Advanced Laser Retroreflectors for Precision Gravity and Lasercomm Tests in the Solar System

Simone Dell'Agnello and the SCF_Lab Team

CSN2, 05/05/2015, GGI, Arcetri, Firenze

SCF_Lab & Elachi (NASA-JPL) + Flamini (ASI)

Outline

- Lunar Laser Ranging
  - Test of General Relativity with "MoonLIGHT-2" reflector
  - Low-energy test of quantum gravity
  - Non-Minimally Coupled Gravity (f1+f2)

- Mars Geo/physical Networks and Lasercomm
  - "INRRI" microreflector for Mars 2020 (NASA) and ExoMars (ESA/ASI)
  - Reflector for Phobos/Deimos

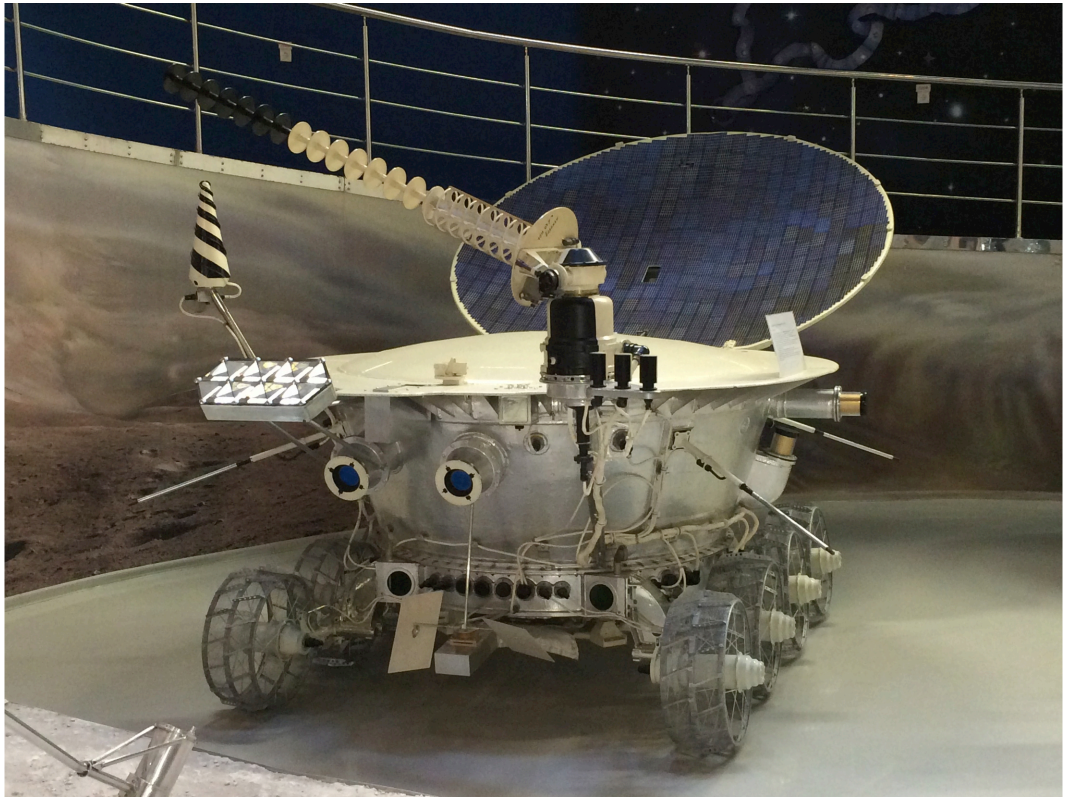
- Asteroid/Comet Exploration and Lasercomm
  - INRRI microreflector
  - "OmniLaserCubes" (Omnidirectional Laser reflector Cubesat)

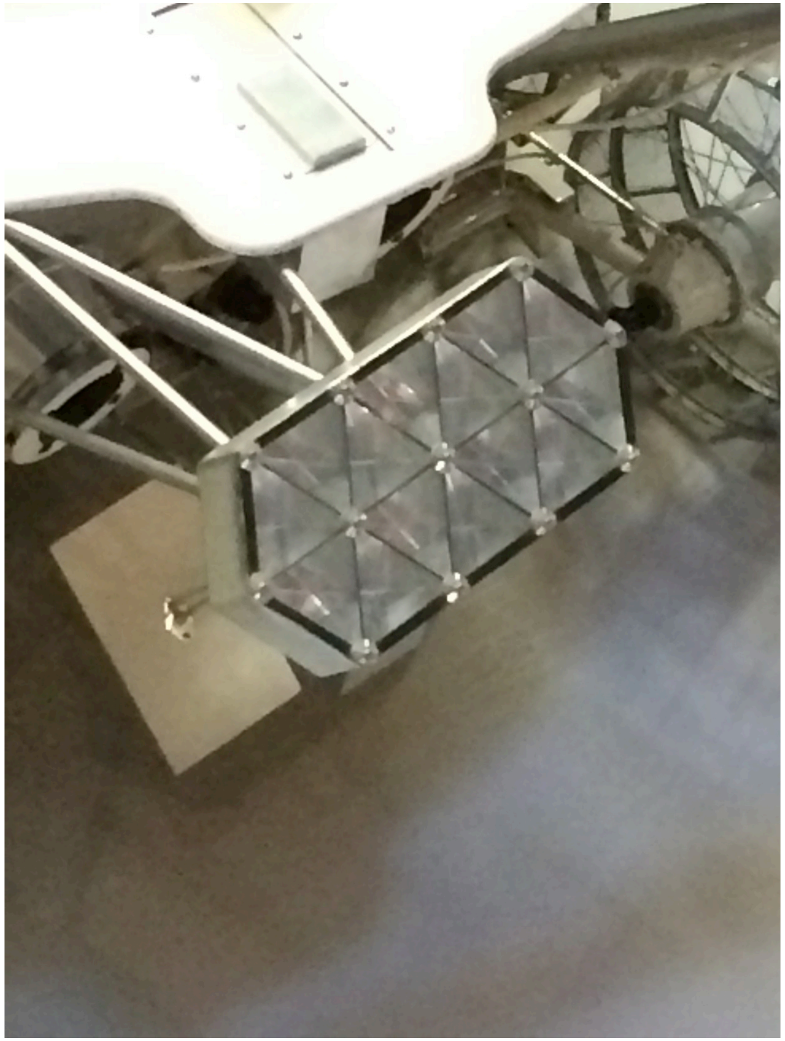
Lunar Laser Ranging (LLR) to Earth's Moon

- The Moon: a laser-ranged test body for General Relativity and new Gravitational Physics
  - Next-generation **single, large, reflector** "MoonLIGHT"
    - Italian Teams: INFN (PI), ASI (G. Bianco, Matera Laser Ranging Observatory et al), U. Padua (P. Villoresi et al)
    - D. Currie, Univ. of Maryland, MD, USA
      - Apollo Veteran
    - J. Chandler, I. Shapiro, Center for Astrophysics, MA
      - Provide Planetary Ephemeris Program (PEP), Solar System orbit reconstruction sw
    - T. Murphy, PI of APOLLO, best LLR station, U. California at S. Diego, CA

