Testing Gravity in the Solar System

(with Solar System Experiments)

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Vulcano Workshop, Italy, May 24, 2018

SCF_Lab
Satellite/Lunar/GNSS
laser ranging/altimetry and Cube/microsat
Characterization Facilities Laboratory

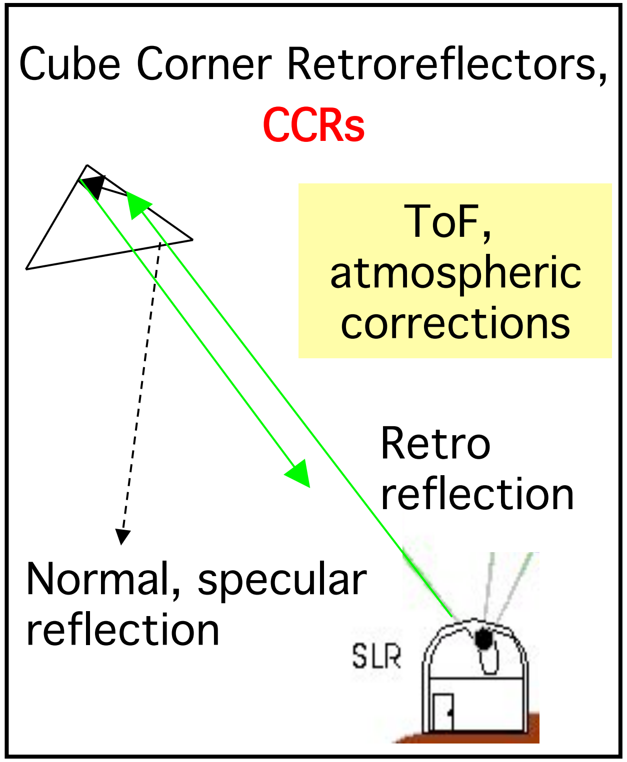
Outline

- Gravity solar system experiments (partial list)
- Testing gravity with a Lunar Geophysical Network (LNG)
  - ✓ Lunar mission opportunities
- Testing gravity with a Mars Geophysical Network (MGN)
  - ✓ Mars mission opportunities
- Conclusions & prospects

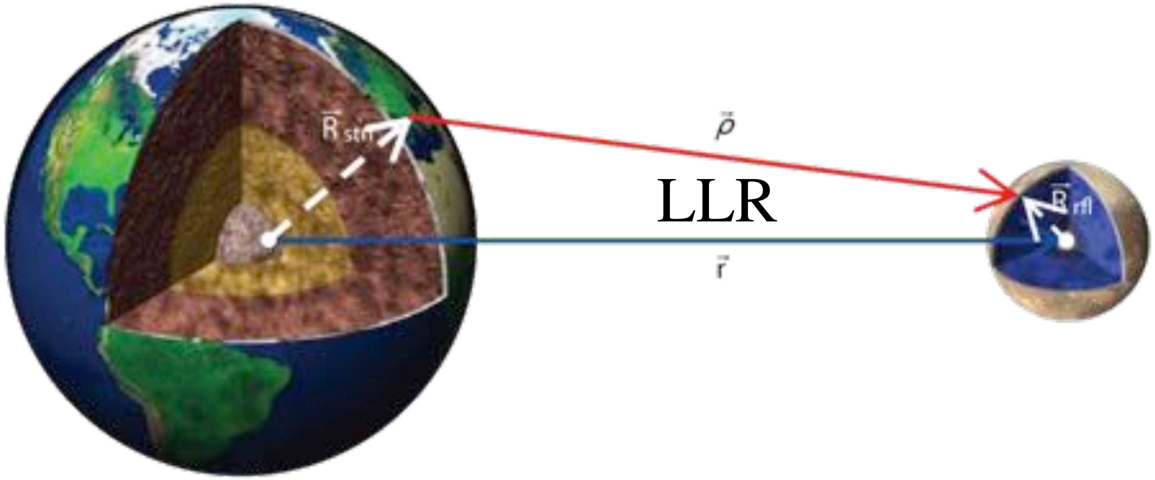
Solar System: versatile lab to test gravity

- Precision test of GR, general relativity
  - ✓ AND of GR extensions (f(R), SME, NMC, torsion, …)
- Theory/intro: Papa/Capozziello talks
- Cassini: 10^{-5} test of spacetime curvature in GR
- Gravity Probe A (GPA): 10^{-4} test of redshift in GR
- GPB-LAGEOS: 20-10 % test of GR frame dragging
- Mercury: MESSENGER
- BepiColombo/GAIA: Iess/Crosta talks: 10^{-5} frontier & …
- ACES on ISS: redshift, fine structure constant
- Moon/ACES: Lorentz invariance violations
- Galileo, 2 eccentric sats: redshift (frame dragging?)
- Combinations of planets/moons/orbiters
- f(R) & '$f_1(R)+f_2(R)$' GR extensions. Yukawa potentials ..
- This talk focus: Moon and Mars as test bodies for GR

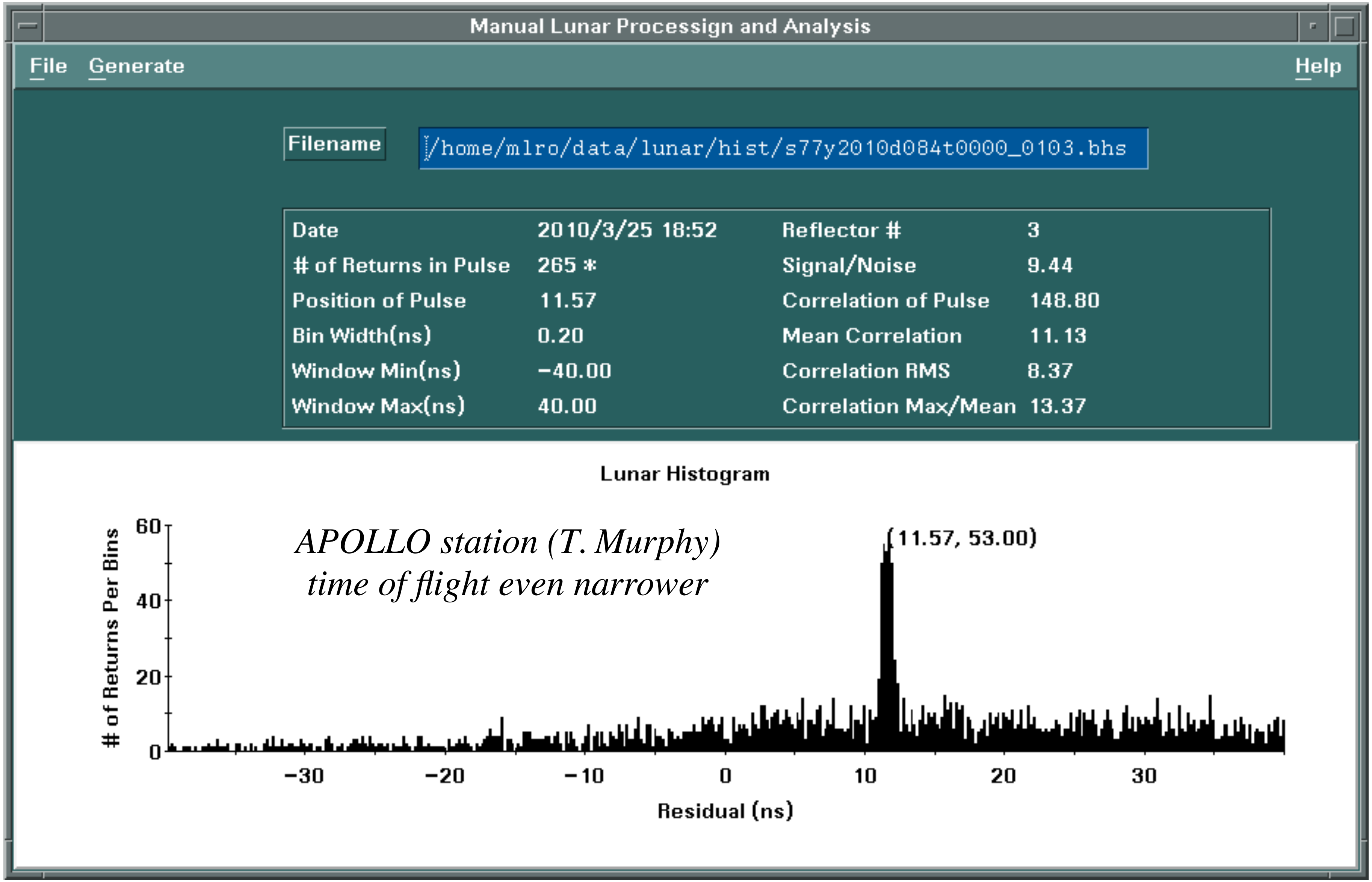
Satellite/Lunar Laser Ranging (**SLR/LLR**)

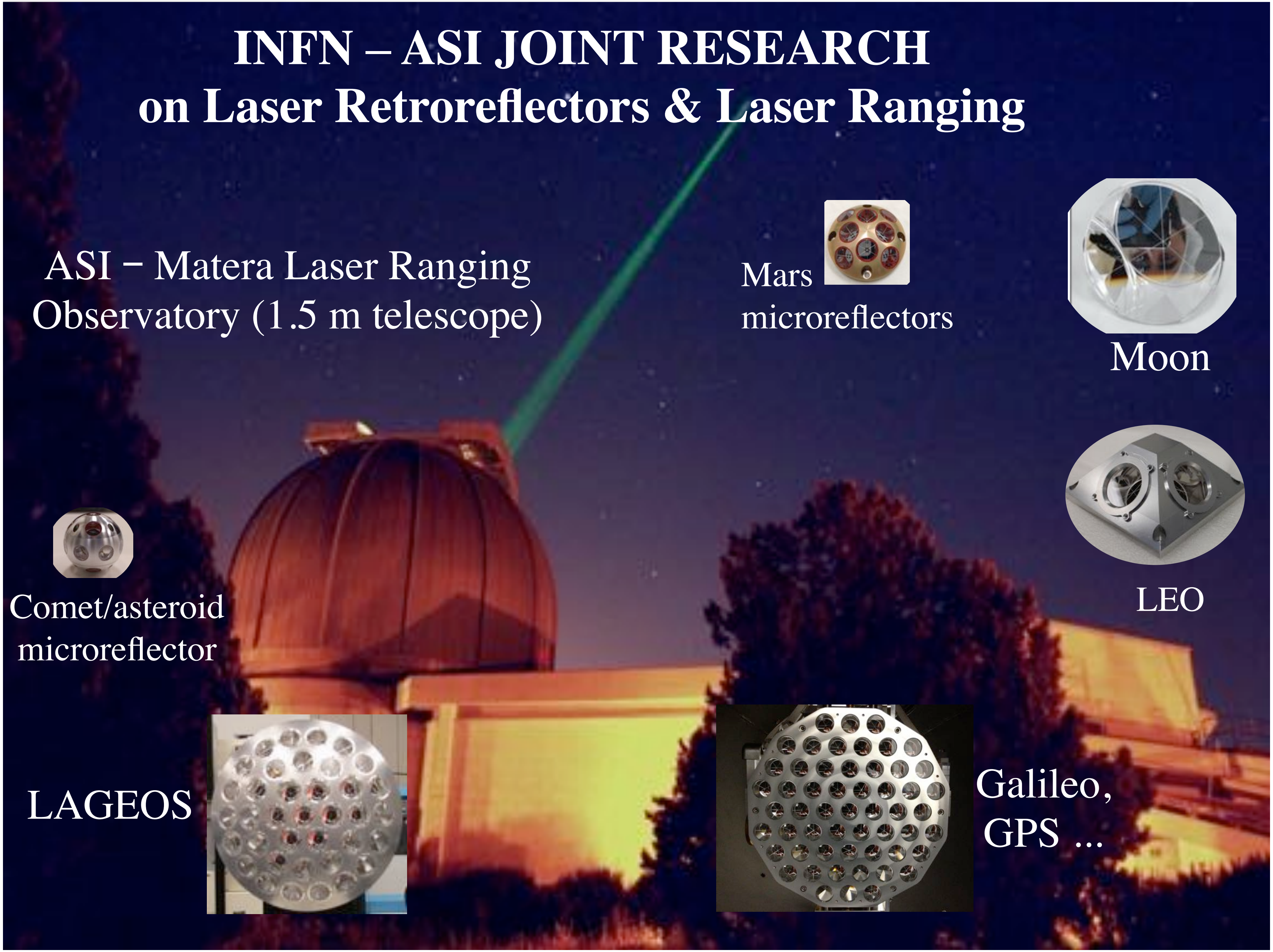


Accurate
Time of Flight
(ToF)
of laser pulses



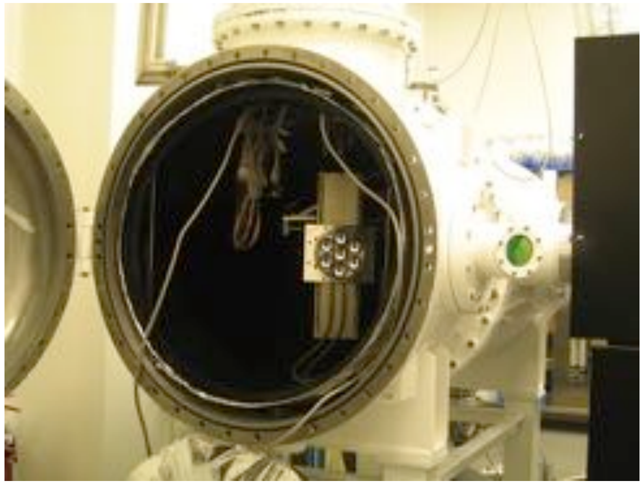
ASI-MLRO LLR (Lunar Laser Ranging) Time of Flight on Apollo 15: ~2 ns rms. Much narrower with next-gen. reflectors

