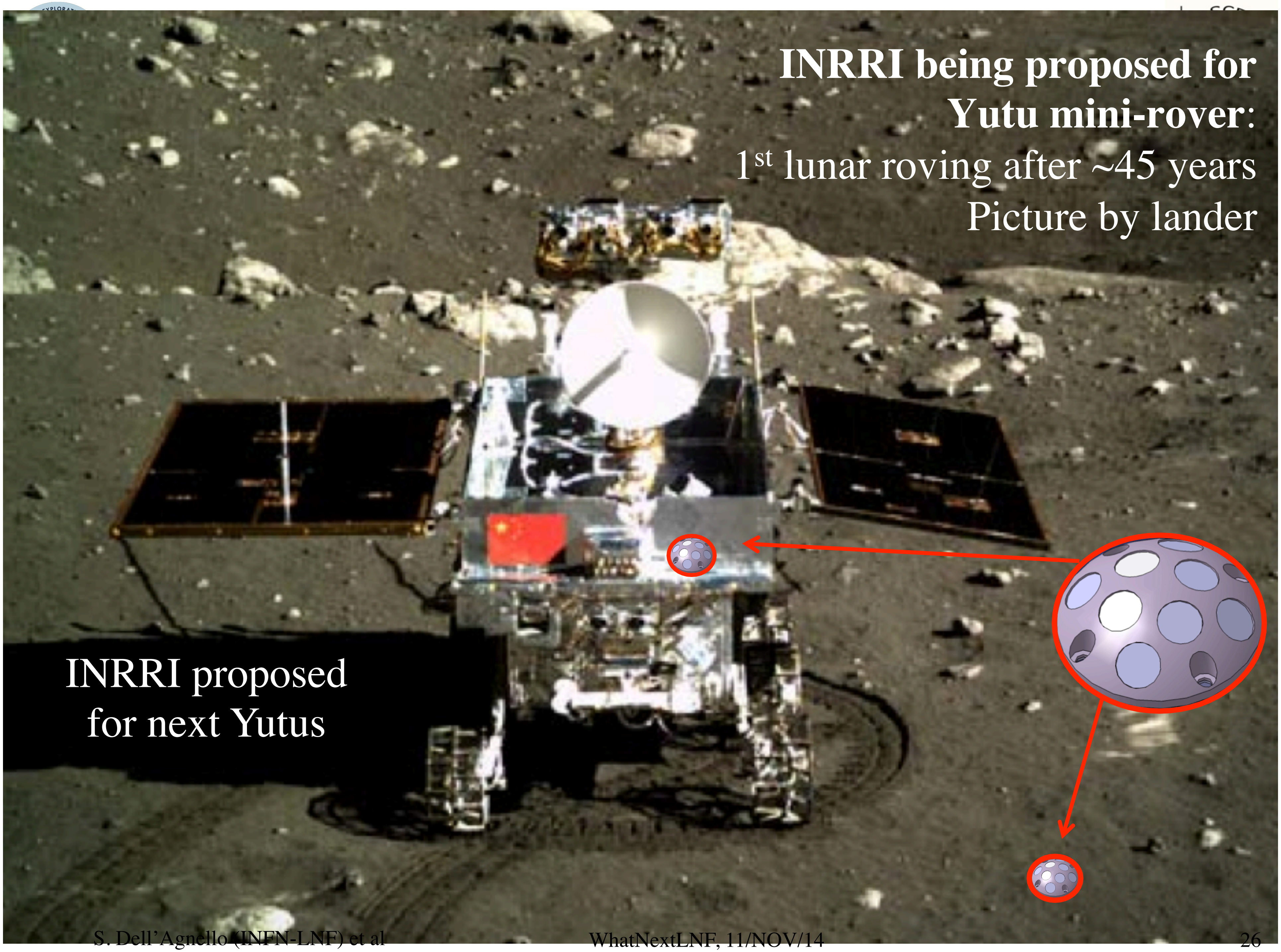
- **Moon Express - 1**, lander for Google Lunar X Prize
  - Launch Dec. 2015
  - Reflectors delivery summer '14
  - Landing site: 45-67N (tbd)



- Proposal to IKI-RAS/Roscosmos for the Lander **Luna-27**
  - Submitted under ESA-Russia Cooperation
  - RAS-INFN valid MoU since mid 1994
  - Under (good) evaluation
- 1st mission to **Pole, most favorable site**
- **Luna 28**: sample return
- **Luna 29**: lunar rover, LUNOKHOD 3 !!

Proposal to CAS for China Chang'E-4/5/6




INRRI being proposed for
Yutu mini-rover:
1st lunar roving after ~45 years
Picture by lander
INRRI proposed
for next Yutus

National Aeronautics and Space Administration

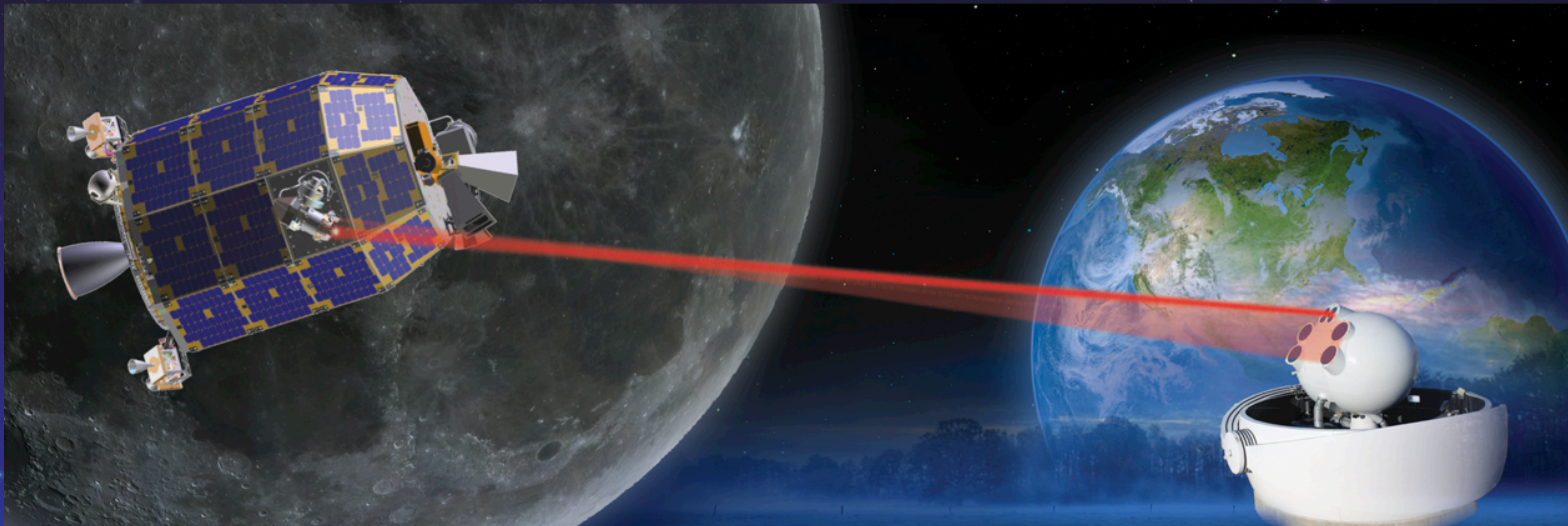
Beyond the Moon with lasercom ….

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.