Lunokhod 3 at NPO-Lavochkin, Moscow

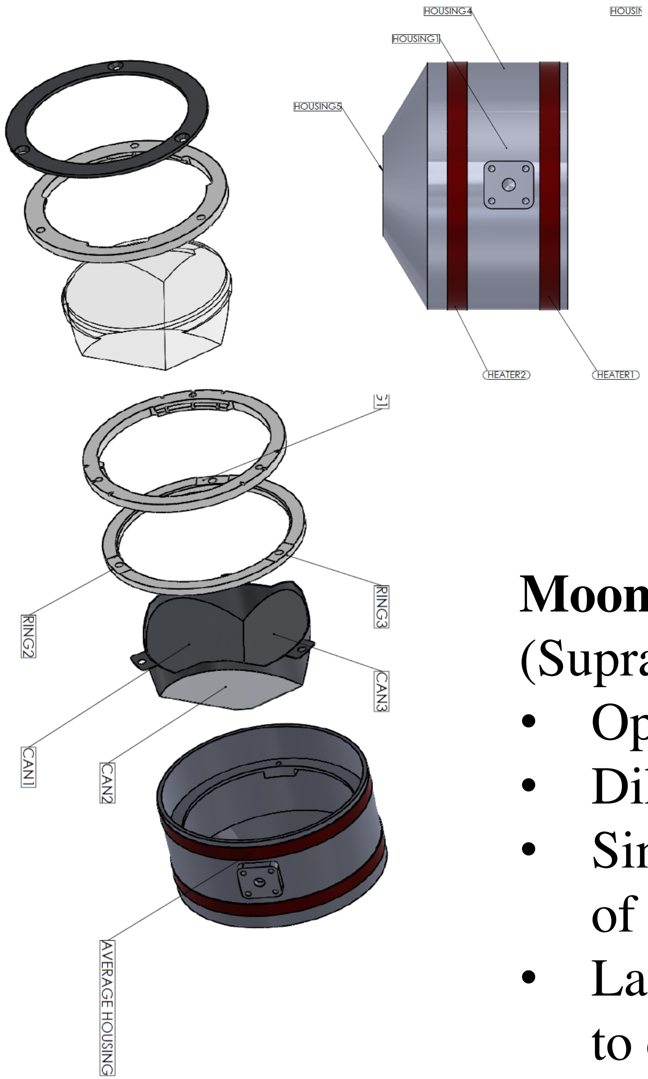
Lunokhod 3 at Space Museum, Moscow

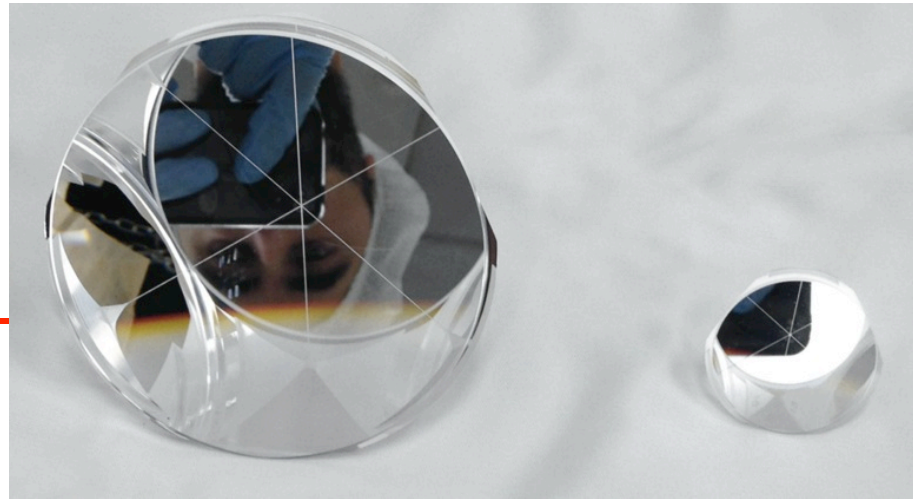




MoonLIGHT laser retroreflector

(Moon Laser Instrumentation for General relativity High accuracy Tests)





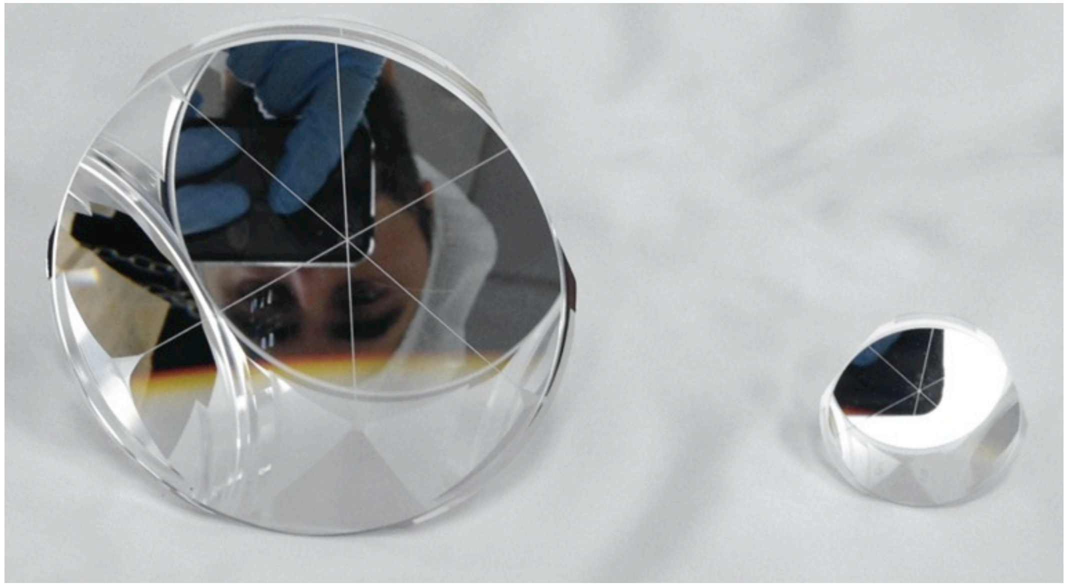
MoonLIGHT single reflector vs. Apollo reflector arrays
(Suprasil 311 vs. Suprasil 1):

- Optical specs wave/10 RMS (**best ever**) vs. wave/4
- Dihedral angles accuracy: 0.2 (**best ever**) vs 0.5 arcsec
- Single reflector 100 mm vs. array of 100-300 reflectors of 38 mm
- Laser return better than Apollo 15 (brightest array) due to degradation, likely due to dust deposit

The ‘tesoretto’ of MoonLIGHTs

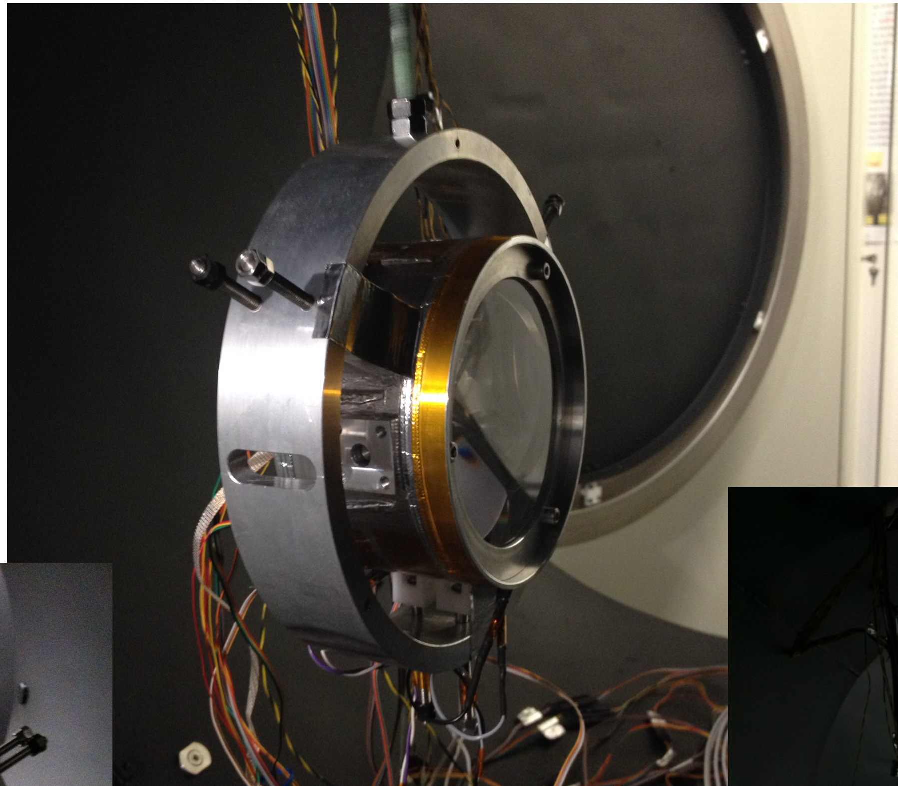
Largest, optically most accurate Suprasil reflectors ever

2 CCRs by INFN
of Suprasil 311,
~100 k€.
Flight quality, with
all formal doc



2 CCRs by NASA
of Suprasil 1
At least EM quality

2014-15 SCF-Test of MoonLIGHT



Science with Lunar Laser Ranging

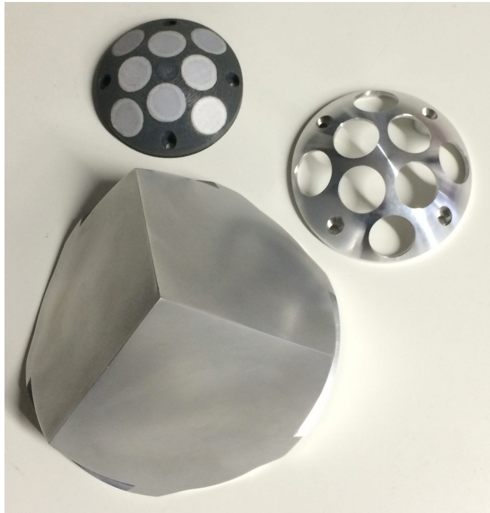
- **General Relativity**: precisions tests, improvement potentially up to ×100, in the long term
- **Selenodesy**: measurement of deep interior; first evidence of molten lunar core; complementary to GRAIL
- **Exploration**: precise positioning of landing site, hopping and roving. GLXP

Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod few cm accuracy*	MoonLIGHTs 1 mm	MoonLIGHTs 0.1 mm
Parameterized Post-Newtonian (PPN) β	$\|\beta-1\|<1.1\times10^{-4}$	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	$\|\dot{G}/G\|<9\times10^{-13}\text{yr}^{-1}$	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)

MoonLIGHT/INRRI (‘big/micro’) opportunities

- **Moon Express 1 (MEX-1)** lander Google Lunar X Prize (GLXP)
- MEX-2, MEX-3, …. C-ILN (Commercial Int. Lunar Network)
- GLXP deadline & MEX-1 launch postponed to mid 2016



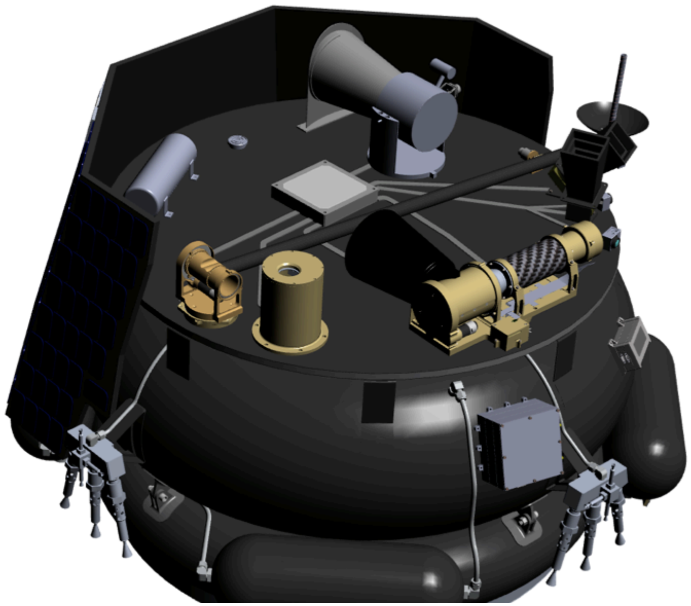
- Pre-Agreement:
  - No taxi fare (2M$/kg), but:
  - Exclusive provision of MoonLIGHT/INRRI to MEX-1/2 ….
- Meetings in May at European Lunar Symposium for agreement