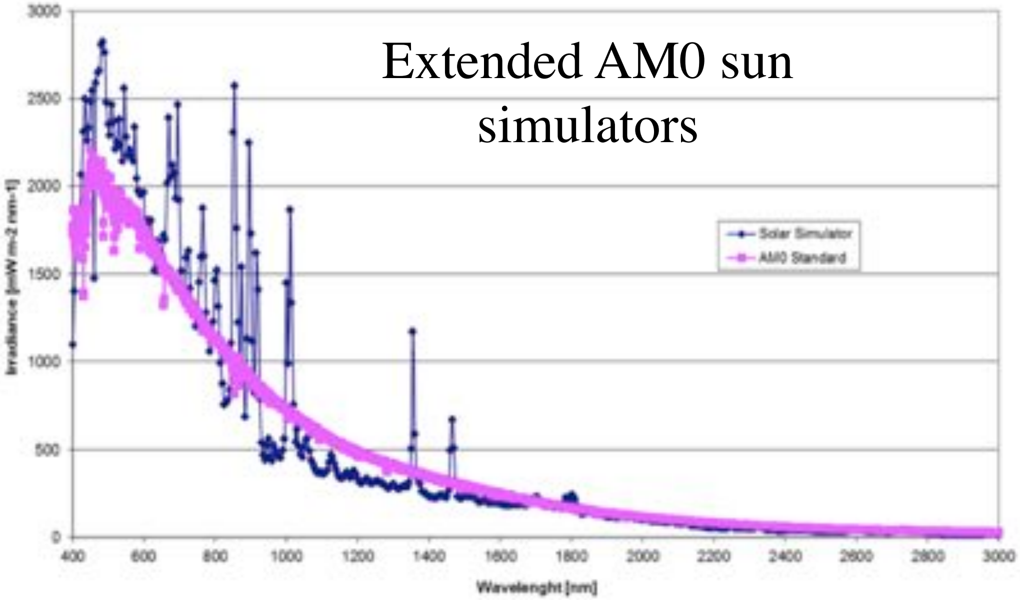



INFN – ASI JOINT RESEARCH
on Laser Retroreflectors & Laser Ranging
ASI – Matera Laser Ranging
Observatory (1.5 m telescope)
Mars
microreflectors
Moon
LEO
Comet/asteroid
microreflector
LAGEOS
Galileo,
GPS …

Two unique Satellite/lunar laser ranging & altimetry Characterization Facilities (**SCF**)

- Next to ESA-ESRIN and ASI-HQ in Frascati (Rome)
- Specialized Optical Ground Support Equipment (**OGSE**)
- **SCF** (top); also lunar and altimetry
- **SCF-G** (bottom) optimized for Galileo
- Two AM0 sun simulators, InfraRed thermometry
- Optical tests: Far Field Diffraction, Fizeau interferometry
- **Allow to establish TRL → 6-7**
- *J. Adv. Space Res. 47 (2011) 822–842*





Space Geodesy Center (CGS)

Giuseppe Colombo

Matera, Italy

ASI-CGS is an SLR, GNSS, VLBI co-located site

agenzia spaziale italiana

G. Bianco,
Director of ASI-CGS,
Chairman of Gov. Board of ILRS
(Intern. Laser Ranging Service)

SLR = Satellite Laser Ranging
GNSS = Glob Navig Satel System
VLBI = Very Long Baseline Interferometry

IAG → ILRS, IVS, IGS ...→ ITRS

LAGEOS

International Laser Ranging Service

ITRS, International Terrestrial Reference System: space geodesy, geodynamics (plate tectonics), sat. navigation & <u>general relativity !!</u>

Space Geodesy, Geodynamics, VLBI, GNSS, General Relativity

Internat. Terrestrial Reference System/Frame (ITRS/F)
Cartesian system/frame co-rotating w/Earth:

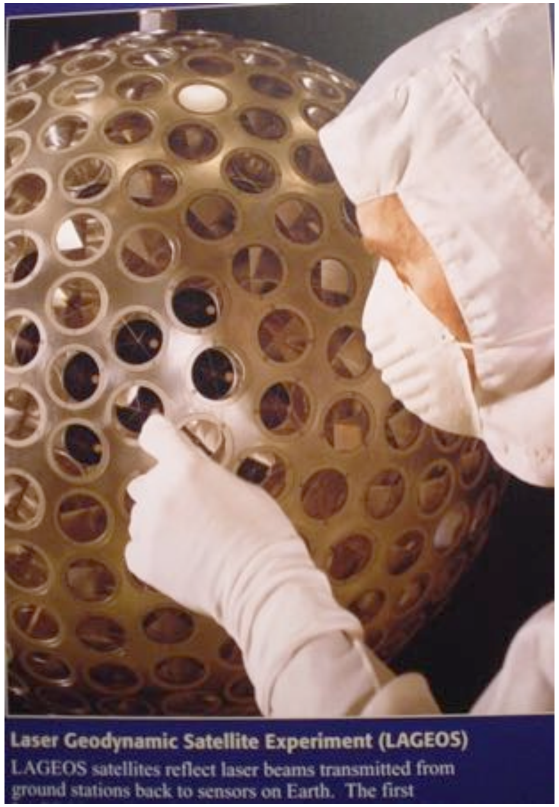
- **SLR => Origin = Geocenter** = centro of mass of the Earth = focii of LAGEOS orbits
- **SLR + VLBI => Scale of length = semi-axis of the** LAGEOS orbit
- **VLBI => Angles,** or orientation of axes = radio measurement of quasars (‘fixed stars’)
- **Frame = Cartesian coordinates of geodetic stations**
- Distribution of ITRS/F: GPS, Galileo, Beidou ...

LAGEOS

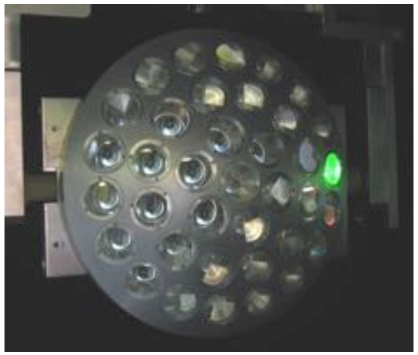
International Laser Ranging Service

ILRS tracks: LAser GEOdynamics Satellites(LAGEOS)

LAGEOS (1976, NASA), LAGEOS II (1993, NASA-ASI)



- Altitude: h ~1 Earth radius
- Primary use, geodesy: definition of geocenter and (with VLBI) scale of length
- Also general relativity: 20-10% test of **Frame Dragging**
  - LARES (ASI, 2011), h ~1/4 Earth radius) improved test of Frame Dragging



LAGEOS "Sector" of NASA-Goddard at INFN-Frascati for optical tests

- LARES-2 (ASI, built by INFN)
  - Altitude: h ~1 Earth radius
  - Primary use: permil-level test of Frame Dragging in general relativity
  - Secondary use, geodesy/metrology

Solar systems science assets

- **MoonLIGHT**, single <u>*big* Lunar</u> laser retroreflector
  - MoonLIGHT: Moon Laser Instrumentation for General relativity High accuracy Tests. **Single 4 inch reflector**
  - <u>Collaboration with Univ. of Maryland (UMD)</u>
- **PEP**, the Planetary Ephemeris Program *orbital SW*
  - Lunar/Martian positioning data. Developed at the Harvard-Smithsonian <u>Center for Astrophysics (CfA)</u>, USA, by Shapiro, Reasenberg, Chandler since 1960s
- **Solar System** & Mars <u>*micro*</u>reflector array
  - LaRRI: microreflector for landing-Roving laser ranging investigations. **Eight ½ inch reflectors**

Testing possible violations of Lorentz transformations symmetry

PRL **119,** 201102 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

Lorentz Symmetry Violations from Matter-Gravity Couplings with Lunar Laser Ranging

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(Received 21 June 2017; revised manuscript received 5 October 2017; published 16 November 2017)

The standard-model extension (SME) is an effective field theory framework aiming at parametrizing any violation to the Lorentz symmetry (LS) in all sectors of physics. In this Letter, we report the first direct experimental measurement of SME coefficients performed simultaneously within two sectors of the SME framework using lunar laser ranging observations. We consider the pure gravitational sector and the classical point-mass limit in the matter sector of the minimal SME. We report no deviation from general relativity and put new realistic stringent constraints on LS violations improving up to 3 orders of magnitude previous estimations.

DOI: 10.1103/PhysRevLett.119.201102

Testing extended gravity, f(R) models

PHYSICAL REVIEW D **91,** 044012 (2015)

Constraining models of extended gravity using Gravity Probe B and LARES experiments

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(Received 30 October 2014; published 9 February 2015)

We consider models of extended gravity and in particular, generic models containing scalar-tensor and higher-order curvature terms, as well as a model derived from noncommutative spectral geometry. Studying, in the weak-field approximation (the Newtonian and post-Newtonian limit of the theory), the geodesic and Lense-Thirring processions, we impose constraints on the free parameters of such models by using the recent experimental results of the Gravity Probe B (GPB) and Laser Relativity Satellite (LARES) satellites. The imposed constraint by GPB and LARES is independent of the torsion-balance experiment, though it is much weaker.

DOI: 10.1103/PhysRevD.91.044012 PACS numbers: 04.50.Kd, 04.25.Nx, 04.80.Cc

Testing f(R) gravity with the Moon

Simulating Solar System constraints in $f(R)$ gravity via Lunar Laser Ranging

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Here we focus on the use of potentially observable anomalies in the solar system investigating the expected values of Post Parameterized Newtonian parameters in view of possible discrepancies got from the aforementioned class of $f(R)$ models. We compare our results with the prediction of General Relativity and we simulate our outcomes by means of the Planetary Ephemeris Program (PEP). In particular, we take into account two different orientations at 87 and 67 N and using real data spanning from 1967 to 2014 we simulate the expected PPN values up to 2030. We thus analyze our bounds over $f(R)$ gravity and we obtain the PPN limits, showing how these results put limits on $f(R)$ derivatives. We thus compare our results with current theoretical hints coming from stability requirements. To do so, we infer the expected σ over $\dot{G}/G$, η and β, respectively the variation of gravitational constant, the weak and strong equivalence principles. We analyze such error bars with and without sunshade, showing that no significative departures occur between the two sets of data. We thus numerically constrain the class of $f(R)$ theories and finally we handle the Sawicki and cosmographic models, providing limits over the free coefficients which turn out to be compatible with recent developments. Our treatment severely fixes further limits on $f(R)$ cosmological theories which every form of $f(R)$ must fulfill to guarantee the weak field limit approximation holds.

Testing nonminimally coupled gravity, $f_1(R)+f_2(R)$ models

PHYSICAL REVIEW D **95,** 024017 (2017)

$1/c$ expansion of nonminimally coupled curvature-matter gravity models and constraints from planetary precession

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(Received 7 July 2016; published 13 January 2017)

The effects of a nonminimally coupled curvature-matter model of gravity on a perturbed Minkowski metric are presented. The action functional of the model involves two functions $f^1(R)$ and $f^2(R)$ of the Ricci scalar curvature R. This work expands upon previous results, extending the framework developed there to compute corrections up to order $O(1/c^4)$ of the 00 component of the metric tensor. It is shown that additional contributions arise due to both the nonlinear form $f^1(R)$ and the nonminimal coupling $f^2(R)$, including exponential contributions that cannot be expressed as an expansion in powers of $1/r$. Some possible experimental implications are assessed with application to perihelion precession.

DOI: 10.1103/PhysRevD.95.024017

GR test improvements with Mercury

While waiting for BepiColombo (see L. Iess talk) ...