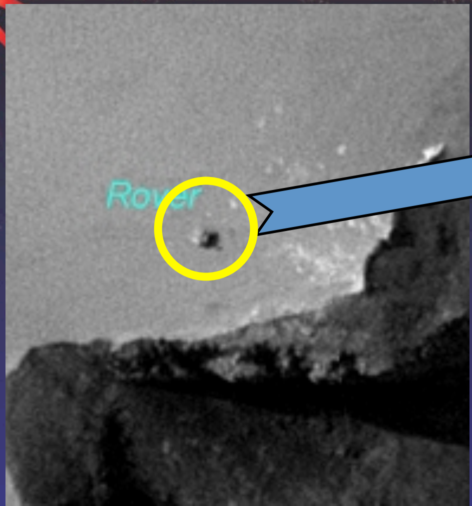
NASA's First, Historic Lasercom Mission



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

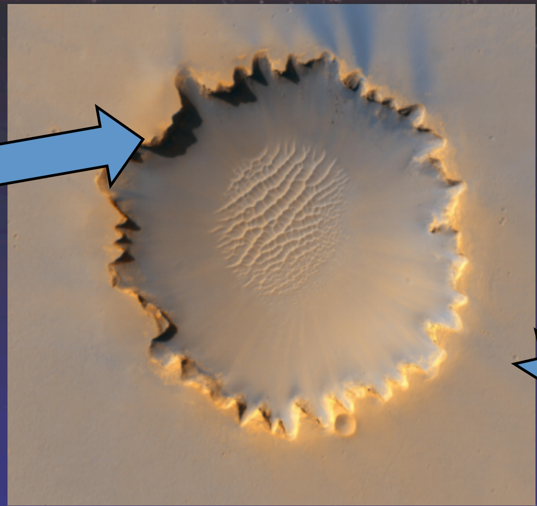
NASA GSFC, MIT Lincoln Laboratory, NASA JPL, ESA

NASA's science data needs are driving faster download data rates…

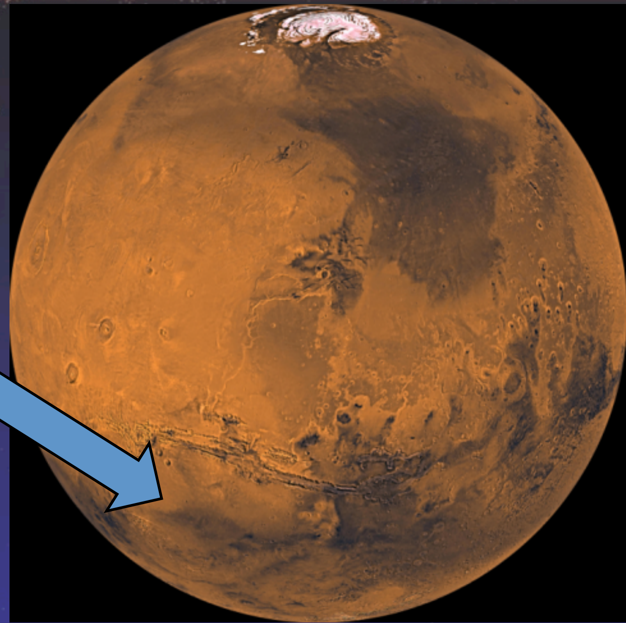


Mars Rover

From HiRISE camera, MRO
Approx 30 cm resolution



Victoria Crater



Mars

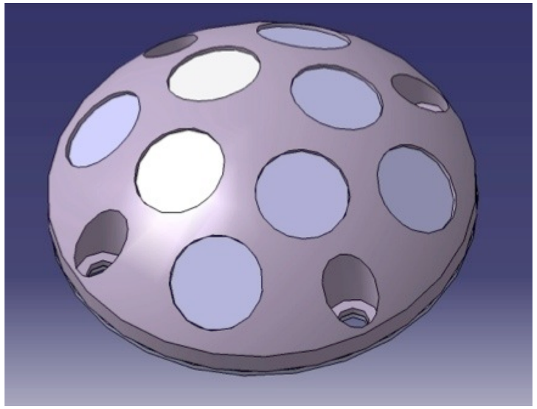
To transmit a 30 cm res map of entire Mars surface (1.6e15 points)

- at 1 bit / pixel:
- 6 Mbps requires 9 years (best Ka-band)
- 250 Mbps requires 9 weeks (JPL's DOT)

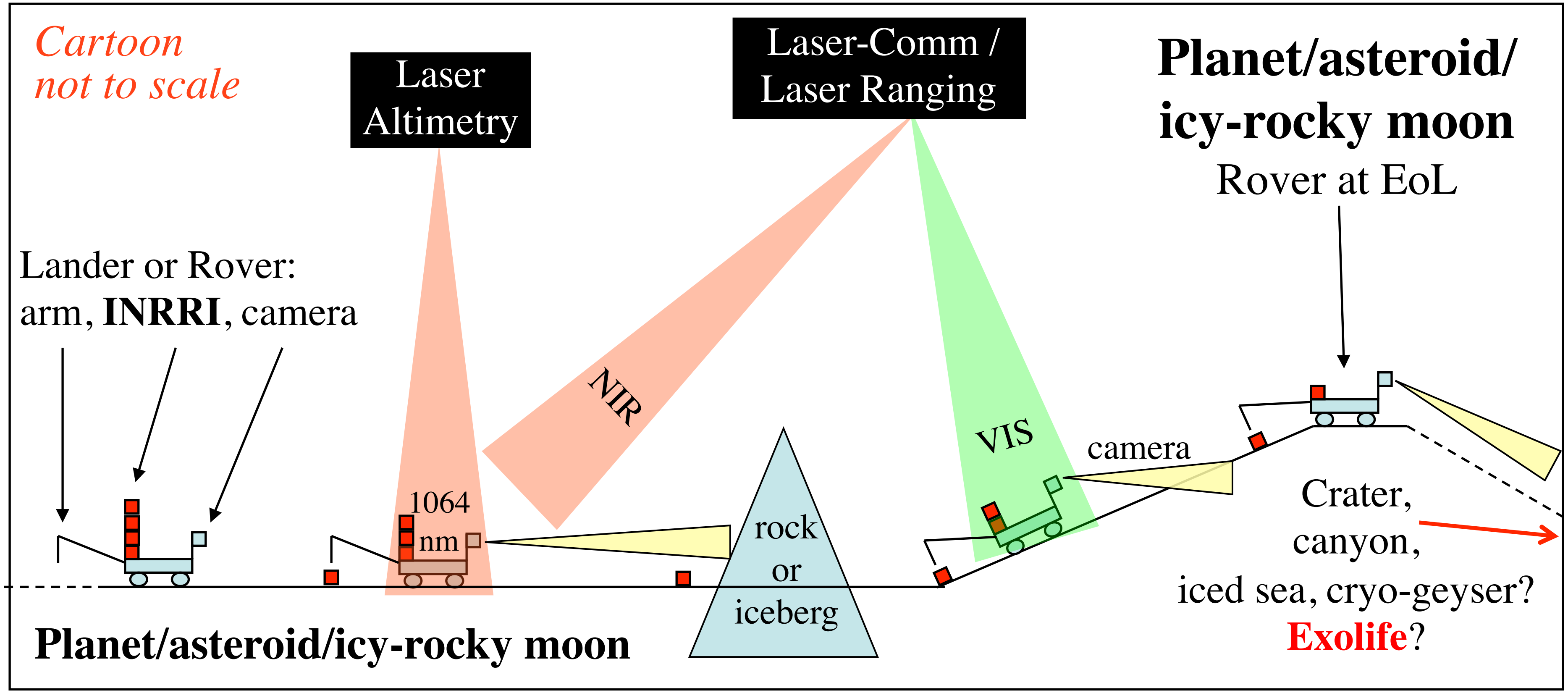
Higher data rates will be required to break through the present-day science return bottleneck

INRRI: INstrument for landing-Roving laser Retroreflector Investigations

- Laser-located by orbiters (LLCD/LADEE-like)
  - **Accurate positioning of landing site and roving exploration activity**
  - **Multiple INRRIs: expand LGN (Lunar Geo/physical Network), establish MGN (Mars Geo/physical Network)**
- Motivated by effort on lasercomm by NASA, ESA …
- 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