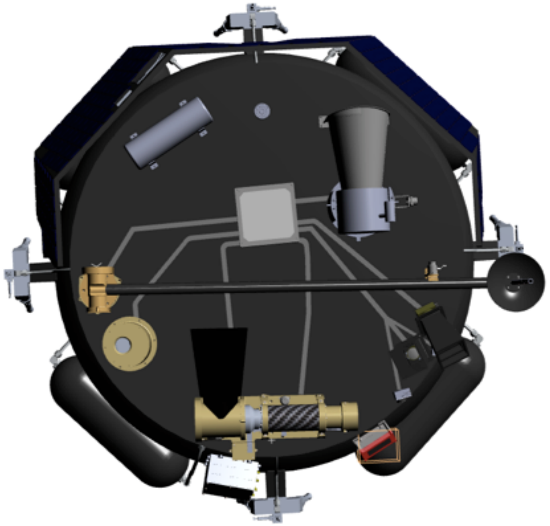
3rd ELS: Berlin, London, now Frascati

- 3rd European Lunar Symposium:
  - Science of the Moon (General Relativity)
  - Science on the Moon
  - Science from the Moon
  - Future Lunar Missions

MoonLIGHT/INRRI launch MEX-1, mid 2016

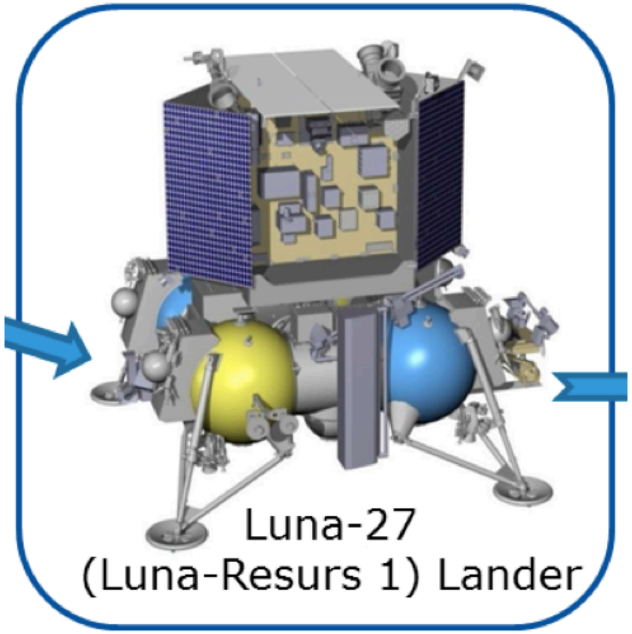
- Lander integrated at NASA-Marshall Space Flight Center
- MoonLIGHT 3D models integrated in lander 3D model
- LNF structural analysis for launch complete
- Vibe/shock test campaign and TVT @INFN/U-Perugia SERMS, ESD @CEM





MoonLIGHT/INRRI Lunar opportunities

- Proposal to IKI-RAS/Roscosmos for the Lander **Luna-27**
  - Also thanks to ESA-Russia relations
  - ESA got mandate & funds at Dec. 2014 Ministerial Council
  - RAS-INFN valid MoU since mid 1990s
  - PI: S. Dell'Agnello
  - <u>Co-PI and Russian Curator</u>:
    - A. Sokolov (RES. & PROD. CORP. «PSI»)
  - Co-Is:
    - D. Currie (INFN-LNF Guest Scientist)
    - G. Bianco (ASI, ILRS, INFN-LNF Associate)