A&A 561, A115 (2014)
DOI: 10.1051/0004-6361/201322124
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Astronomy & Astrophysics

Use of MESSENGER radioscience data to improve planetary ephemeris and to test general relativity

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ABSTRACT

The current knowledge of Mercury's orbit has mainly been gained by direct radar ranging obtained from the 60s to 1998 and by five Mercury flybys made with Mariner 10 in the 70s, and with MESSENGER made in 2008 and 2009. On March 18, 2011, MESSENGER became the first spacecraft to orbit Mercury. The radioscience observations acquired during the orbital phase of MESSENGER drastically improved our knowledge of the orbit of Mercury. An accurate MESSENGER orbit is obtained by fitting one-and-half years of tracking data using GINS orbit determination software. The systematic error in the Earth-Mercury geometric positions, also called range bias, obtained from GINS are then used to fit the INPOP dynamical modeling of the planet motions. An improved ephemeris of the planets is then obtained, INPOP13a, and used to perform general relativity tests of the parametrized post-Newtonian (PPN) formalism. Our estimations of PPN parameters (γ and β) are more stringent than previous results.

Key words. ephemerides – celestial mechanics

Theory and combined experimental limits on spacetime torsion + GR

PHYSICAL REVIEW D **83**, 104008 (2011)

Constraining spacetime torsion with the Moon and Mercury

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(Received 13 December 2010; published 4 May 2011)

We report a search for new gravitational physics phenomena based on Riemann-Cartan theory of general relativity including spacetime torsion. Starting from the parametrized torsion framework of Mao, Tegmark, Guth, and Cabi, we analyze the motion of test bodies in the presence of torsion, and, in particular, we compute the corrections to the perihelion advance and to the orbital geodetic precession of a satellite. We consider the motion of a test body in a spherically symmetric field, and the motion of a satellite in the gravitational field of the Sun and the Earth. We describe the torsion field by means of three parameters, and we make use of the autoparallel trajectories, which in general differ from geodesics when torsion is present. We derive the specific approximate expression of the corresponding system of ordinary differential equations, which are then solved with methods of celestial mechanics. We calculate the secular variations of the longitudes of the node and of the pericenter of the satellite. The computed secular variations show how the corrections to the perihelion advance and to the orbital de Sitter effect depend on the torsion parameters. All computations are performed under the assumptions of weak field and slow motion. To test our predictions, we use the measurements of the Moon's geodetic precession from lunar laser ranging data, and the measurements of Mercury's perihelion advance from planetary radar ranging data. These measurements are then used to constrain suitable linear combinations of the torsion parameters.

Theory and experimental limits on spacetime torsion extension of GR

Gen Relativ Gravit (2011) 43:3099–3126
DOI 10.1007/s10714-011-1226-2

RESEARCH ARTICLE

Constraining spacetime torsion with LAGEOS

Riccardo March · Giovanni Bellettini ·
Roberto Tauraso · Simone Dell'Agnello

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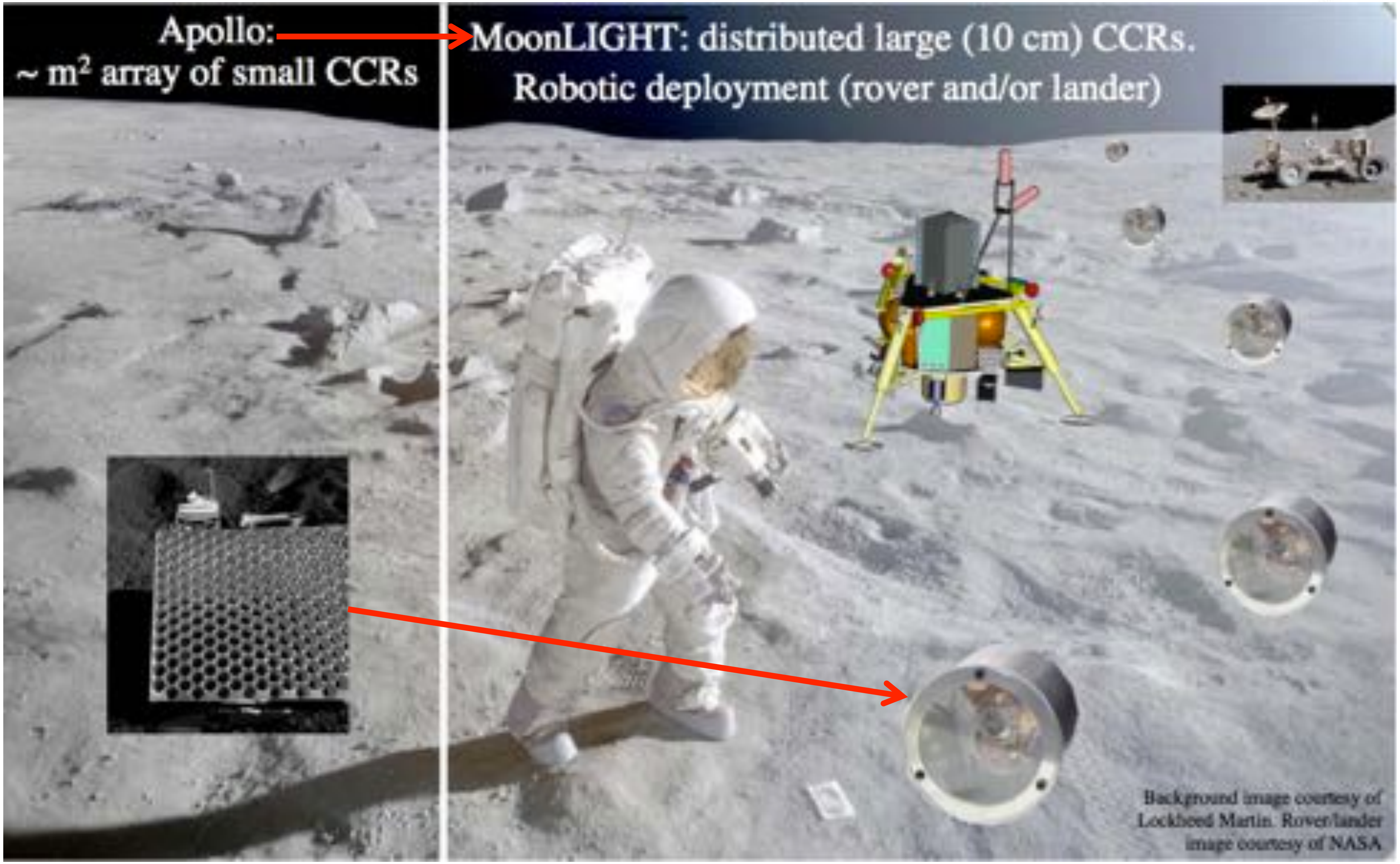
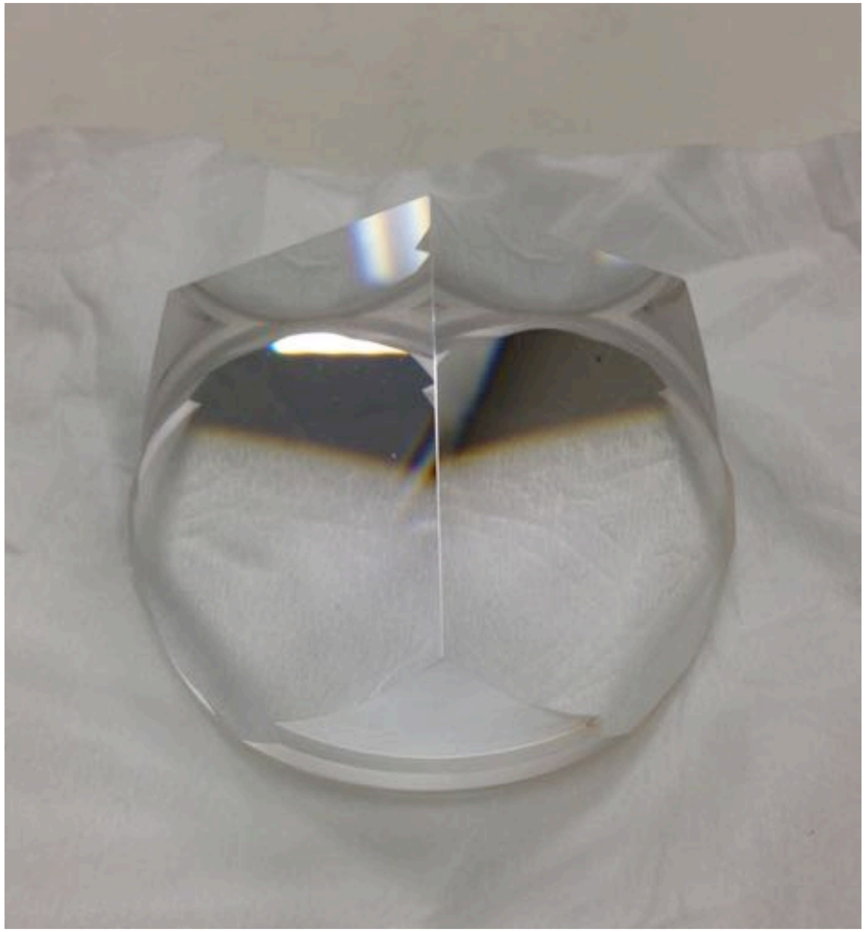
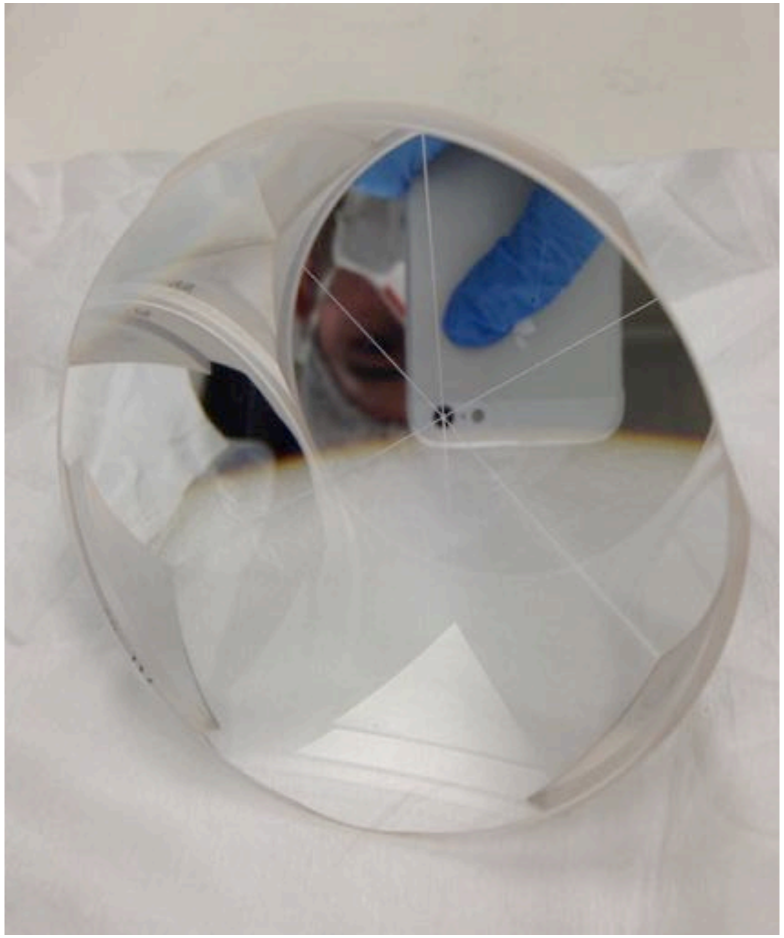
Abstract We compute the corrections to the orbital Lense-Thirring effect (or frame-dragging) in the presence of spacetime torsion. We analyze the motion of a test body in the gravitational field of a rotating axisymmetric massive body, using the parametrized framework of Mao, Tegmark, Guth and Cabi. In the cases of autoparallel and extremal trajectories, we derive the specific approximate expression of the corresponding system of ordinary differential equations, which are then solved with methods of Celestial Mechanics. We calculate the secular variations of the longitudes of the node and of the pericenter. We also show how the LAser GEOdynamics Satellites (LAGEOS) can be used to constrain torsion parameters. We report the experimental constraints obtained using both the nodes and perigee measurements of the orbital Lense-Thirring effect. This makes LAGEOS and Gravity Probe B complementary frame-dragging and torsion experiments, since they constrain three different combinations of torsion parameters.