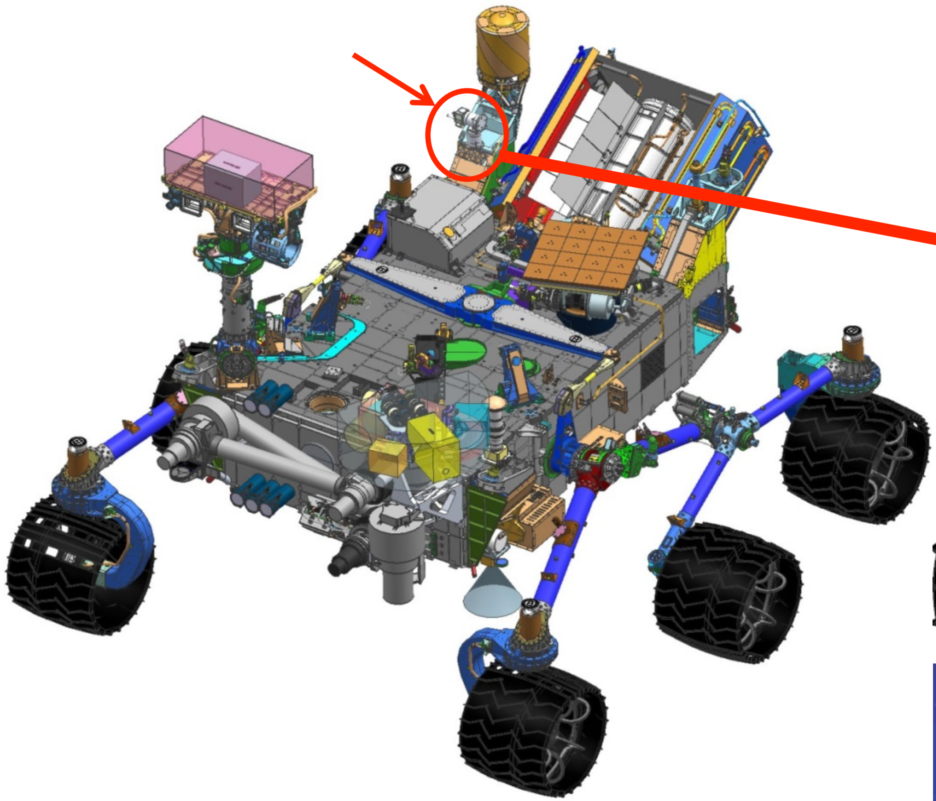


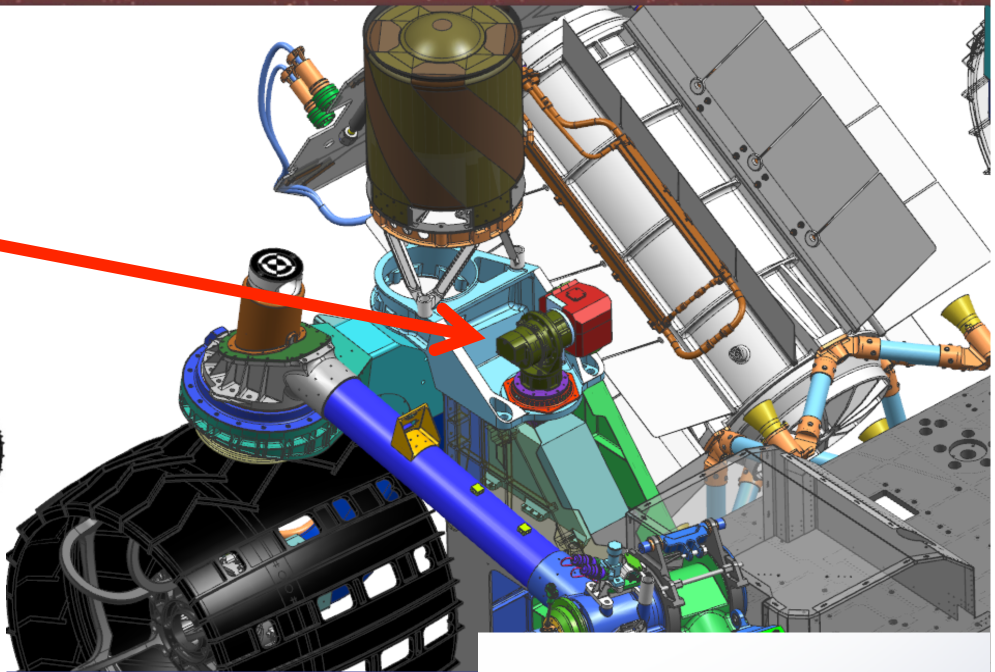
- Selenolocate Rover/Lander with laser retroreflector:
  - Laser Ranging/Comm to reflectors anywhere (LLCD/iROC/OPALS-like)
- **Deploy INRRI networks**. Also on far side of Earth's Moon

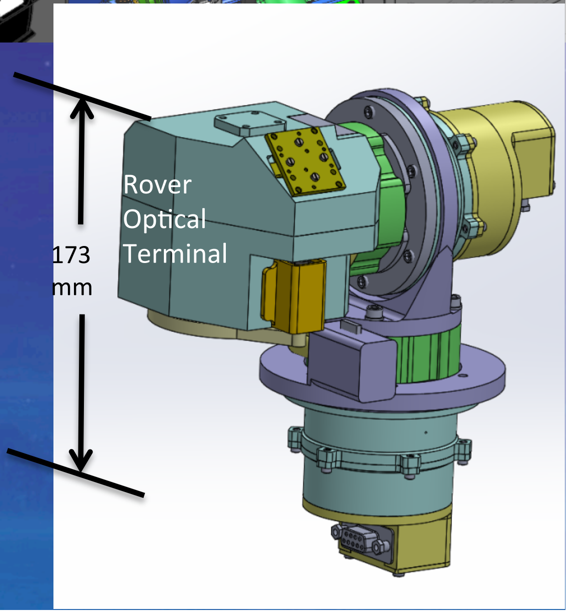
The Martian system: Mars Surface

- Opportunities
  - Mars 2020: direct INFN/ASI-NASA negotiation
  - ESA's ExoMars: through ASI
- Goals for the **Mars surface**
  - Georeferencing of lander or rover exploration activity
  - Multiple INRRIs can establish MGN
  - Define Mars Prime Meridian
    - Now: Airy-0 crater, accurate at 50 m level
  - Lasercomm test/diagnostics (wl independent)
  - Atmospheric trace species detection by space-borne lidar
    - Full column sampling, at varying angles
  - Lidar-based/aided landing