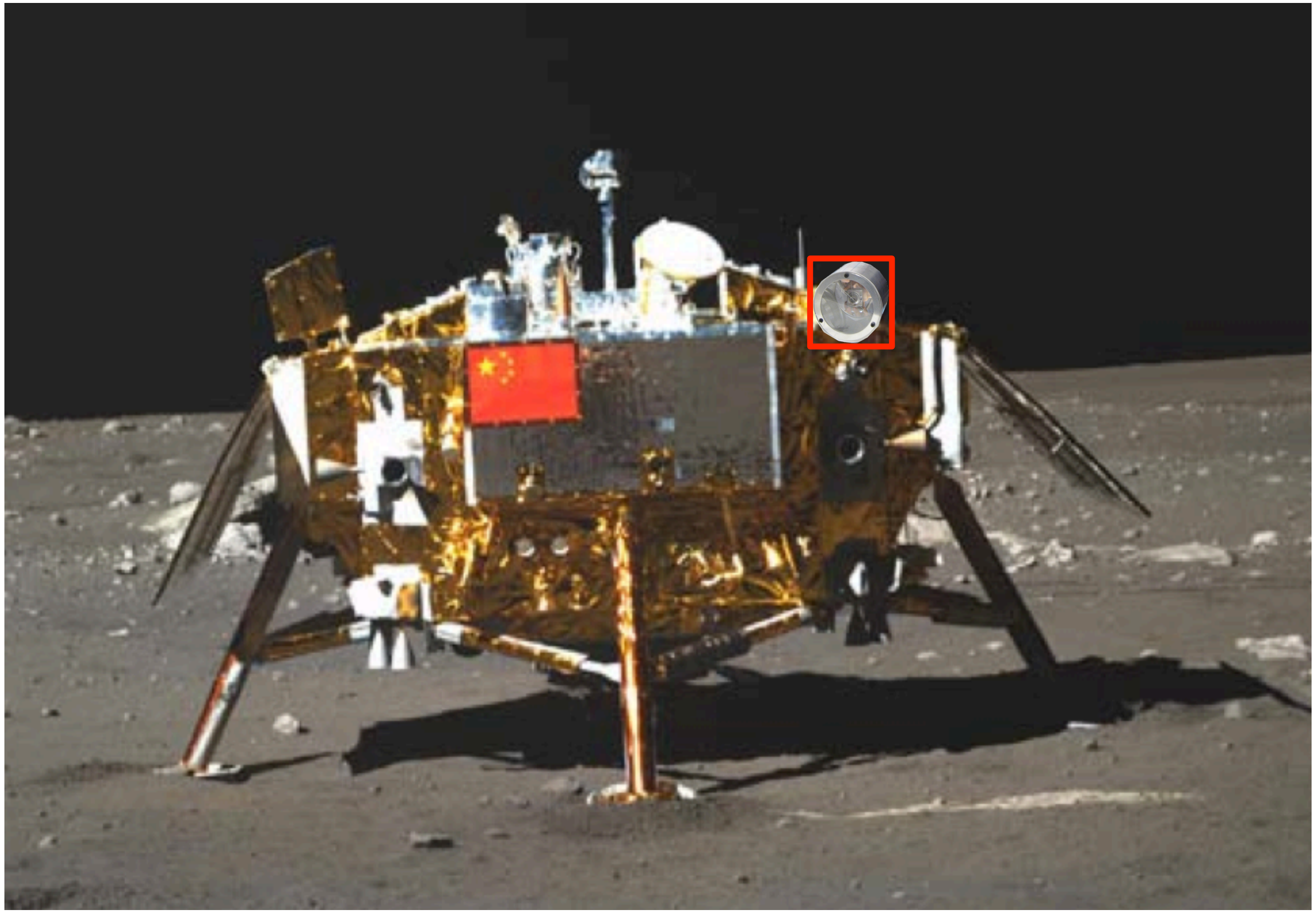


MoonLIGHT on Chang'E-4/5/6

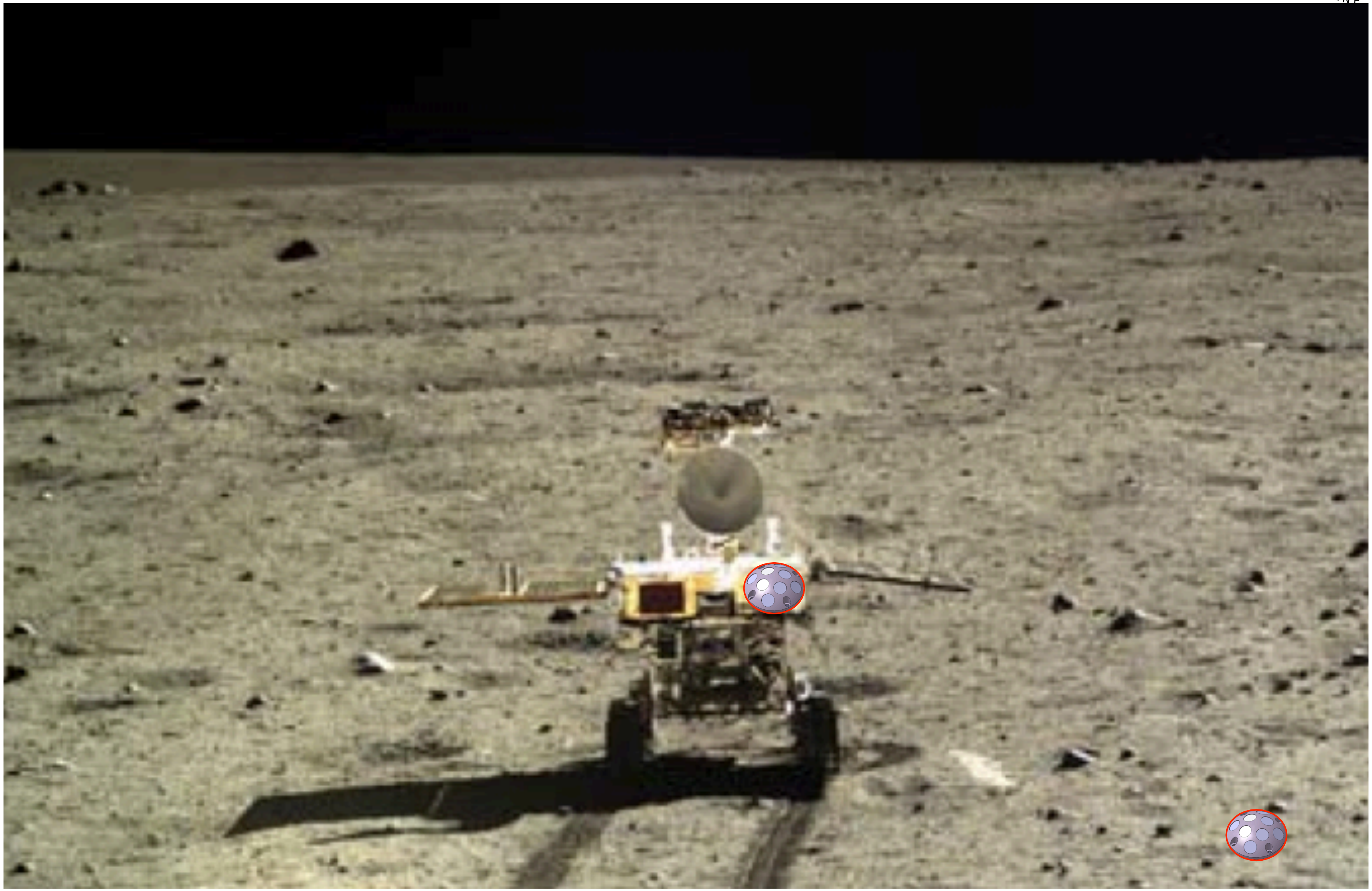
Chang'E-3 seen by Yutu minirover on Dec. 13, 2013

Opportunity for MoonLIGHT/INRRI on Chang'E-4/5/6 >2017:

30-04-15: ASI President will provide institutional contact with China



INRRI on Yutu minirover (seen by lander)



General Relativity, New Gravity Physics

- LLR test of general relativity (GR: PPN β, Gdot/G, WEP/SEP, $1/r^2$ law, 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 GR 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*
  - 3rd ELS: Constraining nonminimally coupled gravity with laser ranging to the moon**,** *Castel-Branco, Paramos, March, Dell'Agnello*
- NEW: Low-energy quantum gravity with Lunar Laser Ranging
  - PRD 91, 084041 (2015), *Battista, Dell'Agnello, Esposito, Simo*

Possible low-energy test of quantum gravity in the Earth-Moon system with Lunar-like Laser Ranging

PHYSICAL REVIEW D **91,** 000000 (XXXX)

Quantum effects on Lagrangian points and displaced periodic orbits in the Earth-Moon system

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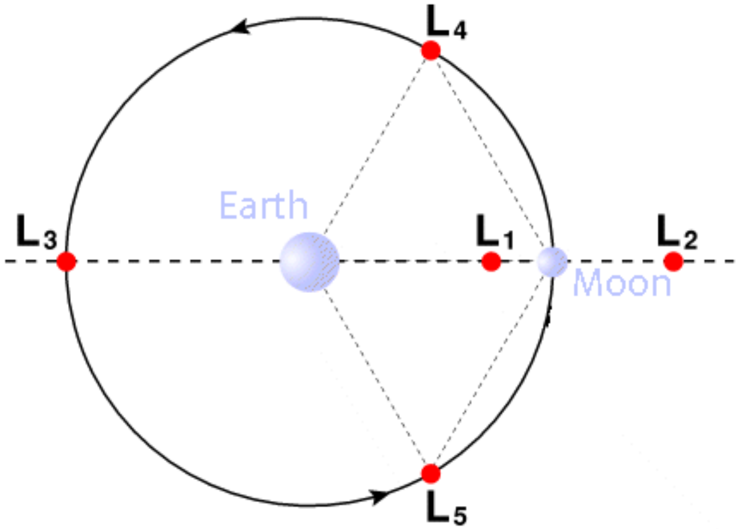
(Received 12 January 2015)

Recent work in the literature has shown that the one-loop long distance quantum corrections to the Newtonian potential imply tiny but observable effects in the restricted three-body problem of celestial mechanics; i.e., at the Lagrangian libration points of stable equilibrium, the planetoid is not exactly at an equal distance from the two bodies of large mass, but the Newtonian values of its coordinates are changed by a few millimeters in the Earth-Moon system. First, we assess such a theoretical calculation by exploiting the full theory of the quintic equation, i.e., its reduction to Bring-Jerrard form and the resulting expression of roots in terms of generalized hypergeometric functions. By performing the numerical analysis of the exact formulas for the roots, we confirm and slightly improve the theoretical evaluation of quantum corrected coordinates of Lagrangian libration points of stable equilibrium. Second, we prove in detail that for collinear Lagrangian points the quantum corrections are also of the same order of magnitude in the Earth-Moon system. Third, we discuss the prospects of measuring, with the help of laser ranging, the above departure from the equilateral triangle picture, which is a challenging task. On the other hand, a modern version of the planetoid is the solar sail, and much progress has been made, in recent years, on the displaced periodic orbits of solar sails at all libration points, both stable and unstable. Therefore, the present paper investigates, eventually, a restricted three-body problem involving Earth, the Moon, and a solar sail. By taking into account the one-loop quantum corrections to the Newtonian potential, displaced periodic orbits of the solar sail at libration points are again found to exist.

Low-energy test of quantum gravity with Lunar-like Laser Ranging



$$V_Q(r) = -\frac{Gm_Am_B}{r}\left(1 + \frac{k_1}{r} + \frac{k_2}{r^2}\right) + O(G^2),$$

where [23]

$$k_1 \equiv \kappa_1 \frac{G(m_A + m_B)}{c^2},$$

$$k_2 \equiv \kappa_2 \frac{G\hbar}{c^3} = \kappa_2 (l_P)^2.$$

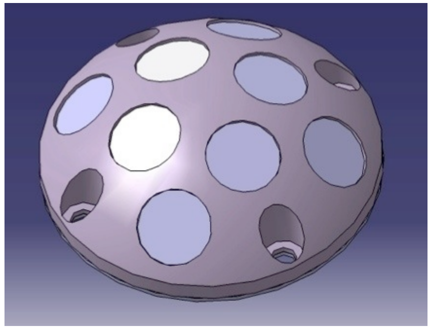
l_p is the Planck length. $\varkappa_1$ is not a free real parameter but depends on $\varkappa_2$: both $\varkappa_1$ and $\varkappa_2$ result from loop diagrams.

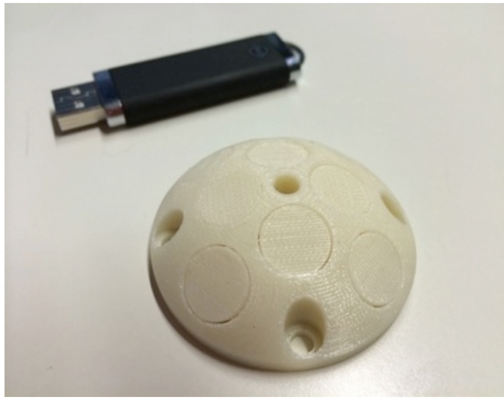
Displacement of quantum from classical equilibrium points:
from few mm to ~1 cm, *measurable with laser ranging.*
Signs of deviations (along L1-L2-L3 and L4-L5): further signature
L4/L5: stable points; L1/L2/L3 are unstable points