Replace arrays with single/large retroreflectors

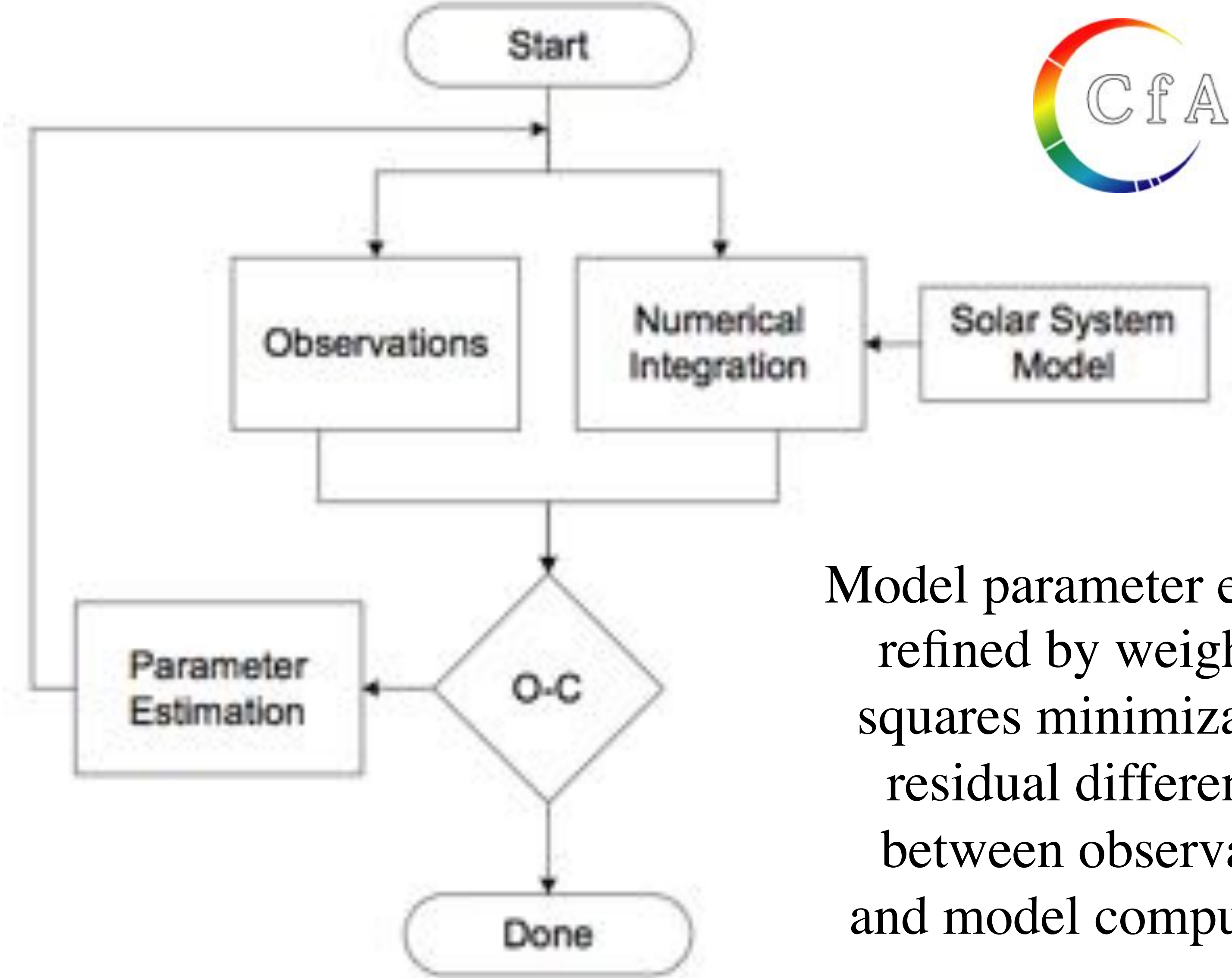


MoonLIGHT laser retroreflector





PEP (Planetary Ephemeris Program by CfA)



Model parameter estimates are refined by weighted least-squares minimization of the residual differences O-C, between observations (O) and model computations (C)

LLR test of General Relativity

Improvements of space segment up to ×100 with MoonLIGHTs plus current LGN of Apollo/Lunokhods

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

* J. G. Williams et al PRL 93, 261101 (2004)

** M. Martini and S. Dell'Agnello, R. Peron et al. (eds.), DOI 10.1007/978-3-319-20224-2_5, Springer Intern. Publishing, Switzerland (2016)

Test of Equivalence Principle (EP)

- Weak EP (*feather vs. hammer*)
  - Composition difference: iron in Earth vs. silicates in Moon
  - Tested by LLR to $\Delta a/a < 10^{-13}$
- Strong EP (*small hammer vs. big hammer*)
  - Applies to gravitational "self-energy"
  - Earth self-energy has equivalent mass ($E = mc^2$)
    - 4.6×10^{-10} of Earth's total mass-energy
  - Does this mass have $M_G/M_I = 1.00000\ldots$?
  - Gravity pulls on gravity. *Nonlinear* aspect of gravity => **PPN β**
- WEP contribution measured in the lab with torsion pairs (miniature Earth and Moon) by EotWash group
- WEP effects subtracted in LLR analysis => access to SEP

LLR test of the Strong Equivalence Principle

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

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

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

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

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

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

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

SEP can only be tested LLR

LLR test of the Equivalence Principle

If EP is violated:

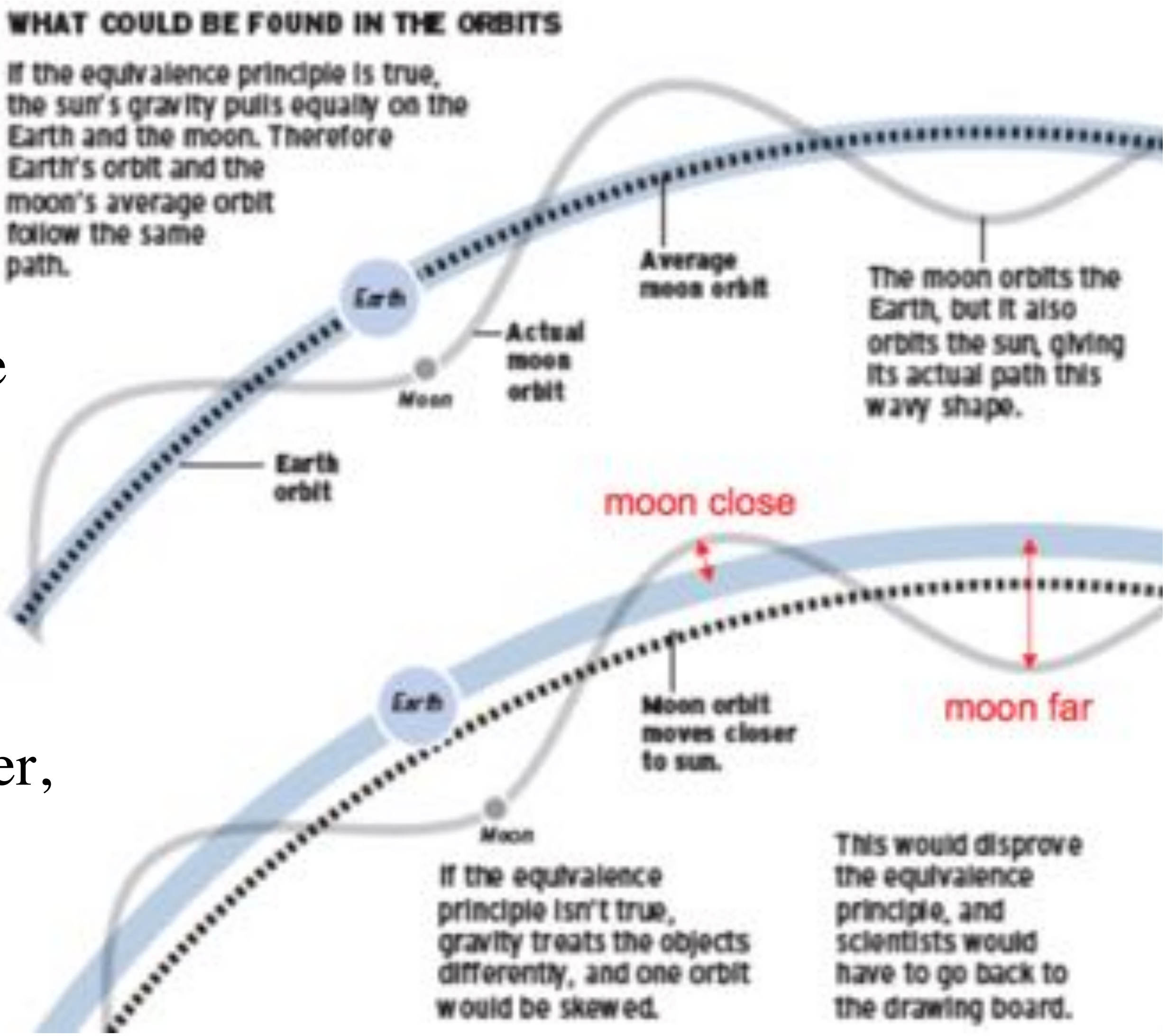
lunar orbit displaced along Earth-Sun line;

periodic variation of Earth-Moon distance

$$\Delta r = 13.1\,\eta \times \cos D$$

D = lunar phase angle

η = Nordtvedt parameter, describes gravitational self-energy



Graphic excerpt from San Diego Union Tribune

LLR SEP test: implications on η and PPN β

- SEP violation is due to self-energy (U) contribution only

$$[(M_G/M_I)]_{SEP} = 1 + \eta\ (U/Mc^2)$$

U/M $\propto$ M => to test SEP need astronomical bodies => only LLR

- Theory prediction

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{SEP} = [U_e/Mc^2 - U_m/Mc^2] \times \eta$$
$$= -\,4.45 \times 10^{-10} \times \eta$$

- Considering in η only PPN β and γ

$$\boldsymbol{\eta = 4\beta - \gamma - 3 = (4.4 \pm 4.5) \times 10^{-4}}$$

- β describes non linearity of gravity associated to a SEP violation
- Using Cassini's value of γ:

$$\boldsymbol{\beta - 1 = (1.2 \pm 1.1) \times 10^{-4}}$$

Best η and β measurement to date

LLR test of Gdot/G

- G variation may be related to expansion of the Universe, in which case Gdot/G = σ × (Hubble constant)

  σ: dimensionless parameter depending on G & the cosmological model which allows for G evolution

- If *G* changes with time, Kepler's law is broken
- Test of temporal variation of G from fit of LLR data gives

$$\text{Gdot/G} = (4 \pm 9) \times 10^{-13}/\text{year}$$

  ✓ Less than 1% change over age of Universe

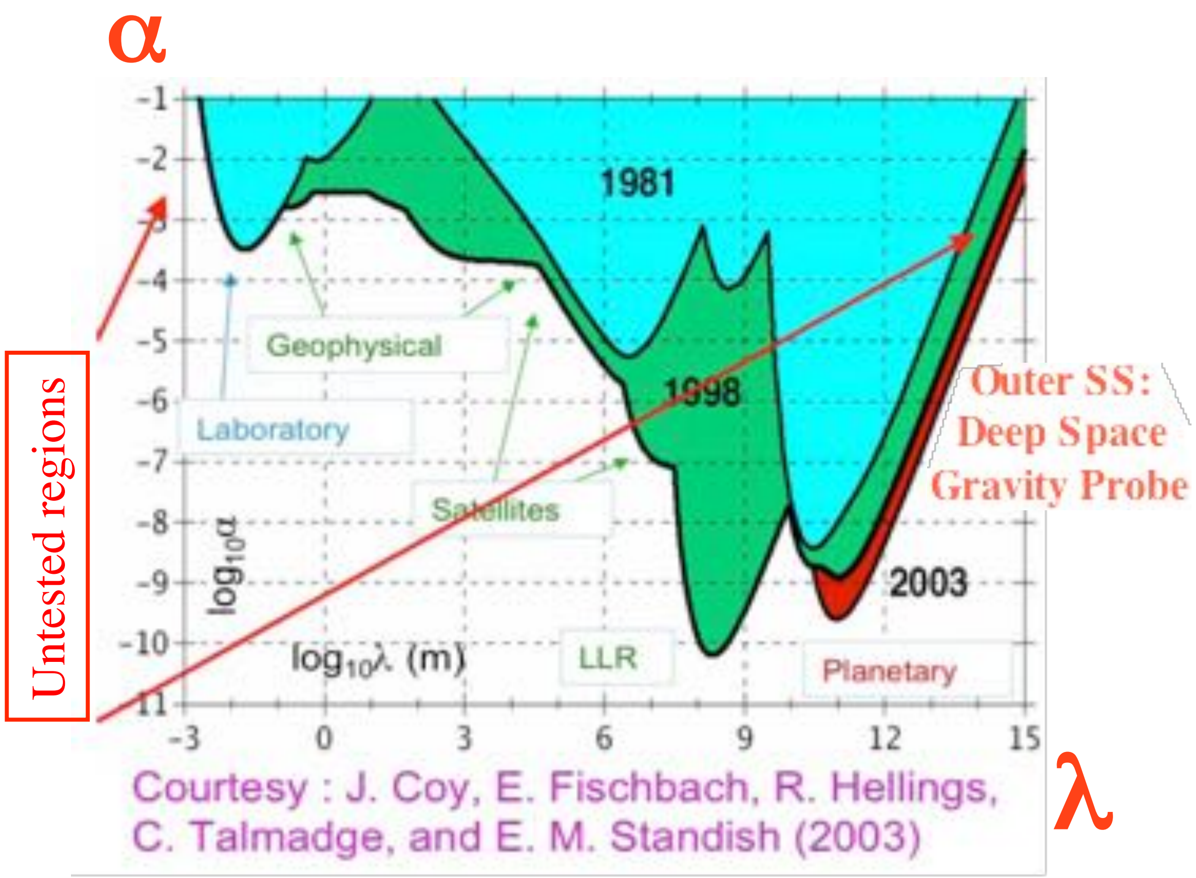
- Error on Gdot/G depends on
  ✓ Accuracy of LLR measurements
  ✓ Square of time span of LLR data