LaserComm for the Mars 2020 Rover



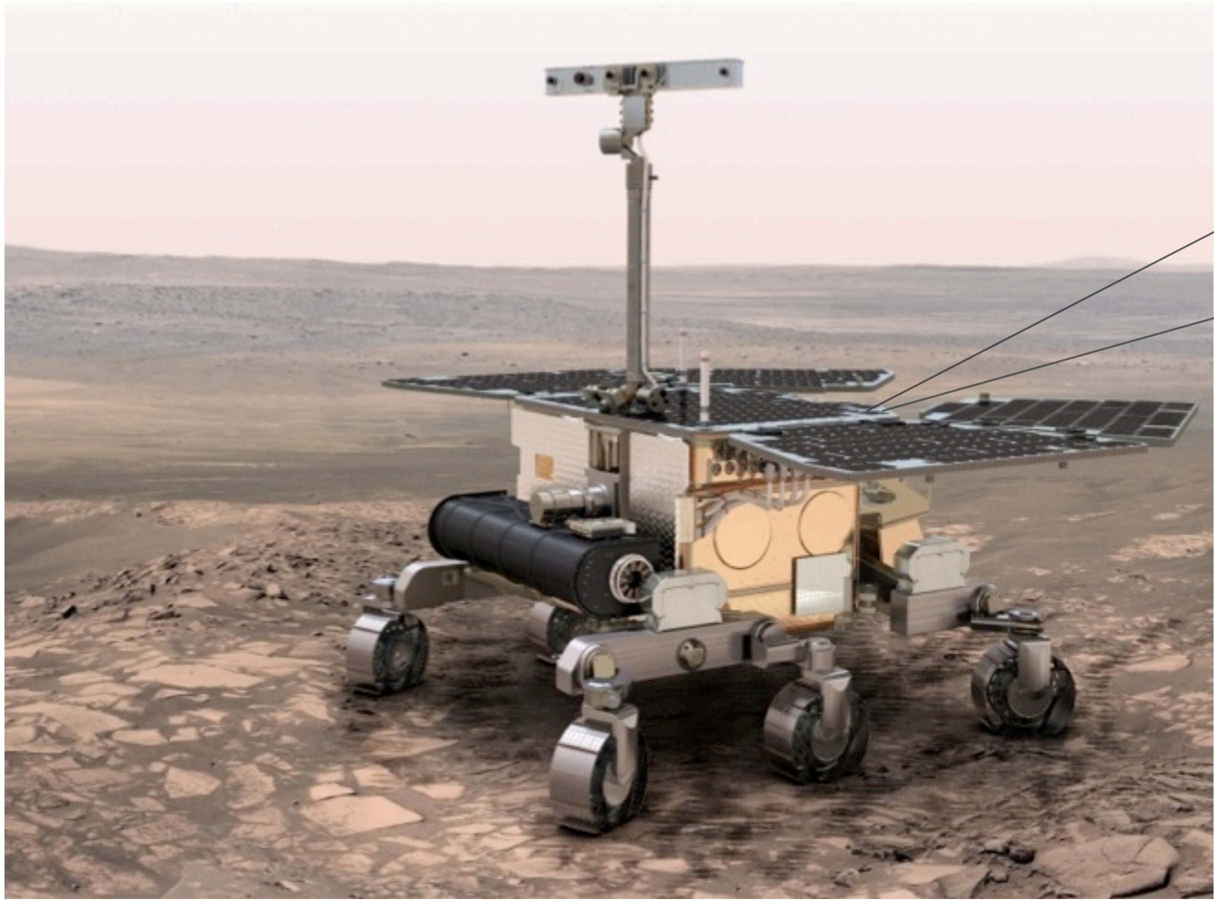


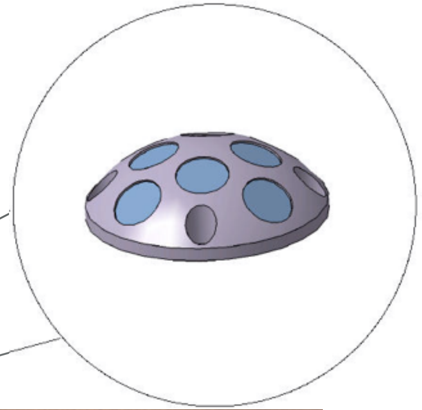


- Optical Terminal will support dual links:
  - "Proximity" link, to optical terminal on orbiter (20 Mb/s max)
  - Direct-To-Earth link (200 kb/s max, from 0.5 AU)
- Optical Aperture Diameter: 5 cm
- Average Laser Power: 1 W
- DC Power Consumption: 50 W
- Mass: 5.7 kg
- Volume: 4.6 liters

INRRI for Mars Rovers (and Landers)

- Geodesy (MGN, Meridian 0). Georeference exploration
- Lidar atmosphere trace species detection
- Lasercomm test & diagnostics



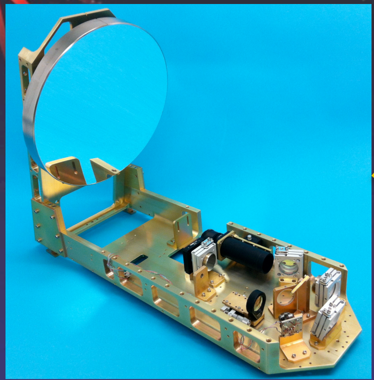


Phobos & Deimos

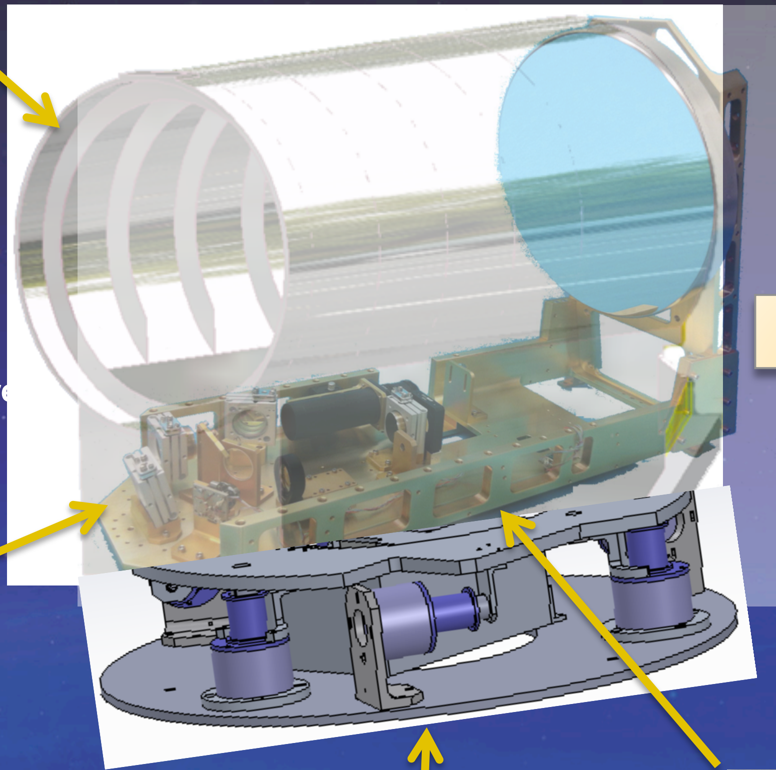
- Gravitational 2-body physics (Sun-Mars): improve up to × 100 γ (spacetime curvature) and Gdot/G
  - 3-body physics (Sun-Mars-Jupiter)
- Physics: SW: PEP by LNF and CfA
- **PANDORA**: Phobos AND DeimOs laser Retroreflector Array
- Direct deployment on Phobos (& Deimos). Or:
- Deployment on PADME, a 2014 NASA Discovery Proposal
- Mars 2020 rover & PADME orbiter, if selected, to fly together!!
- Goal: determine Mars center of mass as focus of laser reconstructed orbit of Phobos (of Deimos), of PADME orbiter
  - Laser: Mars2020 to PADME or Mars2020 to Phobos/Deimos
  - Laser: iROC obiter to Phobos/Deimos

SCaN, STMD, and SMD have been developing the DOT and DSOC since FY11 (now at brassboard)

GOAL is for DOT to be TRL 6 by the End of FY17 for Discovery 2014



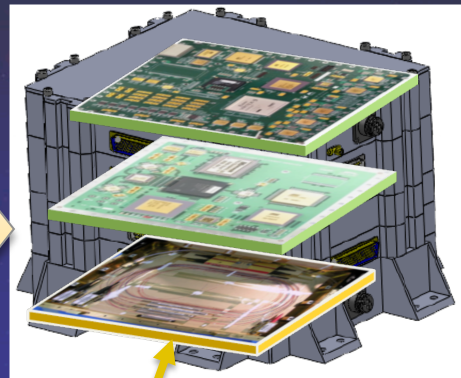
Optics Assembly
- 22cm diameter
- Off-axis Gregorian
- SiC optics and structure
- Uplink receiver
- Downlink transmitter
- TRL5



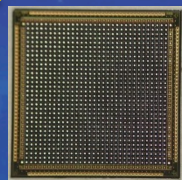
Point-ahead Mirror
- Two-axis
- PZT actuated
- TRL9

Spacecraft Disturbance Rejection Platform
- *Passive and active elements*
- *54dB rejection (0.1 Hz to 10 Hz)*
- *TRL4. TRL5 FY'16. TRL6 FY'17.*

Electronics Assembly
- TRL5 components
- TRL4 subsystem
- TRL5, FY'15. TRL6 FY'16



Laser Transmitter
- Pulsed fiber amplifier
- TRL4/5. TRL5, FY'15
- TRL6, FY16



Photon Counting Space Receiver
- 128x128 InGaAsP, Rad-Tolerant Photon-Counting Array
- TRL4 8x8 array
- TRL3 components and subsystem