Paper lists systematics effects & backgrounds

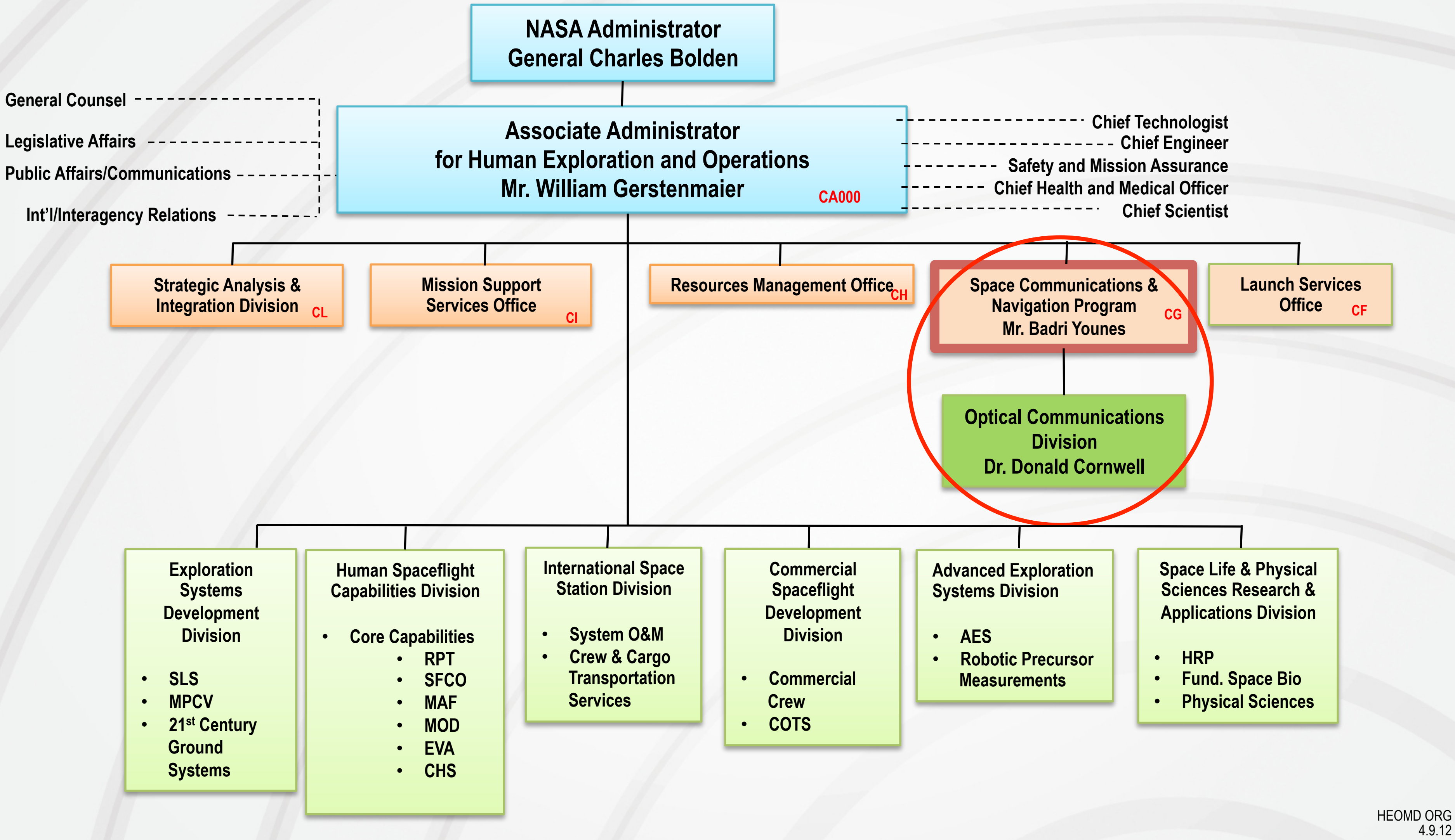
INRRI: INstrument for landing-Roving laser Retroreflector Investigations

- Laser-located by orbiters
  - **Accurate positioning of landing site and roving exploration activity**
  - Laser altimetry (many lunar, Mars, Mercury laser altimeters, ie by NASA)
  - Laser ranging (mission GETEMME for ESA Cosmic Vision)
  - Laser-communications, like NASA lunar mission LADEE
    - Demonstrated laser time-of-flight with ~100 picosec accuracy
- Significant effort on lasercomm by NASA, ESA, etc
- Passive, maintenance-free, lifetime of decades
  - Lightweight: ~30 gr
  - Compact (~5 cm x 2 cm)
  - No pointing required

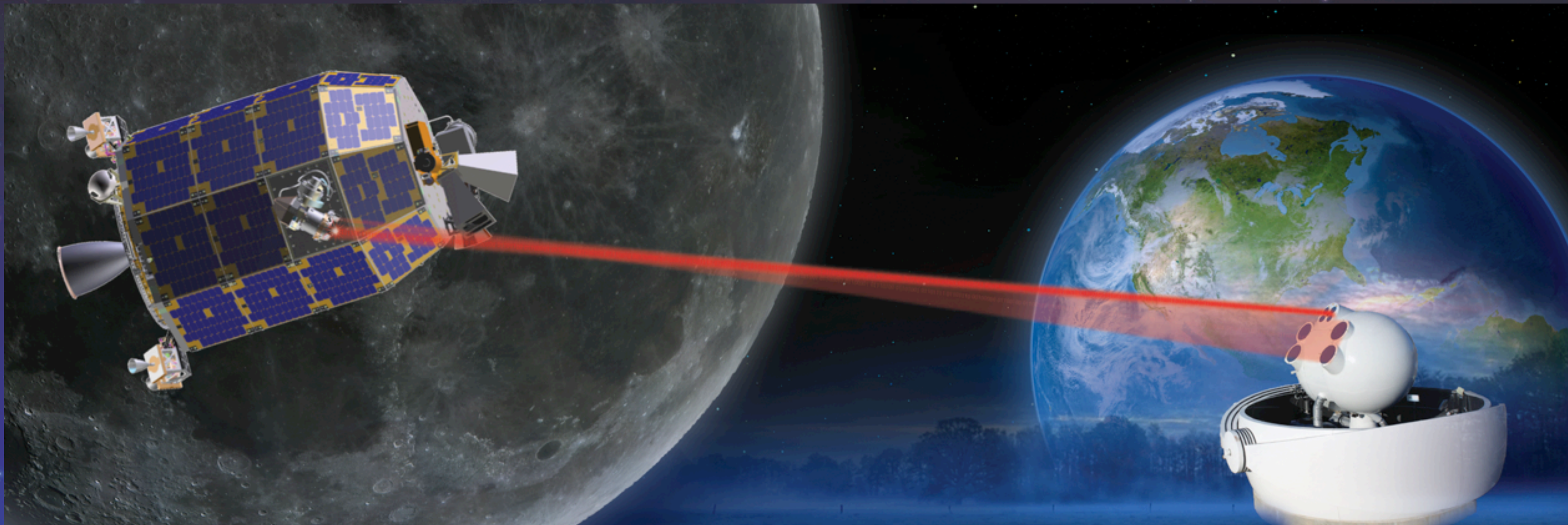




Where is SCaN within NASA?



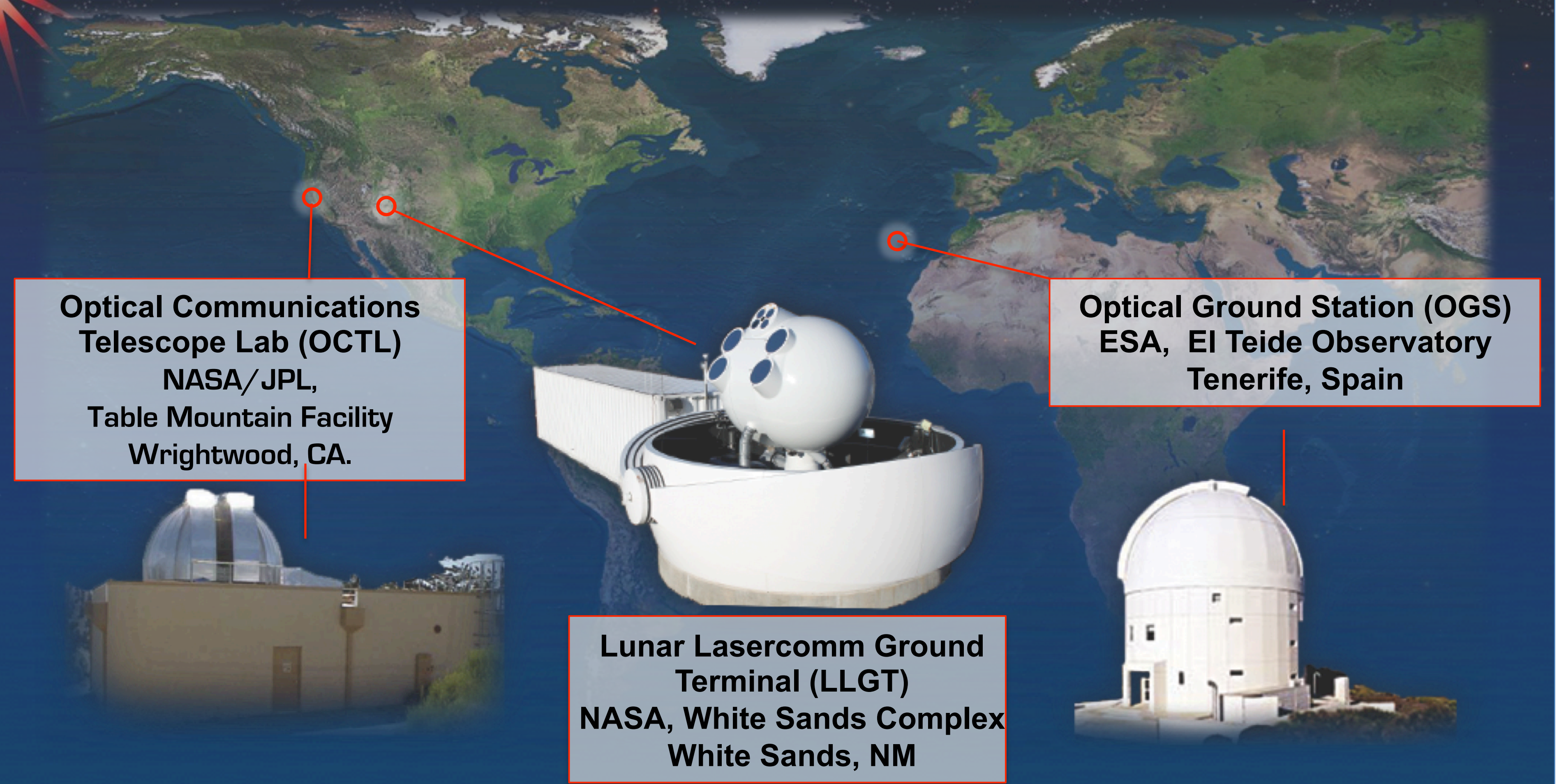
LADEE
NASA's First, Historic Lasercom Mission