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

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

MoonLIGHT provides accuracy 100 times better on the space segment (the reflectors)

When other LLR error sources will have improved up the same level, MoonLIGHT-2 will improve limits from **$\alpha \sim 3\text{x}10^{-11}$ down to $<10^{-12}$ at scales $\lambda \sim$ million km**



LLR for Lunar planetary science

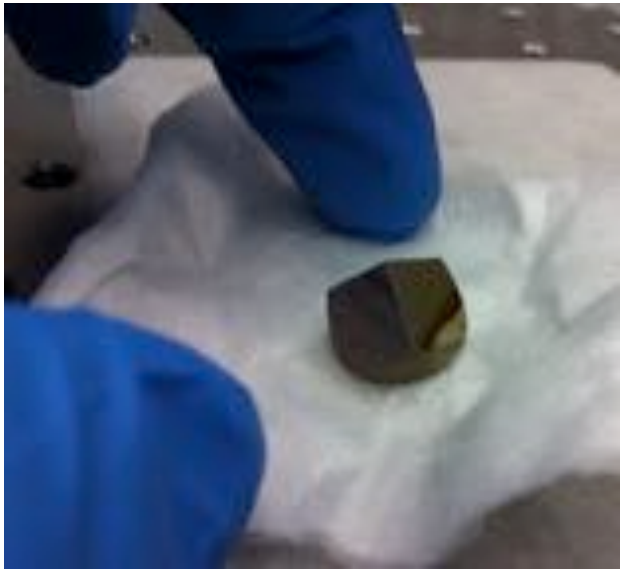
- LLR provided the best data for the deep interior of the moon. Used to supplement the data from the GRAIL mission analysis
  - ✓ In 1998, analysis of the LLR data discovered and measured the size, shape and dissipation of the liquid core of the Moon (Williams et al)
  - ✓ Confirmed by a re-analysis of Apollo Seismometry data (Weber et al 2011)
- Our next-gen retroreflectors will strengthen the collaboration with the study of internal structure of the moon, by providing more accurate data from more stations of the International Laser Ranging Service (ILRS)
- Next: New Frontiers AO on the Moon
  - ✓ Collaboration with C. Neal (PI, U. Notre Dame) & others groups

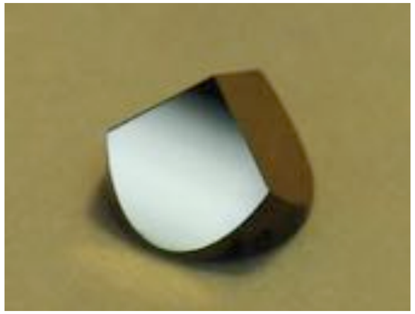
Lunar and Martian interior & geodesy

- **LLR** to surface reflectors provided the best data for the deep interior of the moon and its surface geodesy
- Used to supplement the data from the GRAIL mission analysis
  - ✓ In 1998, analysis of the LLR data discovered and measured the size, shape and dissipation of the liquid core of the Moon (Williams et al 1998)
  - ✓ Confirmed by a re-analysis of Apollo Seismometry (Weber et al 2011)
- **Mars InSIGHT lander** (next slides): similar are some goals of Rotation and Interior Structure Experiment (**RISE**, Folkner et al) on InSight, although with different measurements techniques (X-band radio system & DSN): liquid core of Mars, constraints on its radius and density; superb tie between cartographic and inertial reference frames

Mars: next-generation microreflectors

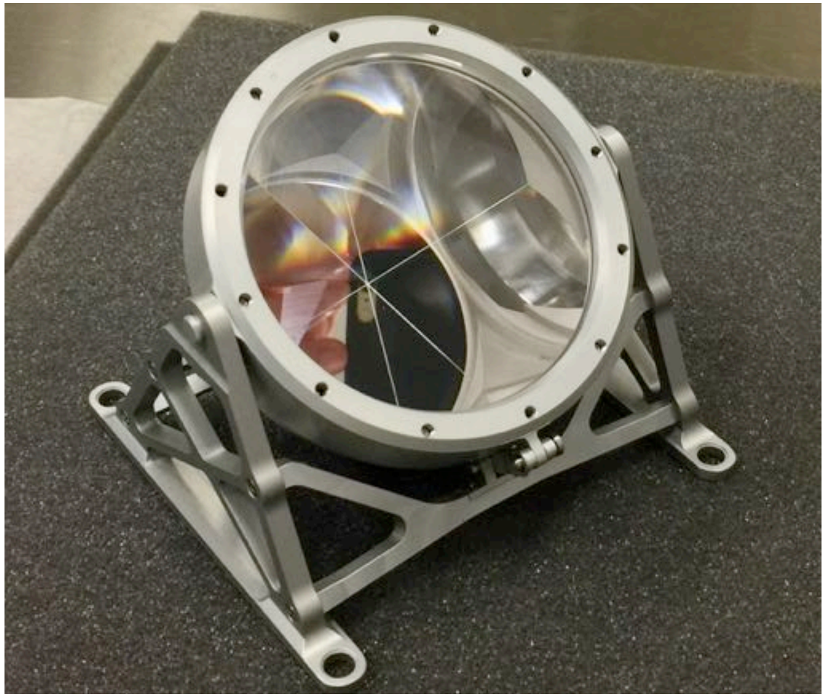
- ½ inch diameter
- Positioning of lander/rovers on Moon/Mars
- Observed from orbiters
- Metrics for all solar system





Lunar landing/roving opportunities

- **TeamIndus 1** (India, commercial)
- **Moon Express 1** (USA, commercial)
- **Astrobotic 1** (USA, commercial)
- **Chang’E program** (China, CNSA)
- **New Frontiers AO** (USA, NASA)

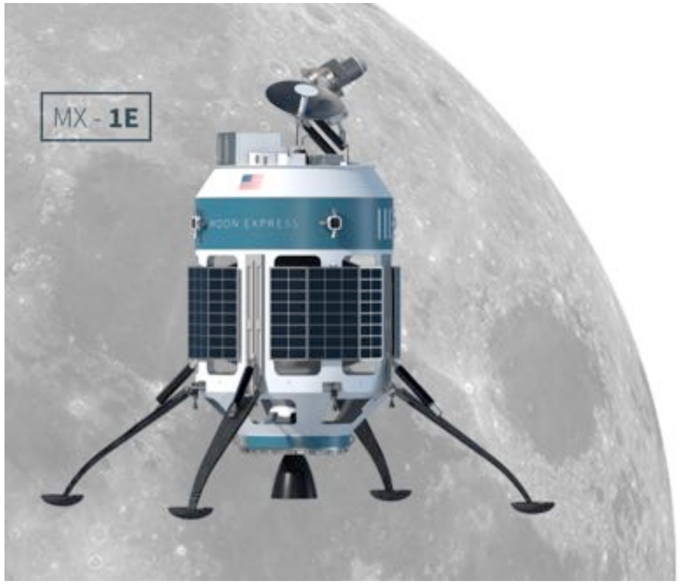


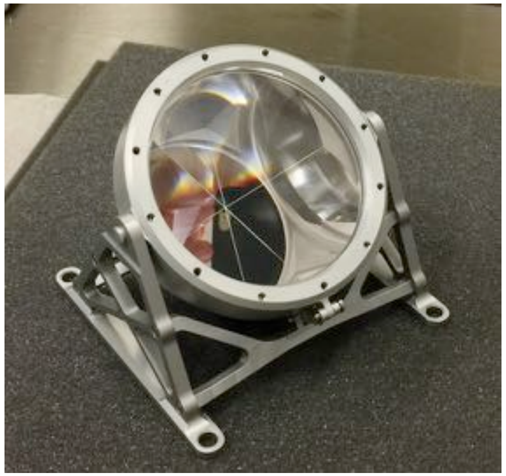
Moon Express mission 1

EXPEDITION ONE: LUNAR SCOUT

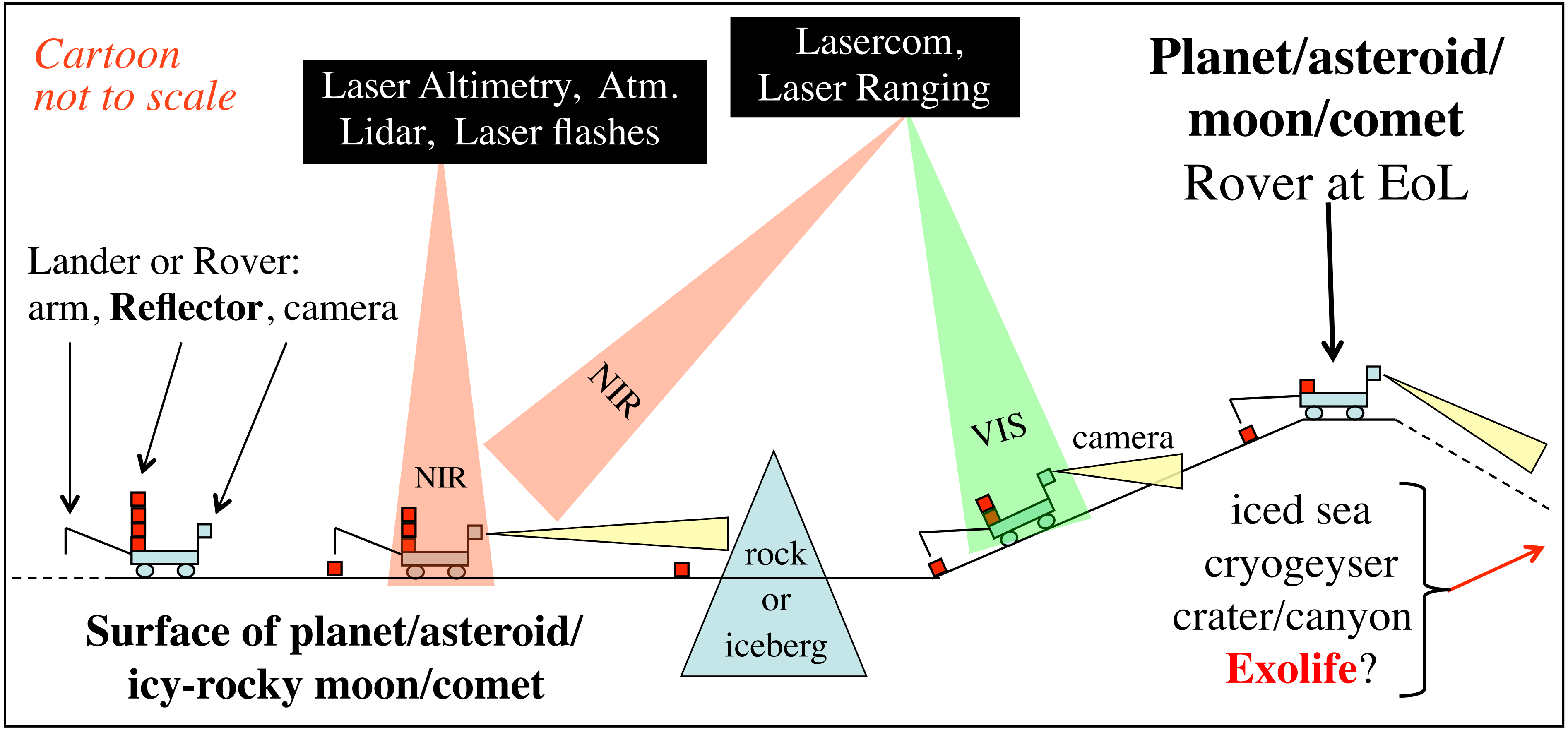
THE 1ST COMMERCIAL VOYAGE TO THE MOON

The ***Lunar Scout*** expedition will be the first commercial voyage to the Moon. This historic expedition will demonstrate the cost effectiveness of entrepreneurial approaches to space exploration, carrying a diverse manifest of payloads including the International Lunar Observatory, "MoonLight" by the INFN National Laboratories of Frascati and the University of Maryland, and a Celestis memorial flight. Following