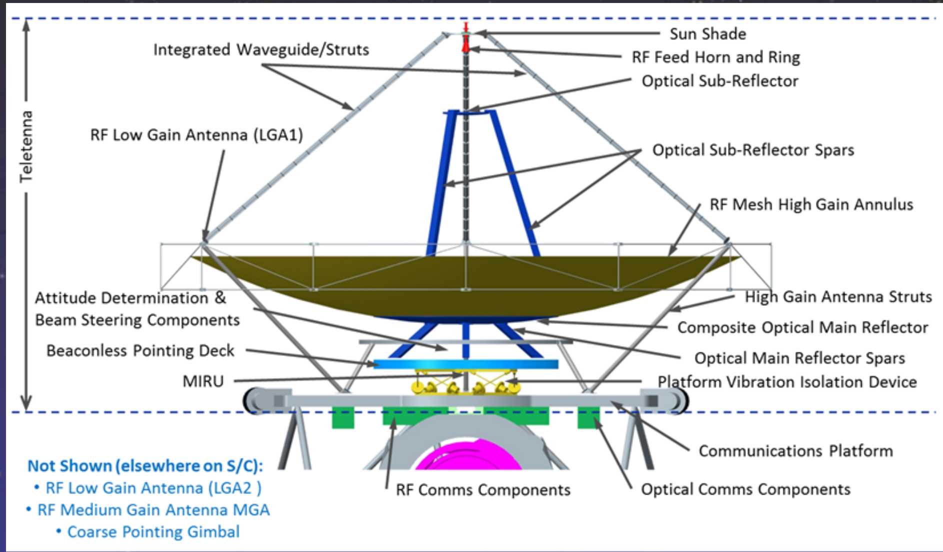
JPL

Integrated Radio and Optical Communications (iROC)

Revolutionary Capability in an Evolutionary Manner

Objectives:

- Combine the best features of deep space RF and optical communications elements into an integrated system
- Increase data throughput while reducing spacecraft mass, power and volume
- Extensible to, and mitigates risk for missions from near Earth to deep space
- Prototype and demonstrate performance of key components to increase TRL, leading to an integrated hybrid communications system demonstration



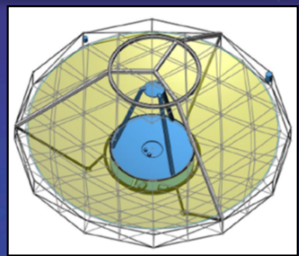
Lead Center: NASA Glenn Research Center, Cleveland, OH
GRC Project Manager: Monica Hoffmann

Co-Principal Investigator: Dr. Daniel E Raible

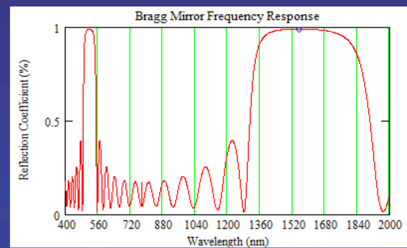
Co-Principal Investigator: Dr. Robert R Romanofsky

Phase:

- **Technology Development/Pre-Phase A**
- **Targeted circa 2022 demonstration**



Integrated RF/optical teletenna



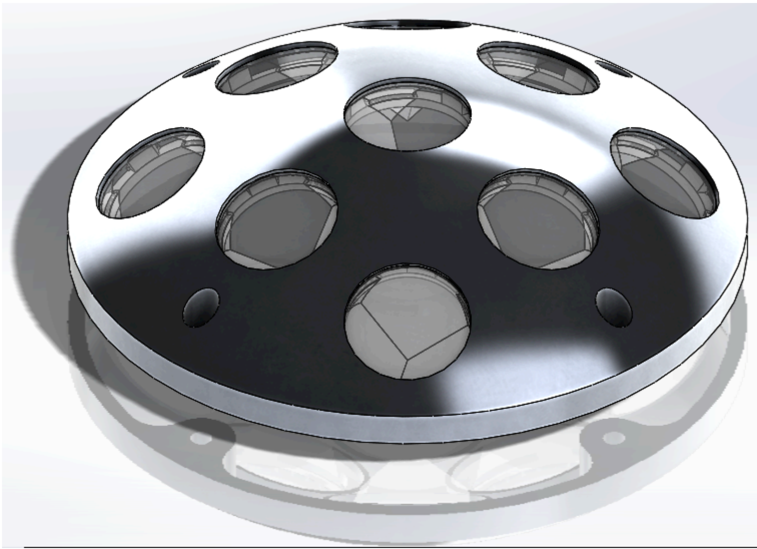
11 Layer hyperbolic Bragg optical sub-reflector

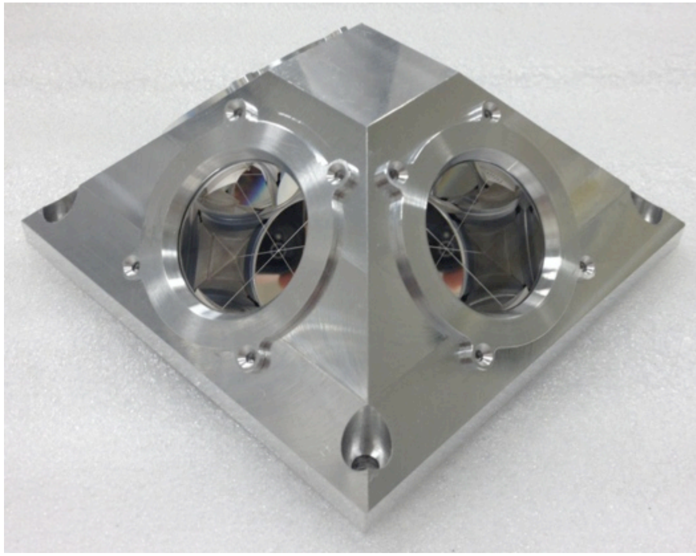
Knitted gold plated molybdenum mesh >98% reflective at Ka-band.

Low density mesh RF annulus

Phobos laser Retroreflector Array

- **PANDORA**: Phobos AND DeimOs laser Retroreflector Array
- Direct deployment on Phobos (& Deimos). Or:
- Deployment on PADME, a 2014 NASA Discovery Proposal
- PANDORA design and prototype





ISS as science platform for INFN (I)

- Built ground positioning devices to geo-reference Earth Observation (EO) maps for Copernicus
  - INFN-CSN5, Ministry of Defense Contract
- Position ground devices accurately with **lasercomm** from ISS
- SCF_Lab devices on ground geo-reference EO maps
- **ETRUSCO-ISS** proposal, SCF_Lab (PI), ASI-Matera
  - Ground devices by SCF_Lab
  - Retroreflectors on ISS to position the ISS
  - Laser by Space Agency with access to ISS
    - <u>OPALS lasercomm by NASA-JPL now on ISS!</u>
    - Other option: ESA

ISS as science platform for INFN (II)

- Laser Quantum Communication Experiment Earth to ISS
  - From ASI - Matera Laser Ranging Observatory (MLRO)
  - Send single photons of known polarization to active terminal on ISS
- **Past Experiment**: passive link to laser retroreflector satellites done by INFN/Univ. Padua group of P. Villoresi
  - Vallone et al *Experimental Satellite Quantum Communications* arXiv:1406.4051
- **New Experiment**: optical terminal on ISS built at SCF_Lab to demonstrate active quantum link Earth to Space
  - INFN/Univ. Padua (PI), SCF_Lab, MLRO, Rome I
- Next slide by G. Vallone at LNF Workshop
  - "Fundamental & Quantum Physics with Lasers", Oct. 23, 2014
- Future: test photon entanglement Earth-Space and viceversa

New QKD satellite protocol using retroreflectors

On the base of this experiment, we propose a two-way QKD protocol for space channels:

- In the ground station, **a linearly polarized train of pulses** is injected in the Coudé path
- The beam is directed toward a satellite with **CCRs having a Faraday Rotator** (or equivalent), that rotate the returning polarization by θ, according to QKD protocol
- A measure of the intensity of the incoming beam avoid Trojan horse attack
- In the CCR a suitable attenuator lowers the mean photon number to the **single photon level**
- The state measure is done as in present experiment

G. Vallone *et al.*, *Experimental Satellite Quantum Communications*, **[arXiv:1406.4051]**

Outlook: SCF_Lab 2015-2030

- Precision Test of Fundamental Gravity
  - Lunar Laser Ranging: MoonLIGHT-2 Program
  - NASA-INFN Partnership for Research in the Solar System, up to Enceladus …
  - Gravitational Redshift: Galileo satellites
- Intern. Space Station (ISS) as science platform
  - Laser Positioning Metrology for Copernicus
  - Laser Quantum Physics in Space
- Expansion/evolution of SCF_Lab capabilities for CSN2 experiments?