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

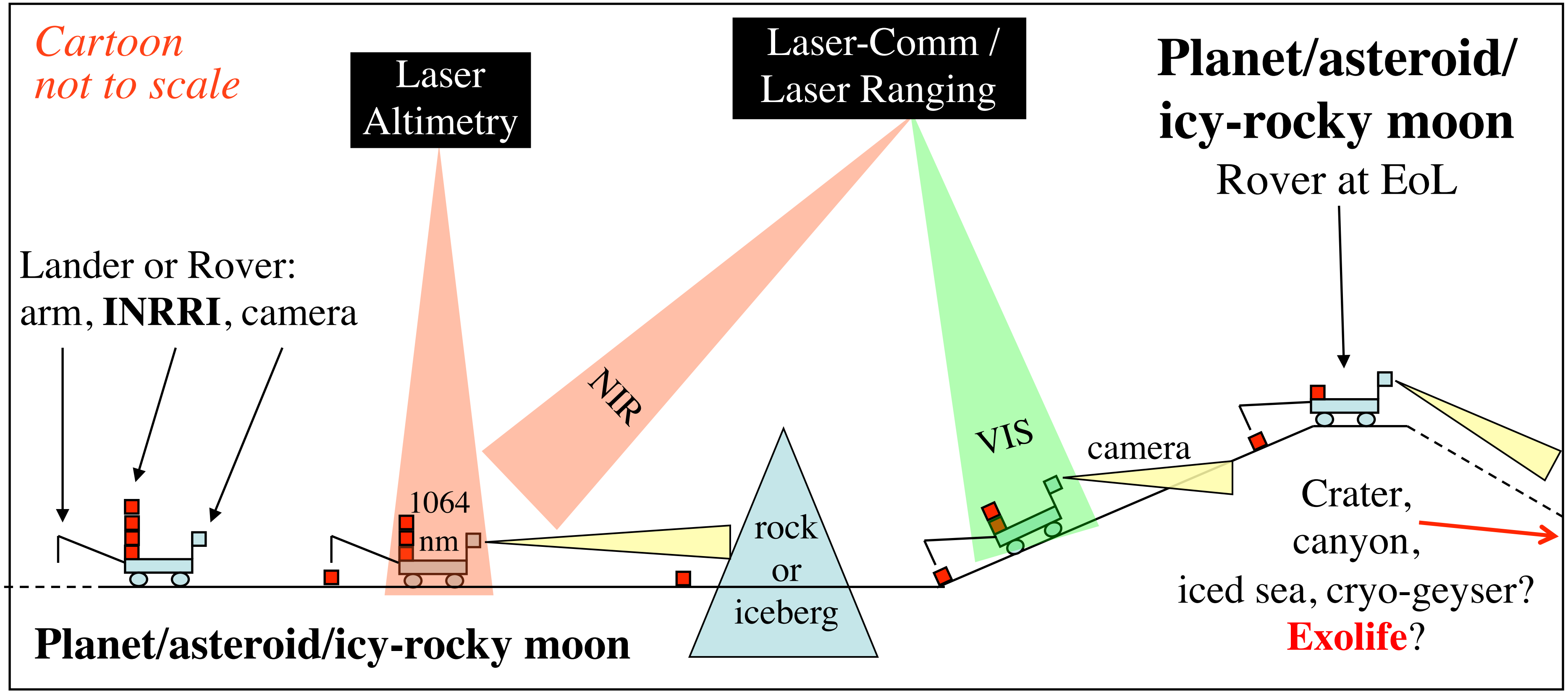
NASA GSFC, MIT Lincoln Laboratory, NASA JPL, ESA

LLCD's Multiple Ground Terminals:
An International Collaboration



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

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

Mars surface (rovers/landers) physics goals - I

- Multiple INRRIs: Mars Geo/physics Network (MGN)
  - Apollo/Lunokhod reflectors: Lunar Geo/physics Network (LGN)
- Enabling technology to test General Relativity
  - Mars center of mass to be estimated with INRRIs like Selenocenter with Apollo/Lunokhod reflectors
- Enabling technology for lasercomm quantum physics at Mars
- GR test improvements with an MGN in the long term:
  - PPN Gamma (Sun-Mars) up to x 100
    - **Shapiro time delay** with Viking landers in the 1970s
  - Gdot/G, 1/r2 law at 1.5 AU: up to x 100
    - PPN beta (Sun-Mars-Jupiter) not competitive with the Moon
- Orbit sw: PEP (Planetary Ephemeris Program) by Shapiro/ Chandler (we use it daily for lunar laser ranging)
  - Very suited because it uses the whole solar system data to fit orbits

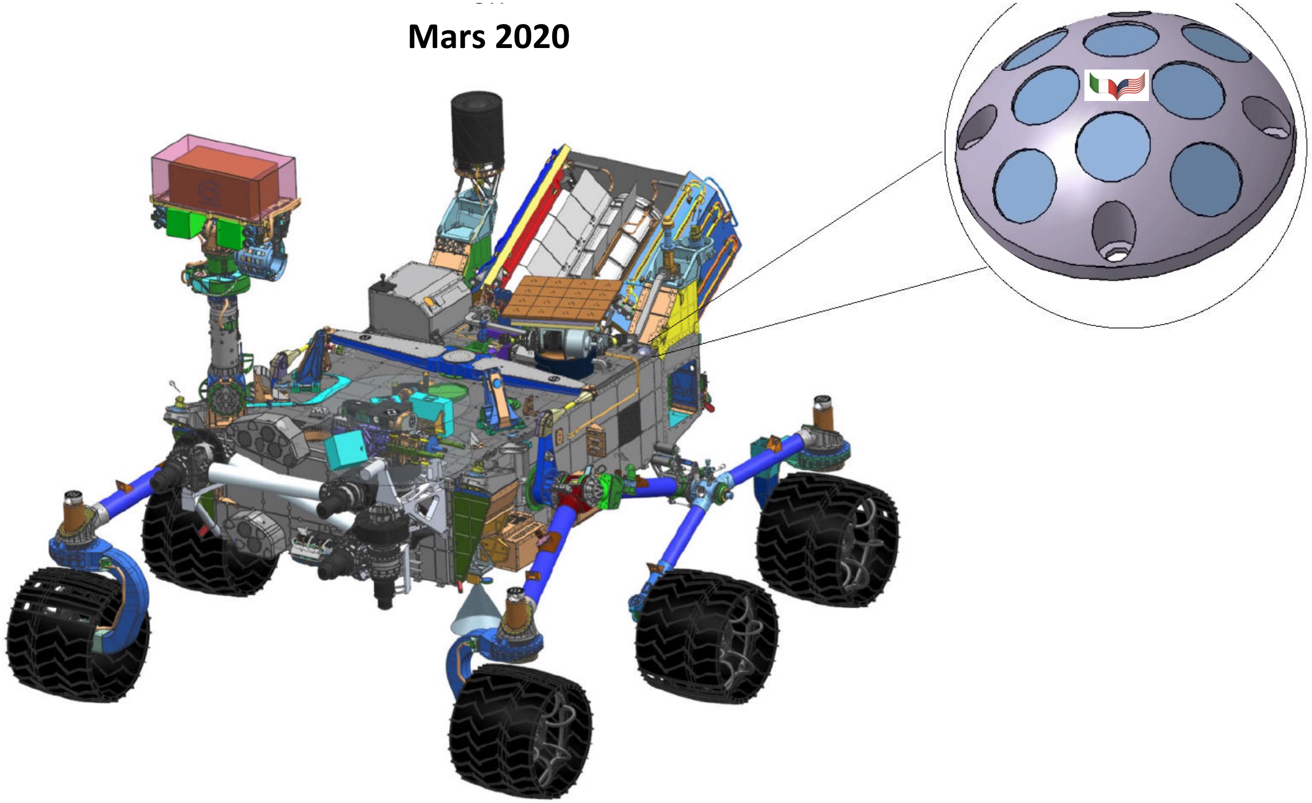
Mars surface exploration and science goals - II

- Georeference exploration activity
- Define Mars Prime Meridian (Meridian 0, the Martian 'Greenwich')
  - Now: Meridian 0 = Airy-0 crater, accurate at 100 m level
- Lasercomm test/diagnostics (wavelength independent)
- Atmospheric trace species detection by space-borne lidar
  - Full column sampling, at varying angles
- Lidar-based/aided landing
- Topography/geodesy by laser flashes + vis. cameras

INRRI for Mars 2020 (NASA)