μreflectors on Moon/Mars, asteroids/comets, icy/moons



Laser-locate Rover/Lander w/reflector <u>from orbiters</u>. Moon far side

Global and local reflector networks to serve Exploration, Planetary Science, Geodesy and test Fundamental Gravity

GLAS laser altimeter, on ICESat mission, observed
laser retroreflectors <u>distinct</u>
from laser returns by non-cooperating ground
at White Sands, NM, USA

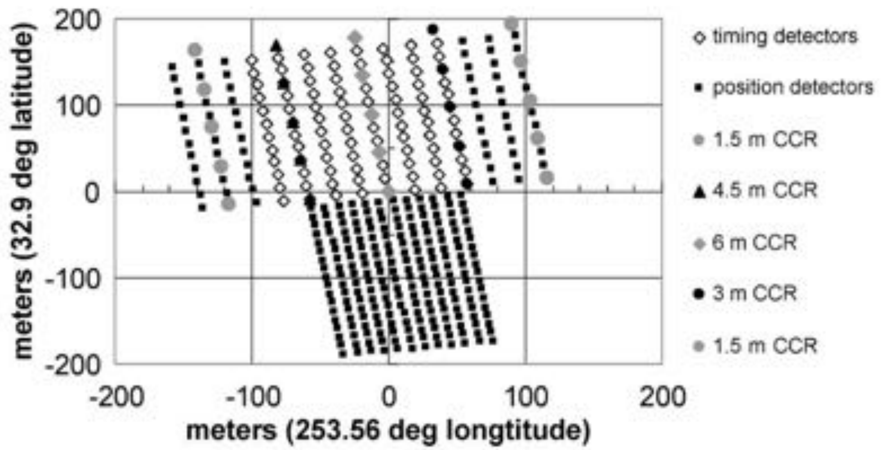
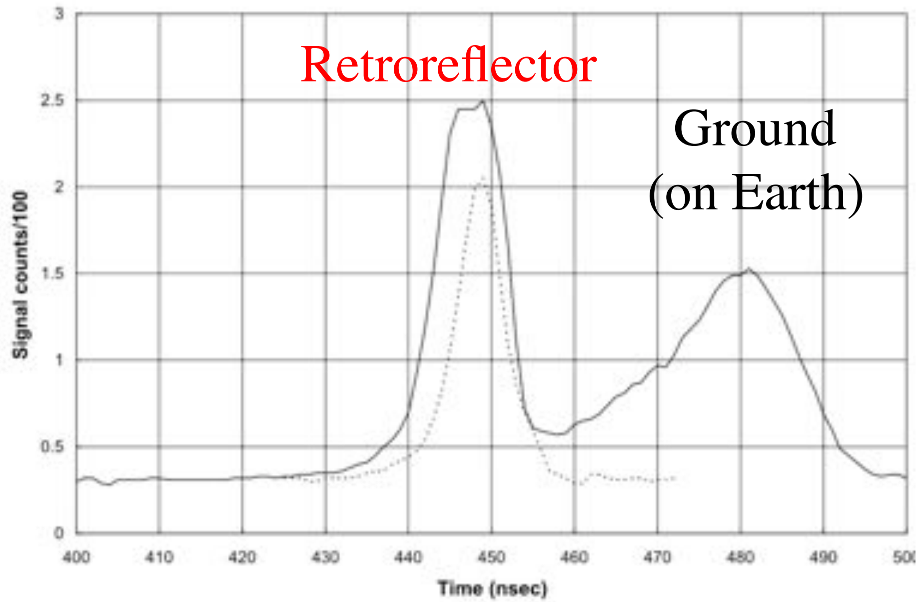


Fig. 2. WSSH ground calibration system geometrical arrangement of equipment.



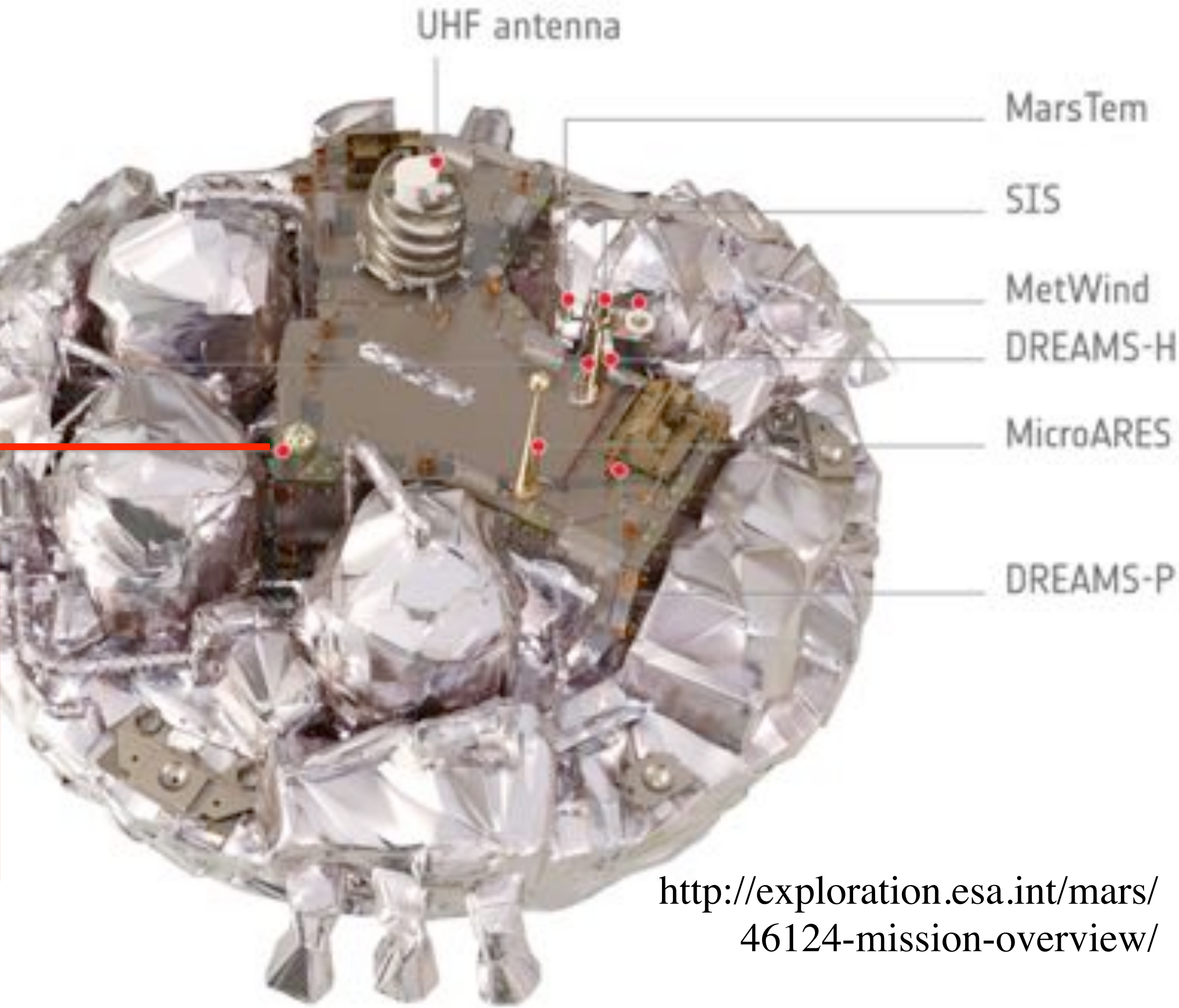
Microreflector network: science/exploration

- **Laser ranging/altimetry (or lasercom) by orbiters**
  - **Microreflector on any available Rover/Lander location**
- **Test of General Relativity and its extensions**
- **Accurate positioning of landing-roving**
- Absolute geolocation of the Rover site at end-of-life
  - Possibly tied to local metrics established by Rover Pan/Cameras
- Improved definition of Meridian 0 (*Mars Greenwich*), much better than current Airy 0 crater (~100 m accuracy)
- Lasercomm test & diagnostics. Future: MRRs
  - ESA/ASI fund R&D on MRRs (*Modulated RetroReflectors*) for Mars surface
- Lidar-based/aided landing (return to Lander/Rover site)
- Atmospheric trace species detection by lidar on orbiter
  - Future: couple orbiting lidar, retroreflector w/lander atmosph. station

ExoMars 2016: 1st laser retroreflector on Mars

Science payloads on the Lander Schiaparelli

25 gr, ~5cm×2cm



http://exploration.esa.int/mars/46124-mission-overview/

ExoMars EDM 2016

(Schiaparelli lander)

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 59 (2017) 645–655

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

INRRI-EDM/2016: the first laser retroreflector on the surface of Mars

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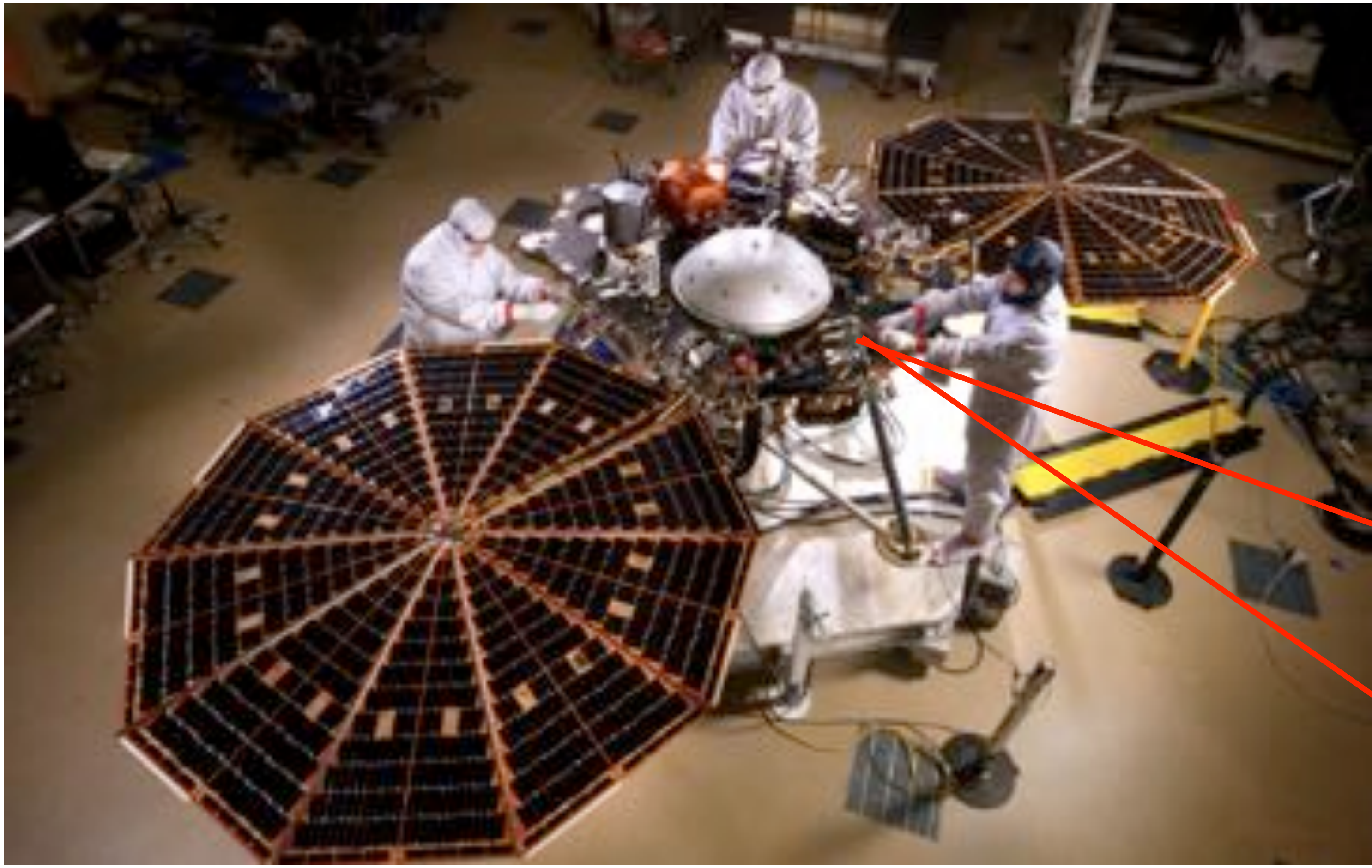
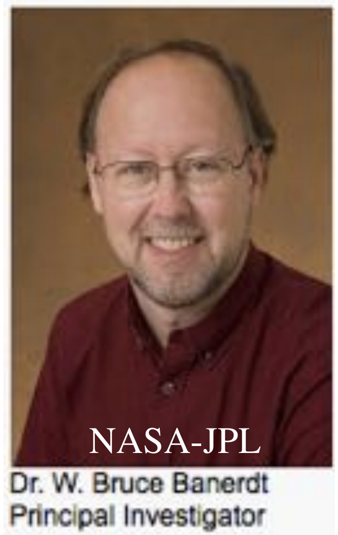
NASA-ASI Agreements, InSight & Mars 2020

- **LaRRI** = Laser RetroReflector for InSight
- **LaRA** = LAser Retroreflector Array for Mars 2020
- Two Agreements signed by NASA & ASI in 2017
- <u>Excerpt the from Mars 2020 NASA-ASI Agreement</u>:

> Once the Mars 2020 rover is on the surface of Mars and an orbiter capable of laser ranging, laser altimetry, or both, is in orbit around Mars, the LaRA will be able to provide accurate positioning measurements of rover drive activities. Over time, the LaRA will also be able to help define Mars Meridian 0 and support atmospheric trace species detection. Additionally, the LaRA could support locating the Mars 2020 rover and accompanying samples by a future Mars sample retrieval mission.
>
> SCF Lab (Satellite/lunar/gnss laser ranging and altimetry Characterization Facility Laboratory) of the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF) in Italy will design and build the LaRA, under the coordination of ASI. ASI will provide the LaRA to the NASA Mars 2020 mission. NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, will manage the Mars 2020 mission for NASA.