Spares

Fund. Physics with Galileo: Gravitational Redshift (GRS)

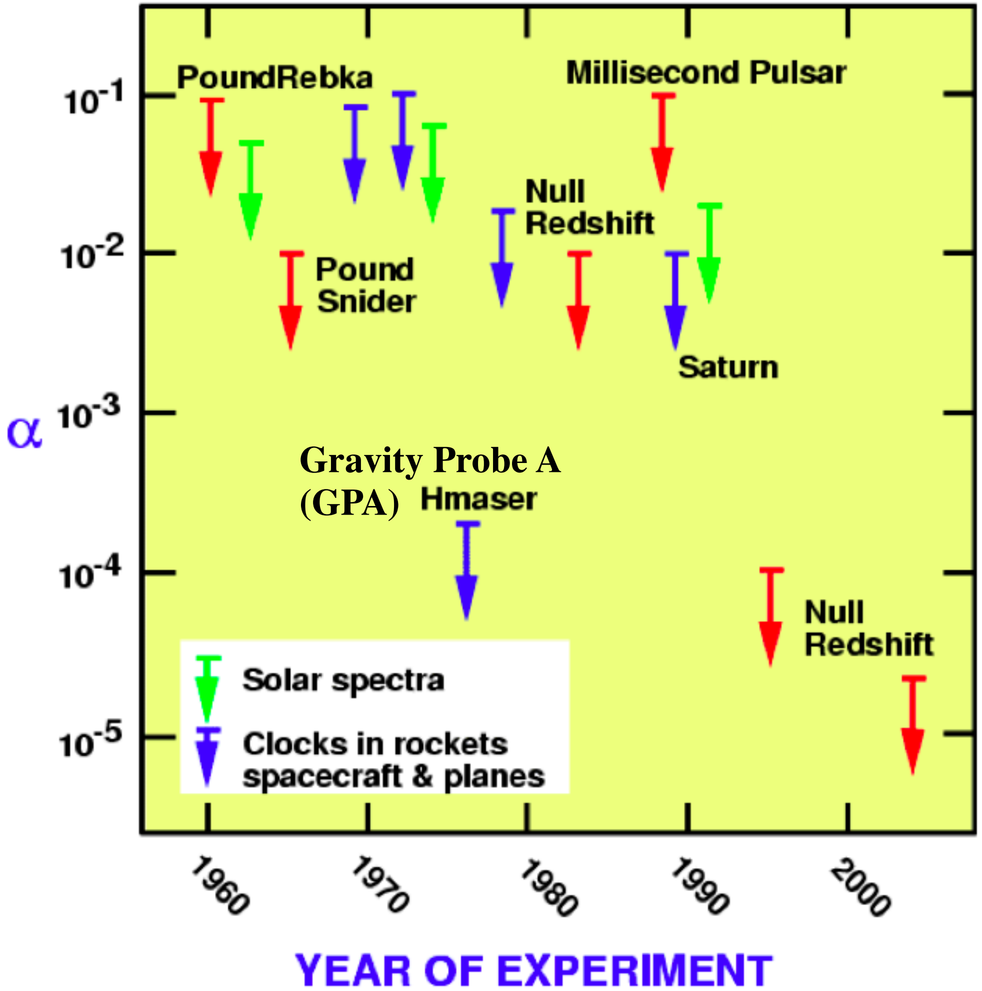
Classical precision test of General Relativity, originally proposed by Einstein
Test of Local Position Invariance (LPI) of all metric theories of gravity.

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

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

where:
U is the gravitational potential
ν is the clock frequency
With Galileo Hmasers and retroreflectors can improve over GPA **up to a factor 100**

Figure courtesy of C. Will



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

- 1 Hydrogen-maser clock
- Maximum orbital height of 10000 Km
- Took data for ≈ 2h

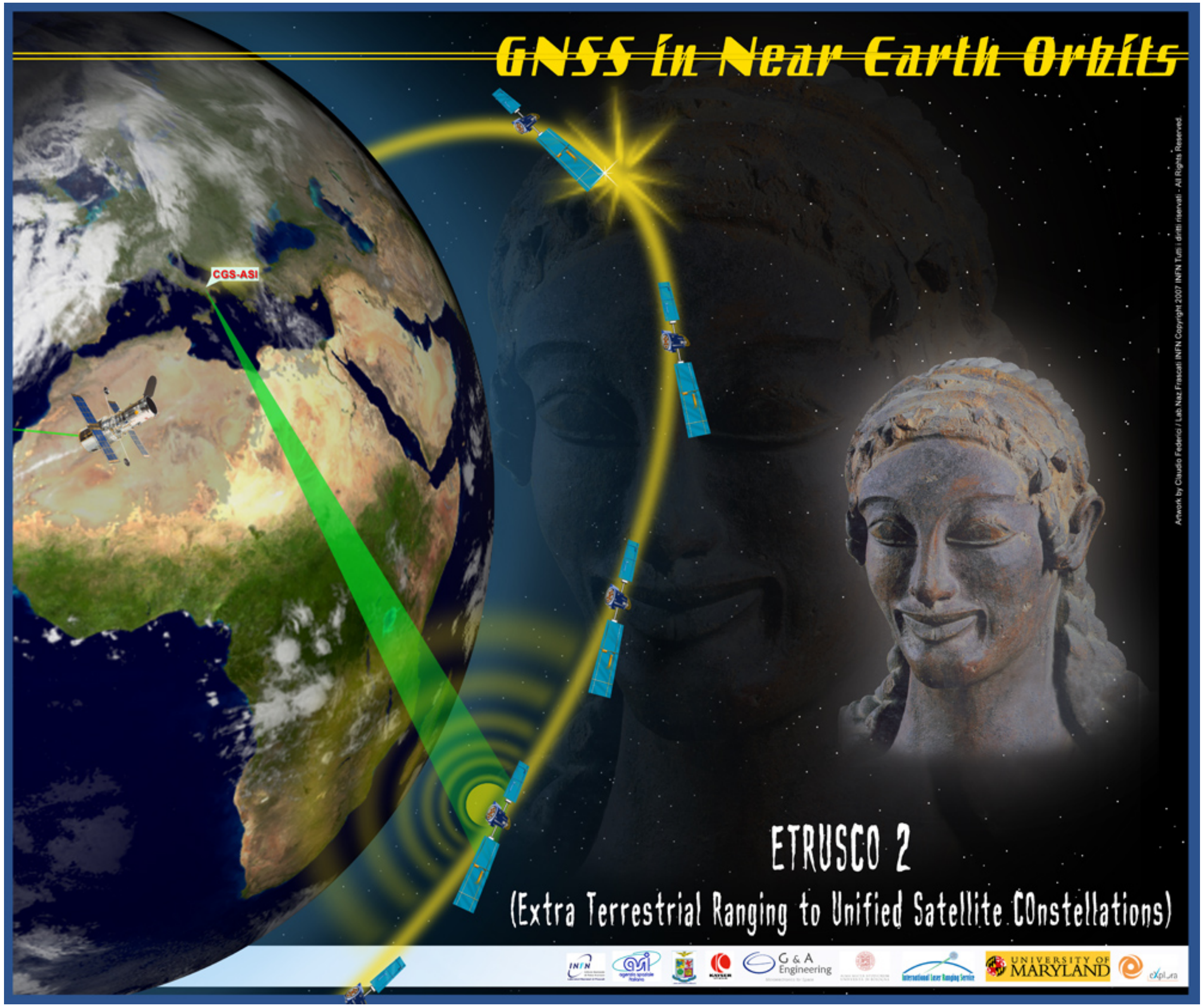
Laser Ranging to Galileo, a 'Premiale'