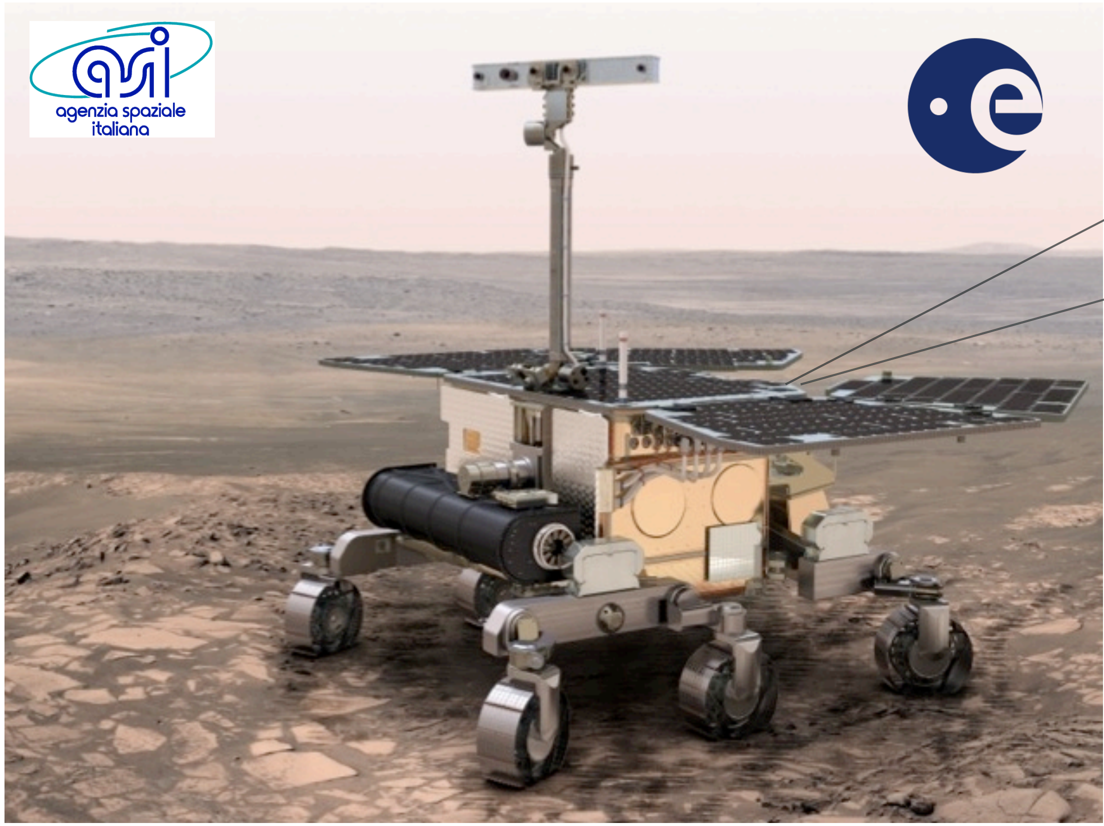
- Enabling technology for General Relativity (like Apollo/Lunokhod)
- Georeference exploration
- Geodesy: 1st node of MGN; Definition of Meridian 0 (‘Greenwich’)
- Lidar atmosphere trace species detection
- Lidar-based landing (return to astrobiologically relevant site)
- Lasercomm test & diagnostics

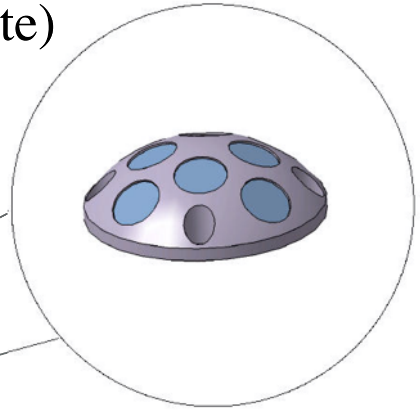
Mars 2020



INRRI for ExoMars (ESA-ASI, ~2018)

- Enabling technology for General Relativity (like Apollo/Lunokhod)
- Georeference exploration
- Geodesy: 1st node of MGN; Definition of Meridian 0 ('Greenwich')
- Lidar atmosphere trace species detection
- Lidar-based landing (return to astrobiologically relevant site)
- Lasercomm test & diagnostics

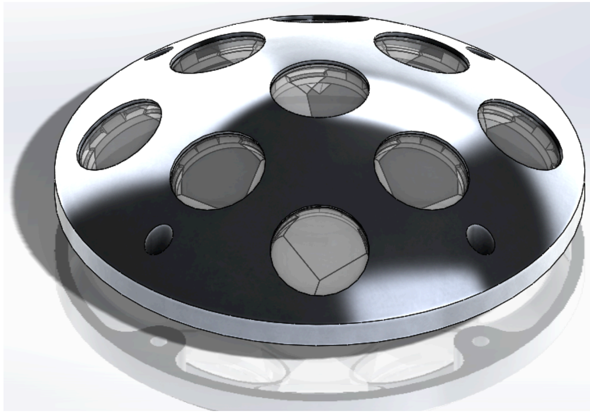




INRRI (12.7 mm) and INRRI+ (17 mm) precursors built for Moon Express

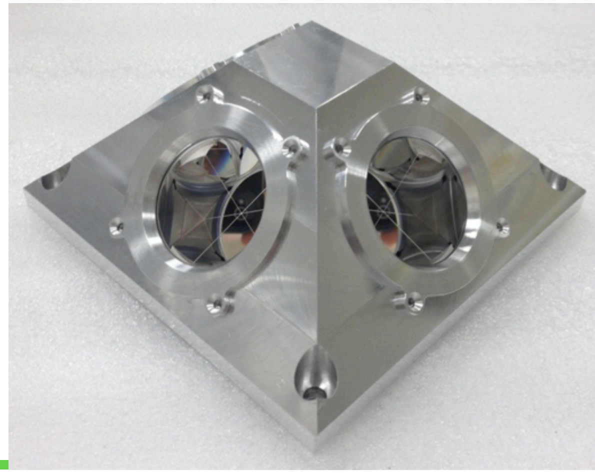
Phobos/Deimos

- PANDORA: Phobos AND DeimOs laser Retroreflector Array
- Submitted for Phase A of NASA Discovery AO 2014, Mars orbiter PADME (Phobos And Deimos, Mars Environment)
  - With ASI letter of endorsement
    - PANDORA concept for PADME →



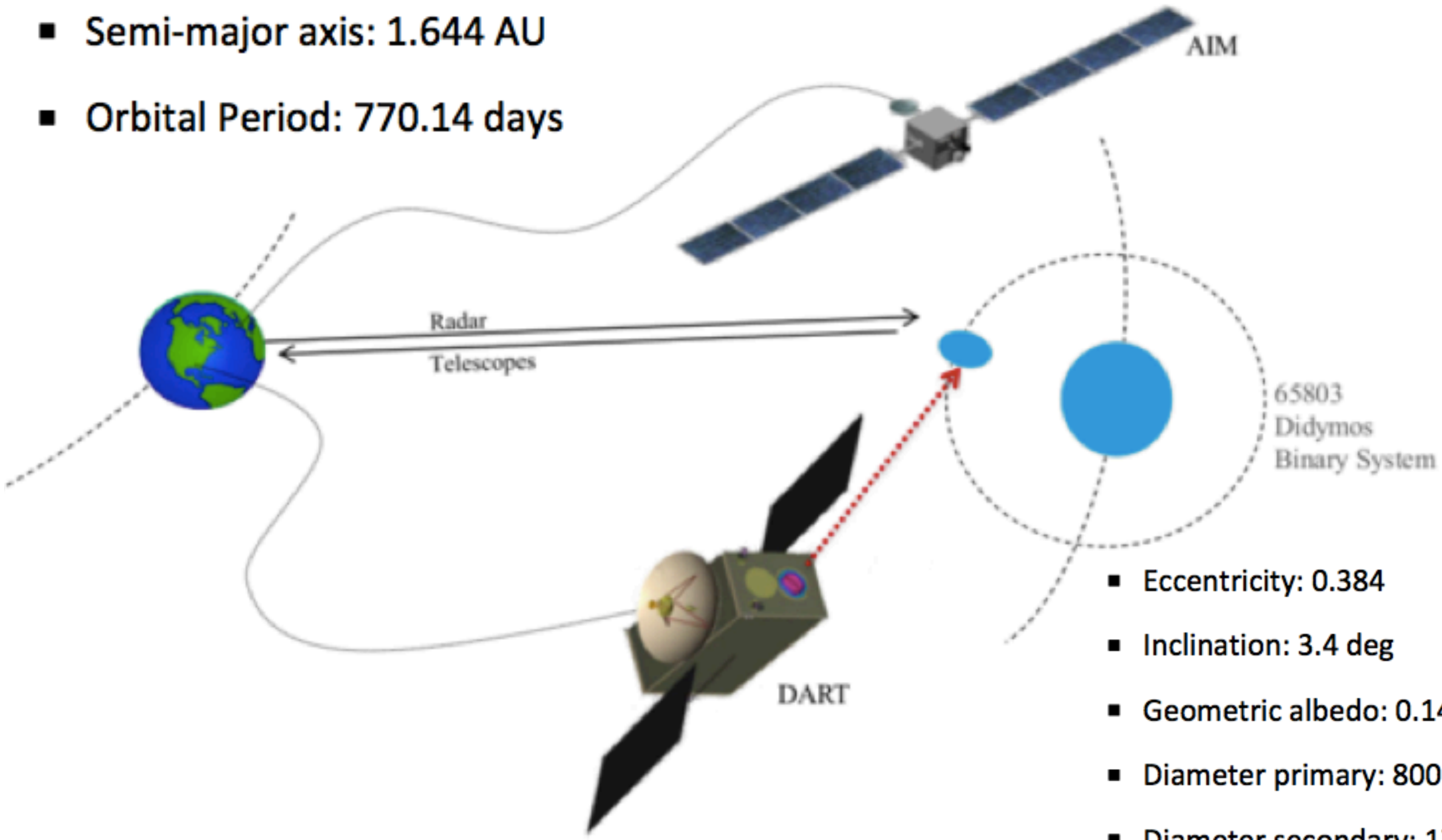
- Mars center of mass for General Relativity
- Lidar science from Mars surface

- Other proto by ETRUSCO-GMES
  - Developed in CSN5 with Min. of Defense
  - COpernicus Retroreflector Array (CORA) →
  - Earth Observation



AIM(ESA)/DART(NASA) Mission to Didymos

- Semi-major axis: 1.644 AU
- Orbital Period: 770.14 days



- Eccentricity: 0.384
- Inclination: 3.4 deg
- Geometric albedo: 0.147
- Diameter primary: 800 m
- Diameter secondary: 170 m
- Separation: 1100 m
- Orbital period secondary: 11.9 h