NASA’s InSight Mars Lander (Discovery 2010)



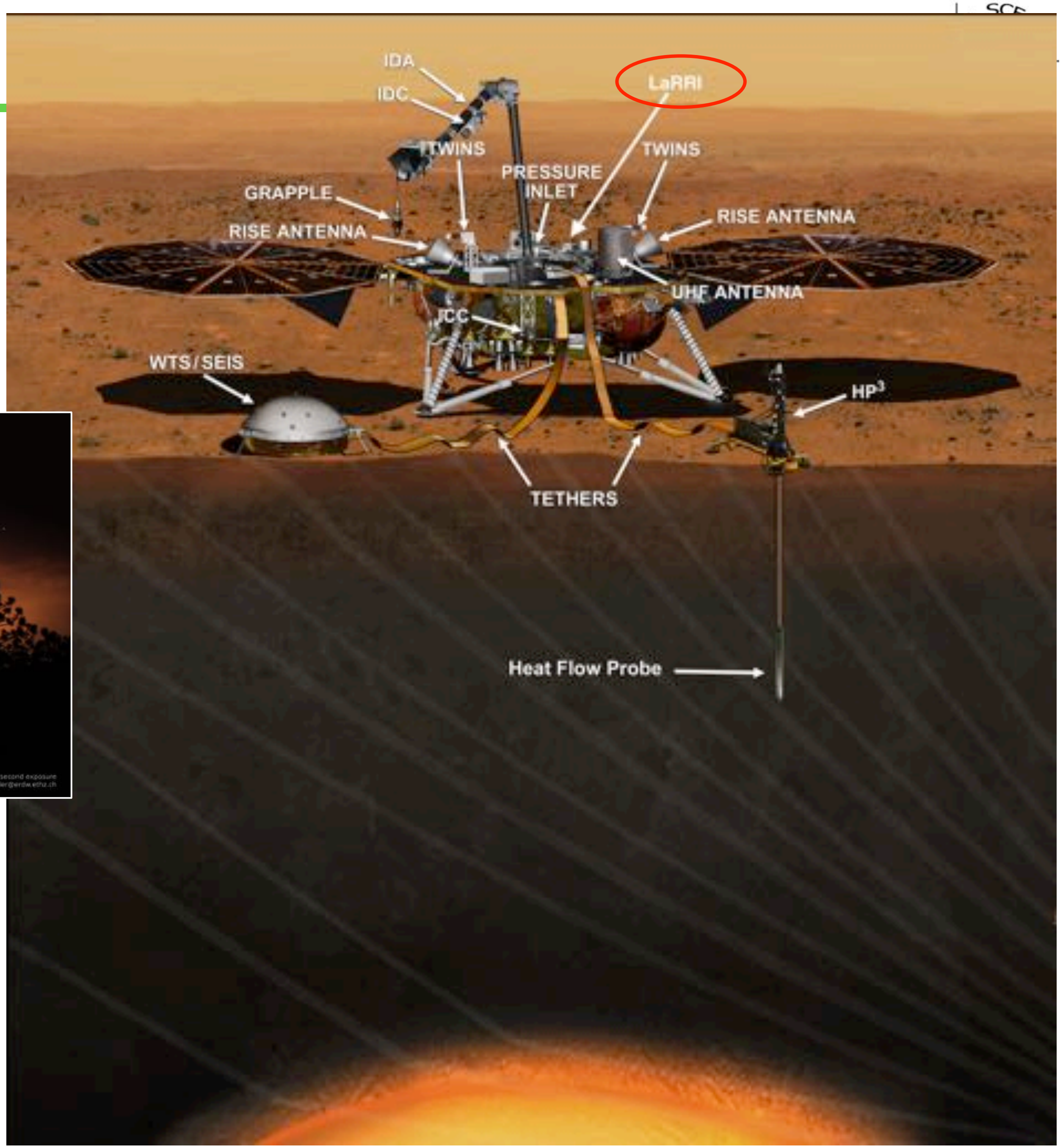


InSIGHT = Interior exploration using Seismic Investigations, <u>Geodesy</u> and Heat Transport

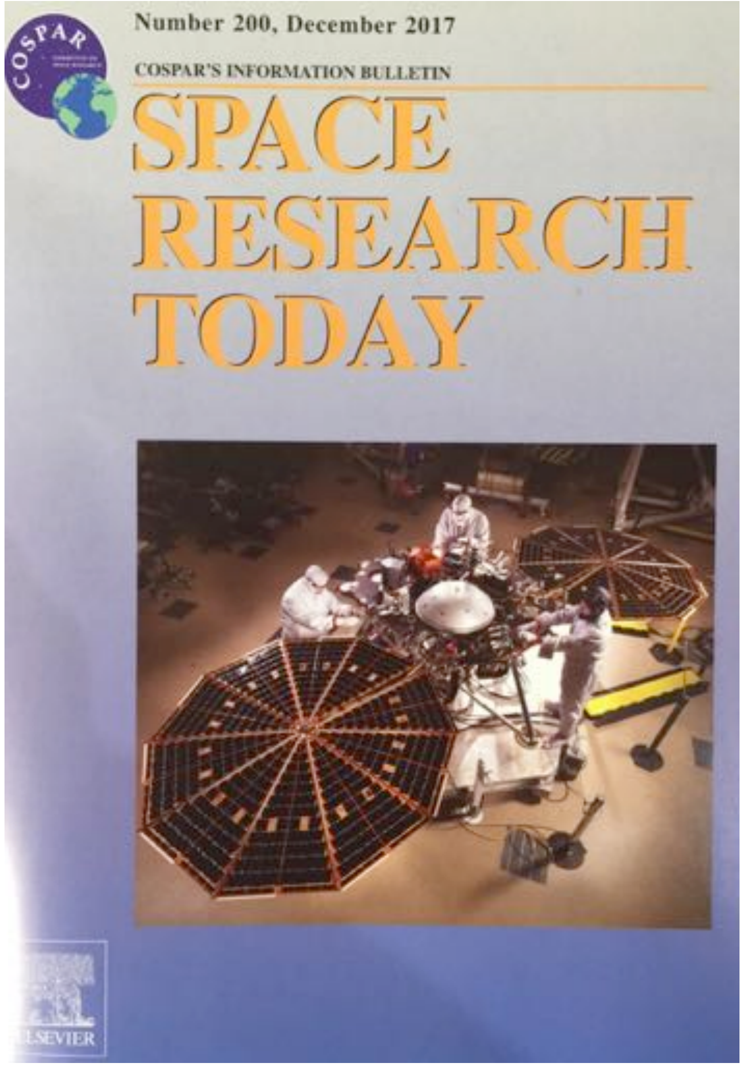
LaRRI = Laser (micro)RetroReflector for InSight

May 5, 2018, from Vandenberg AFB: **InSight** launched!

Entry, Descent and Landing on Mars: Nov 26, 2018



1st paper on InSight Mars Lander



Research Highlights

LaRRI: Laser Retro-Reflector for InSight Mars Lander

[By S. Dell'Agnello (INFN-LNF, Italy), G. Delle Monache (INFN-LNF, Italy), E. Ciocci (INFN-LNF, Italy), S. Contessa (INFN-LNF, Italy), M. Martini (INFN-LNF, Italy), C. Mondaini (INFN-LNF, Italy), L. Porcelli (INFN-LNF, Italy), L. Salvatori (INFN-LNF, Italy), M. Tibuzzi (INFN-LNF, Italy), R. Vittori (Aeronautica Militare Italiana, Italy), M. Maiello (INFN-LNF, Italy), E. Flamini (Agenzia Spaziale Italiana (ASI) HQ , Italy), E. Marchetti (ASI HQ, Italy), G. Bianco (ASI-CGS, Italy), B. Banerdt (Jet Propulsion Laboratory (JPL), USA), J. F. Grinblat (JPL, USA), M. Kokorowski (JPL, USA).]

Abstract

During 2017, INFN-LNF's SCF_Lab[1] Team carried out the final activities of manufacturing, qualification for space flight and integration of LaRRI on the NASA-JPL's spacecraft InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport), which is scheduled to fly to Mars in 2018. LaRRI is the second microreflector array of its kind manufactured at INFN-LNF, after INRRI for the ExoMars EDM ESA spacecraft [1], and, exactly like its forefather, it is a pocket-size, yet fully functional, array of cube corner laser retroreflectors. LaRRI underwent the same fabrication process of INRRI and it will enable the laser-location of InSight from Mars orbiters through several techniques [1]. Once on the surface of Mars, and unlike its unfortunate progenitor, LaRRI will serve as a passive, maintenance-free 'milestone' for laser interrogation by future orbiters. LaRRI is expected to be the first-ever operational retroreflector on Mars and the second flown to the Red Planet after INRRI. Both of them were designed, manufactured and space tested at INFN-LNF and at SERMS s.r.l., in Italy. In the present contribution, we first summarise the rationale of the investigations that may be carried on thanks to INRRI/LaRRI-like devices, then, the space qualification activity especially tailored for NASA Martian missions.