Project funded by Ministry of Research (MIUR)

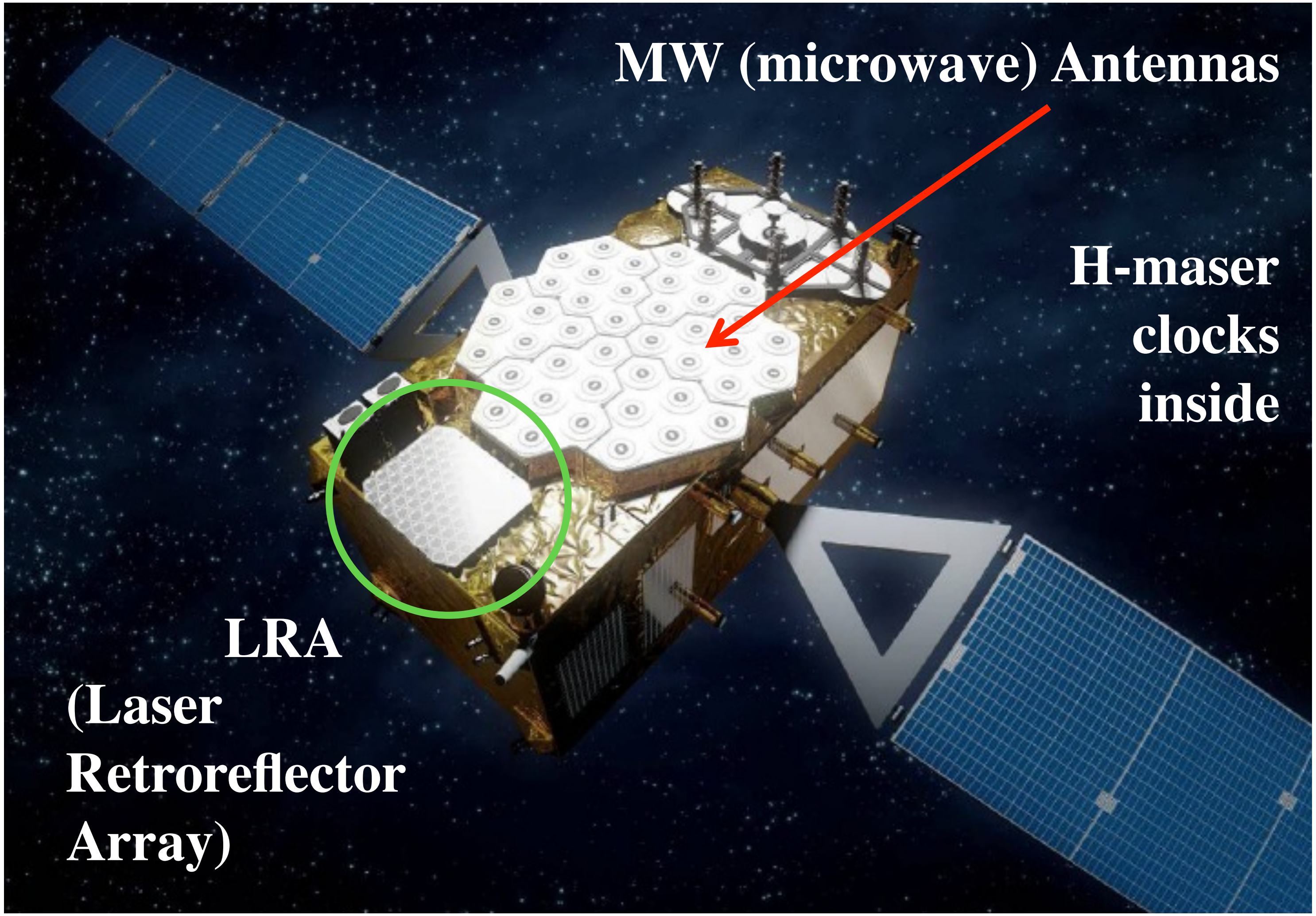
Laser Ranging to Galileo
(ASI-INFN, 2015-16)

ETRUSCO-2
(ASI-INFN, 2010-15)

ETRUSCO
(INFN, 2006-09)



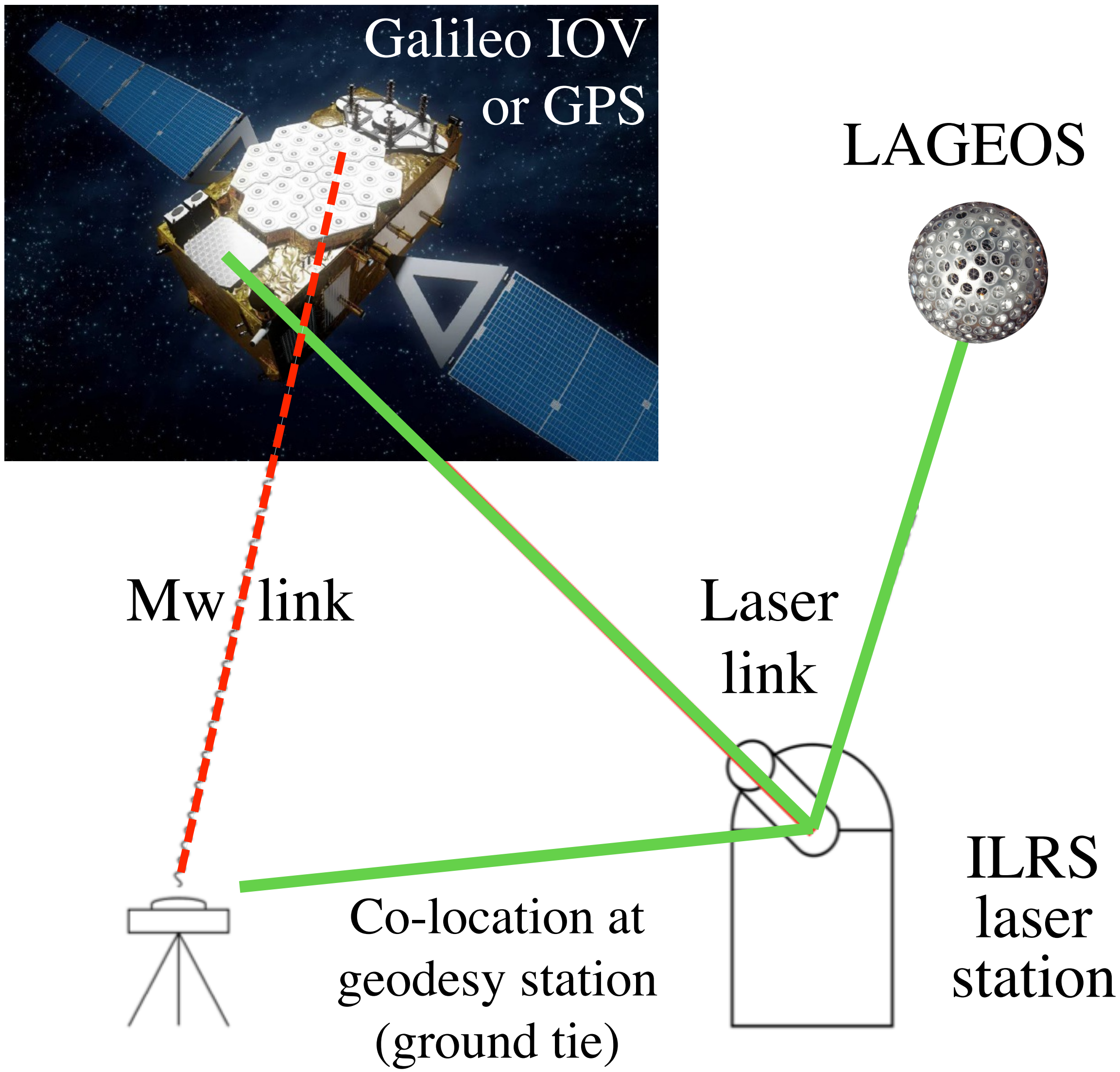
Galileo In-Orbit Validation satellite (IOV)