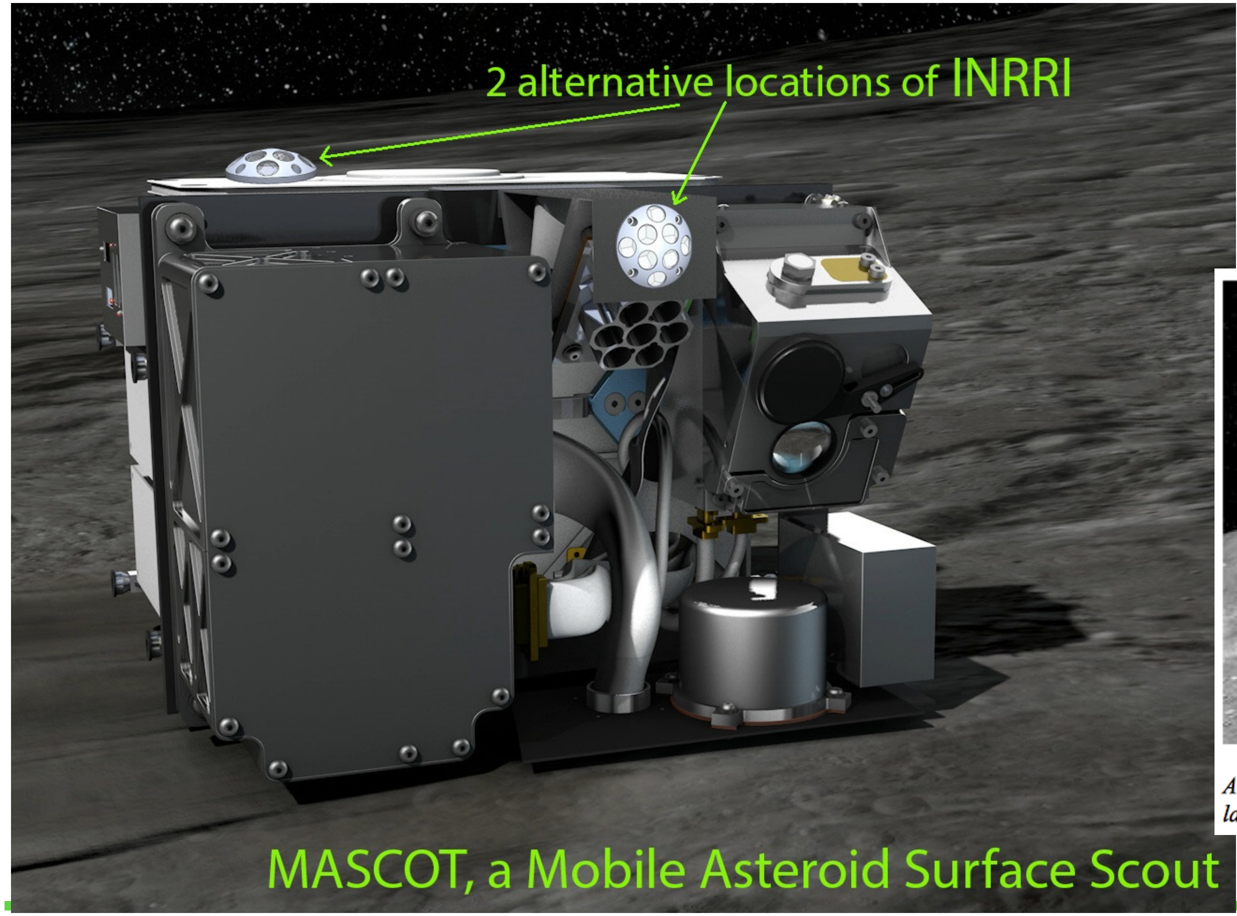
ESA-NASA "AIM-DART" mission to the

Didymos double asteroid (1-2 AU from Earth)

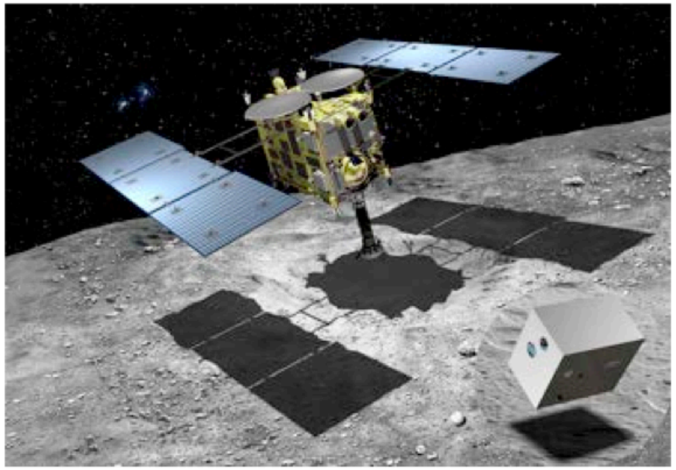
Cubesats with retroreflector & laser georeferencing proposed for ESA

Sysnova ITT: *PoliMi (PI: M. Lavagna), OHB, INFN-LNF, INAF-IAPS*

A**SIMOV**: Aim Supporting & Interactive Multiple nanO Vehicles



Laser altimeter/lasercomm (OPTEL-D) by RUAG
MASCOT by DLR

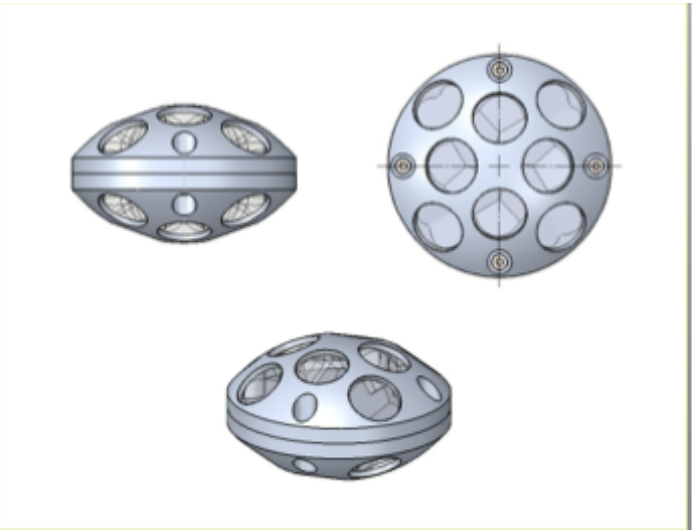


Artist's conception of HY-2 during sampling, also showing MASCOT landed on the surface. CREDIT:JAXA/Akihiro Ikeshita.

NEO (Near Earth Objects): asteroids/comets

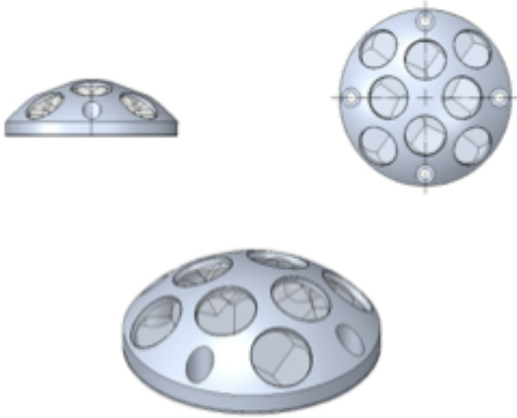
- Asteroid retrieval, redirection, deflection (ion-beam, laser?)
- **Laser-reflector marking NEOs** to support their laser tracking
  - LRAs useful also to guide directed forms of energy or ballistic interceptors
- Depending on asteroid and on mission:

INRRI-Disk

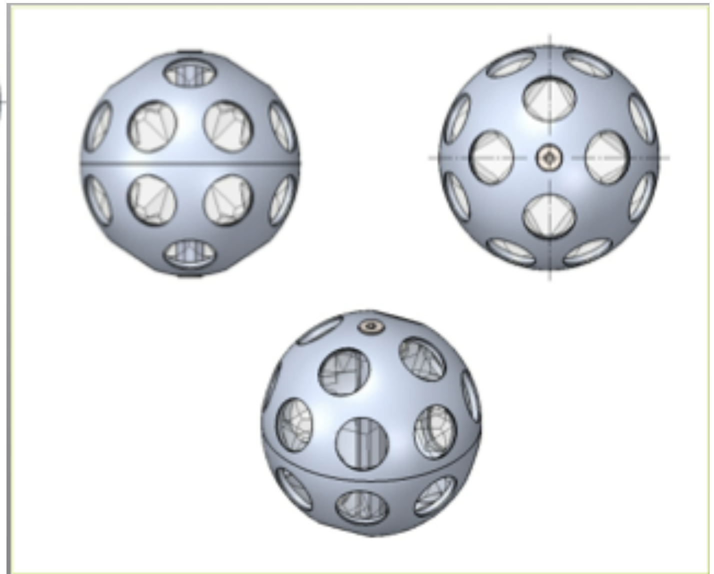


INRRI-D LRA, equipped with sixteen CCRs. Diameter is about 1.5 x 2 inches; total mass is about 50gr

INRRI



INRRI-Sphere



INRRI-S LRA, equipped with twenty four CCRs. Diameter is about 2 inches; total mass is about 65gr

Science summary:
General Relativity, New Gravity Physics

- LLR test of general relativity (GR: PPN β, Gdot/G, WEP/SEP, $1/r^2$ law, 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 GR with Spacetime Torsion
  - PRD **83**, 104008 (2011), *March, Bellettini, Tauraso, Dell'Agnello*
  - GERG (2011) 43:3099–3126, *March, Bellettini, Tauraso, Dell'Agnello*
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  - Physics Letters B 735 (2014) 25–32, *Castel-Branco, Páramos, March*
  - 3rd ELS: Constraining nonminimally coupled gravity with laser ranging to the moon, *Castel-Branco, Paramos, March, Dell'Agnello*
- Low-energy quantum gravity with Lunar Laser Ranging
  - arXiv:1501.02723 [gr-qc], Accepted by PRD, *Battista, Dell'Agnello, Esposito, Simo*