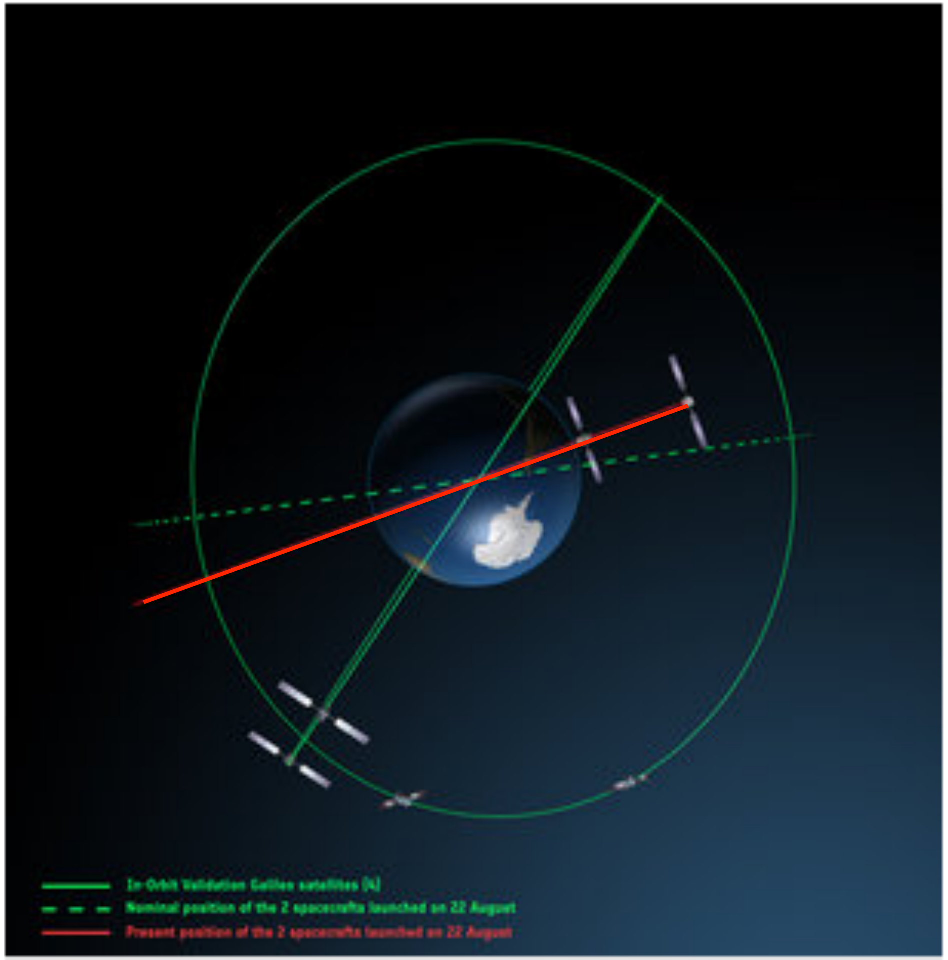
Co-location of SLR & Galileo positioning

Co-location at the GNSS satellite (space-tie)

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



GRS test with lower/elliptical orbits of Galileo 5 & 6



16 September 2014 The fifth and sixth Galileo satellites have been in a safe state since 28 August, fully under control from ESA's centre in Darmstadt, Germany, despite having been released on 22 August into lower and elliptical orbits instead of the expected circular orbits.

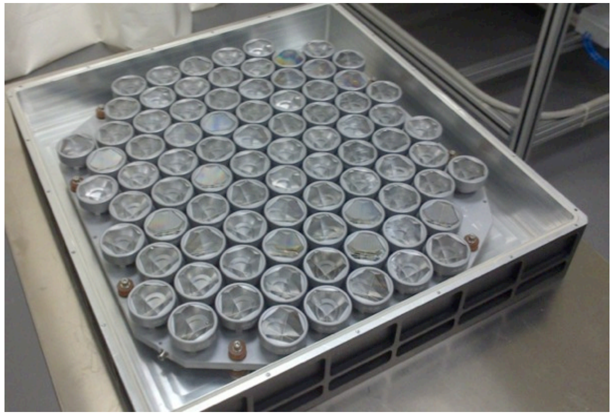
The potential of exploiting the satellites to maximum advantage, despite their unplanned injection orbits and within the limited propulsion capabilities, is being investigated.

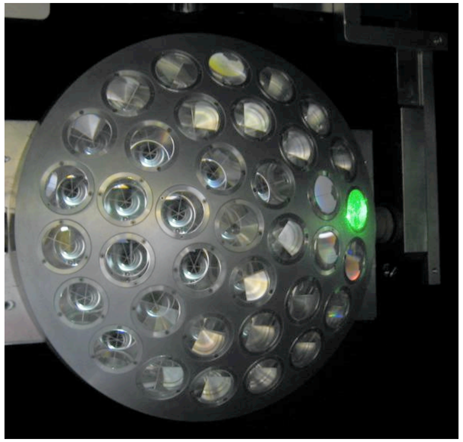
MLRO

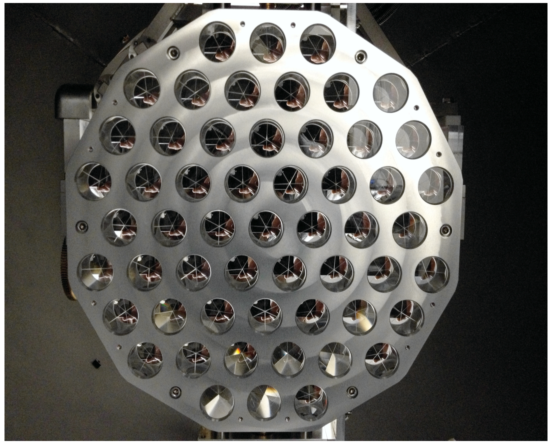
Matera Laser Ranging Observatory.
Led by G. Bianco, PI of “Laser Ranging to Galileo” for ASI
Telescope diameter = 1.5 m
SLR. LLR since 2010
asi
agenzia spaziale
italiana

MIUR Project "Laser Ranging to Galileo"

- ASI & INFN instrumentation upgrades (MLRO & SCF_Lab)
- ASI Laser ranging and SCF-Test of Galileo, GRA and LAGEOS







Macro-Activity 1 Year 1 and 2	Macro-Activ. 2 Year 1	Macro-Activ. 3 Year 1	Macro-Activity 4 Year 2	Macro-Activity 5 Year 2	Macro-Activity 6 Year 2	Macro-Activity 7 Year 2
MLRO-SCF_LAB Harmonization: Harmonization of MLRO and SCF_LAB upgrades and integration of the results of the upgraded MLRO and SCF_LAB (includes Management)	**MLRO@CGS**: Equipment Upgrade	**SCF_LAB@LNF**: Infrastructure Upgrade	**Upgraded MLRO**: Laser Ranging to LRAs onboard Galileo satellites	**Upgraded SCF_LAB**: Lab Characterization of Galileo LRA Flight Model (on loan to LNF from ESA)	**Upgraded MLRO**: Laser Ranging to LAGEOS	**Upgraded SCF_LAB**: Lab Characterization of LAGEOS Engineering Model (on loan to LNF from NASA)

LRA = Laser Retroreflector Array

Europa/Encelado, the icy/rocky moons

- Europa/Enceladus Cube Corners retroreflectors for Exploration/Exolife
  - Recent NASA AO on Europa did not include landing/roving
  - 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:
  - Different geometries
  - Varying sizes & n. of reflectors
  - Depending especially on s/c (velocity aberration)