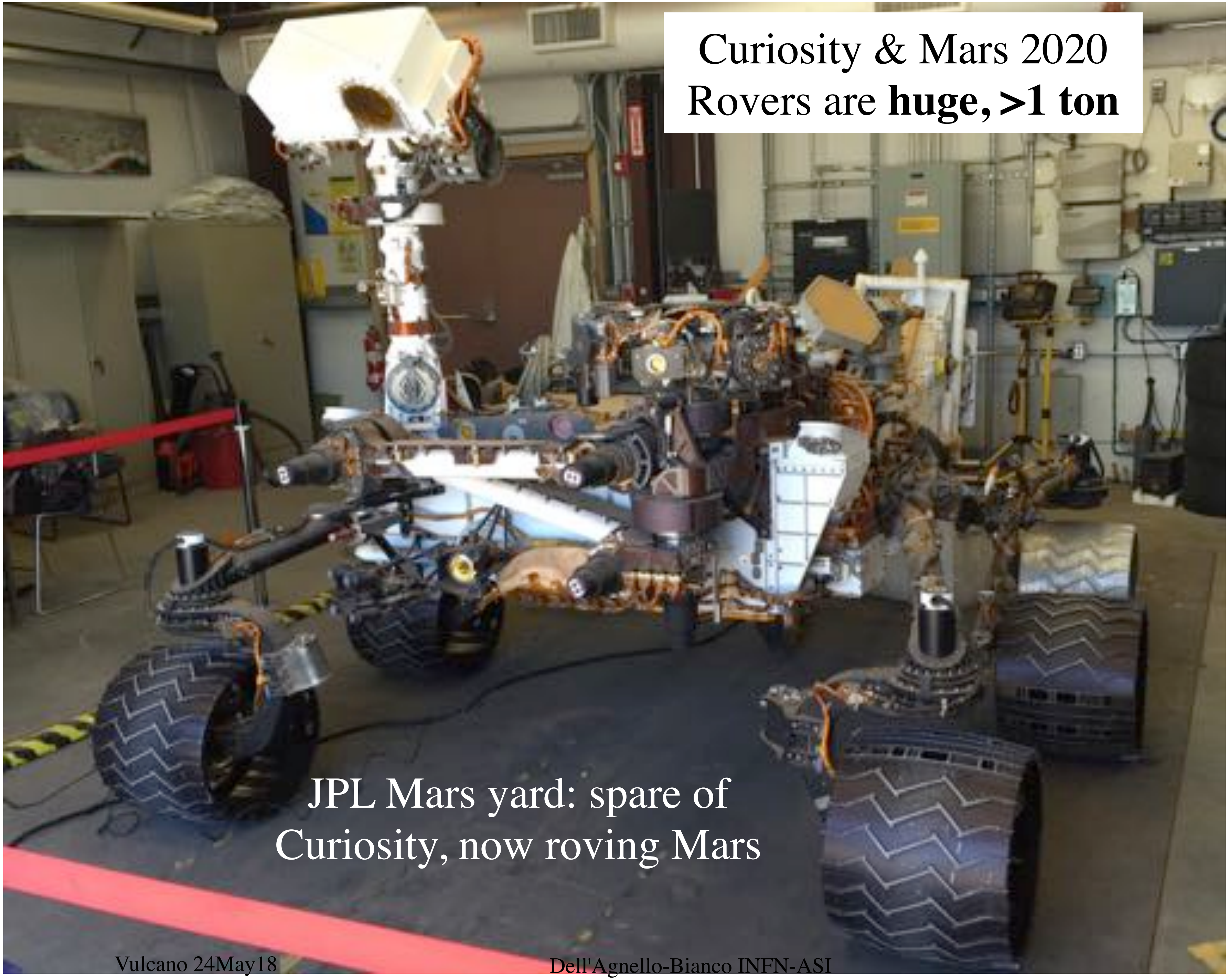
Overview

LaRRI (Figure 1) is a pocket-size, yet fully

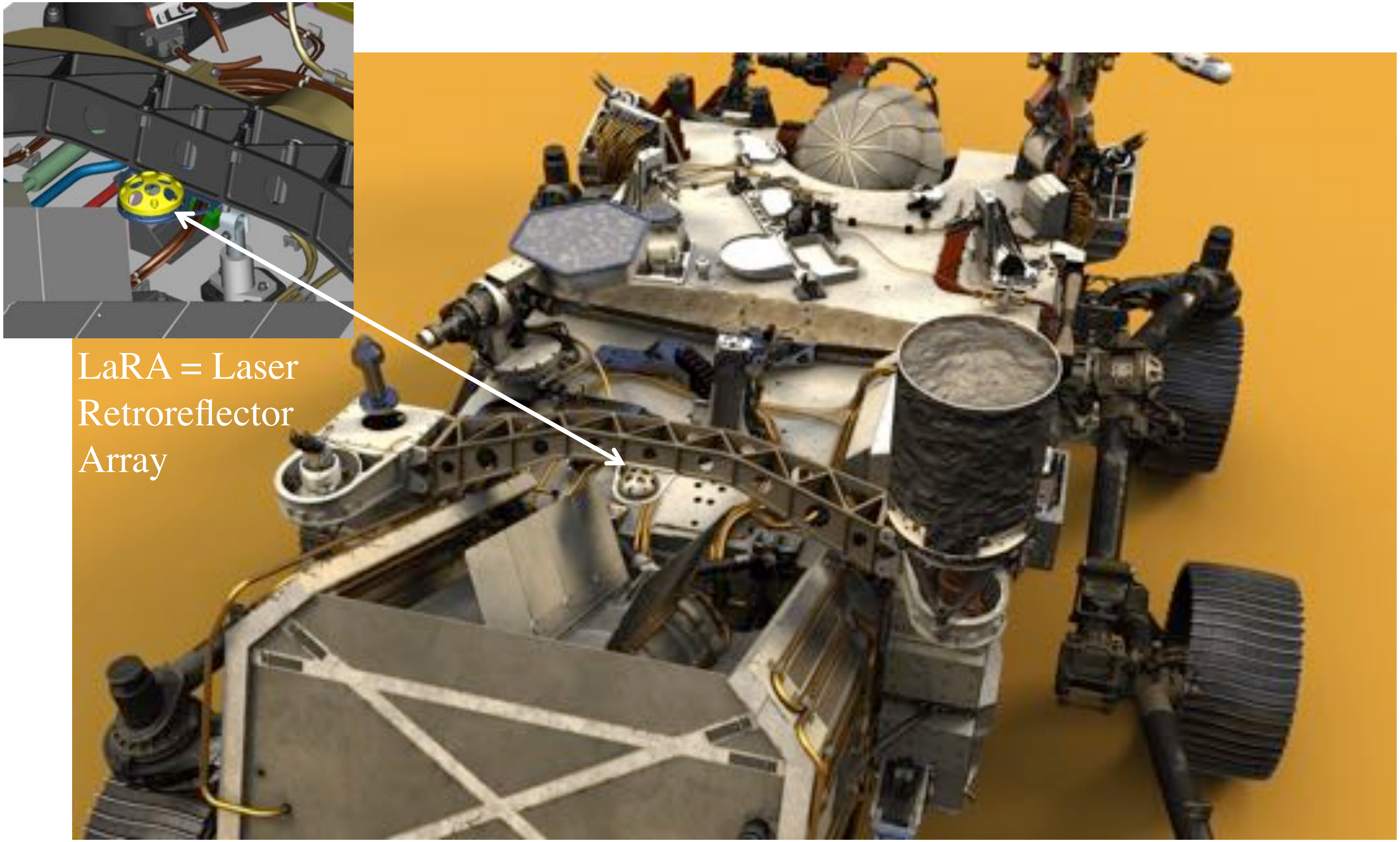
[1] Satellite/lunar/GNSS laser ranging/altimetry and cube/microsat Characterization Facilities Laboratory

25

Curiosity & Mars 2020 Rovers are **huge, >1 ton**



JPL Mars yard: spare of Curiosity, now roving Mars


LaRA = Laser Retroreflector Array

InSight, Mars 2020, ExoMars 2020:

nodes of the passive microreflector network

SkyCrane @JPL Mars 2020-Curiosity Clean Room

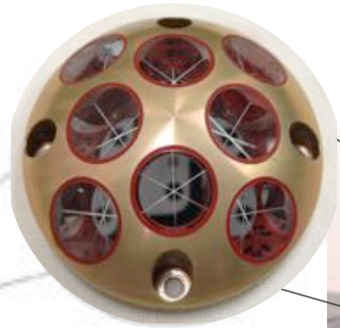
Mars Geophysical Network (MGN)

of microreflectors

NASA: Insight 2018 Lander, Mars 2020 Rover

ESA-ASI: Schiaparelli Lander, ExoMars 2020 Rover

Mars 2020 (NASA)



ExoMars 2020 (ESA)

Test General Relativity w/Mars rovers/landers

- Network of passive microreflectors
- Test of General Relativity at 1.5 AU
  - Estimate Mars center of mass like Selenocenter with LGN
  - PPN gamma, Gdot/G, $1/r^2$ law (Sun-Mars)
  - PPN beta (Sun-Earth-Mars-Jupiter)
- PEP (Planetary Ephemeris Program) simulations
- Literature & physics discussion (a few picks):
  - 'Historic' Shapiro time delay with Vikings, 1970s
  - J. Anderson, J. Williams, Class. Q. Grav. 18 (2001) 2447
  - S. Turyshev et al, arxiv:1003.4961v2, 3 Sep 2010 & its many refs.
- Similar program possible w/reflectors on Phobos & Deimos

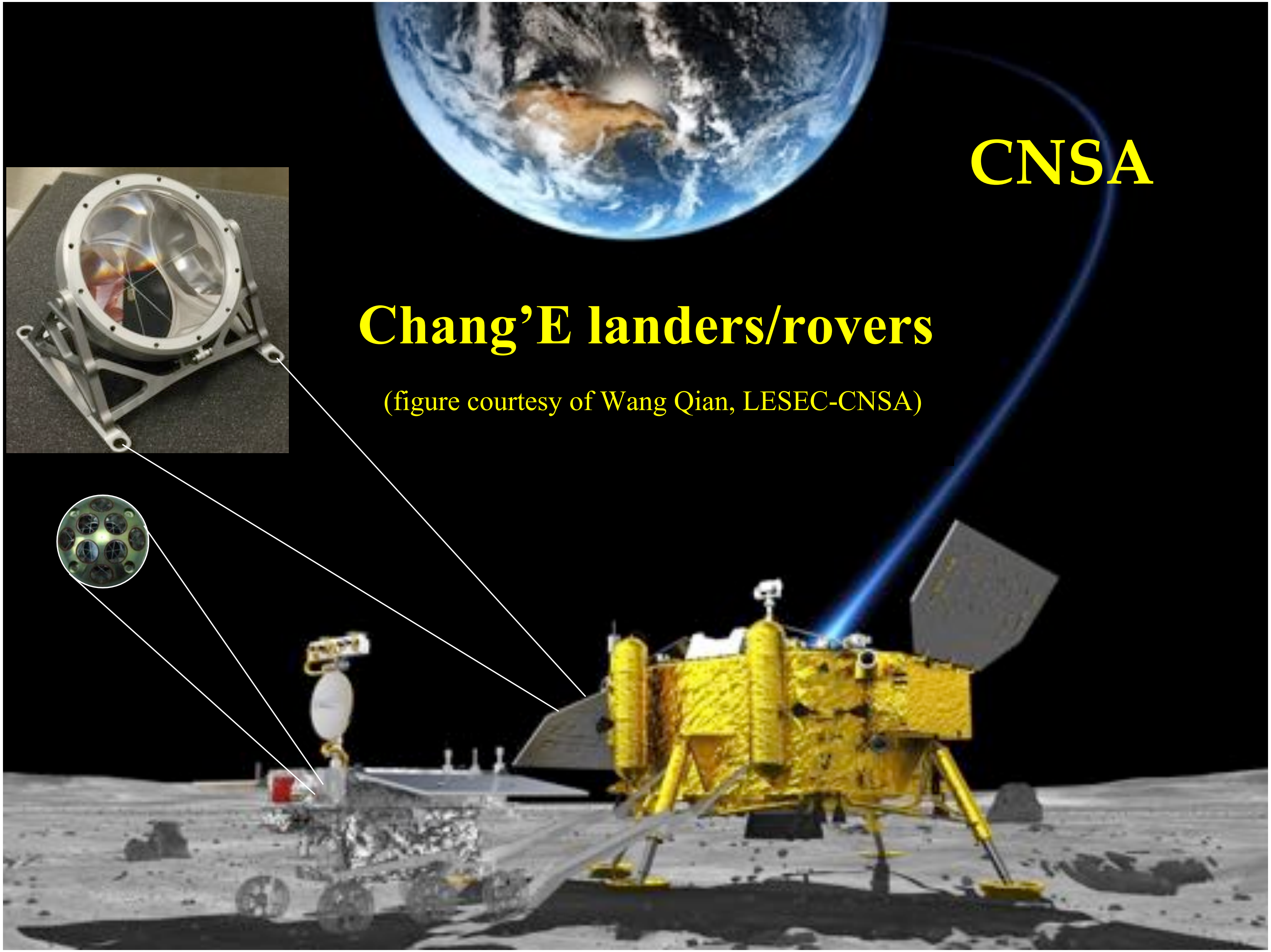
Mars test of General Relativity (*PEP preliminary*)

- Assume MGN of microreflectors (non-ideal, ~all north)
  - Phoenix (68N, 234E), Viking1 (22N, 50W), Viking 2 (48N, 258W)
  - Curiosity (4S, 137E), Opportunity (2S, 354E)
- Assume data rate: 1 laser normal point (NP) every 7 Sols
  - Weather/ops limitations; visibility from orbiter like MRO is once/Sol
- Accuracy: 10 cm-10 m (Mars ephemeris ~100-50 m)
  - Earth-orbiter: radio ranging; or laser (à la LLCD) or laser transponder experiments (MLA/MOLA). Orbiter-surface: laser ranging/altimetry

Time span/NP Accuracy	Accuracy on β-1	Accuracy on γ-1	Accuracy on $\dot{G}/G$
10 years / 10 m	1.7 x E-04	7.2 x E-04	3.8 x E-14
10 years / 1 m	3.7 x E-05	1.6 x E-05	1.4 x E-14
10 years / 10 cm	7.4 x E-07	3.2 x E-06	2.9 x E-15
Best accuracy now Data/mission *Analysis group*	**<1 x E-04** Lunar/Merc. Ranging *JPL, CfA-INFN, …*	**2.3 x E-05** Cassini *Bertotti et al*	**9 x E-13** Lunar Laser Ranging *JPL, CfA-INFN, …*

Collaboration on precision lander/rover positioning & test of General Relativity

- China-Italy collaboration
- INFN-Frascati & ASI-Matera, collaboration with:
- Planetary Dynamics and Radio Science research group - National Astronomical Observatories (**NAOC-CAS**)
  - PI: Prof. Jinsong Ping (jsping@nao.cas.cn), Beijing
- Planetary Mapping and Remote Sensing Lab - State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing and Digital Earth (**RADI-CAS**)
  - PI: Prof.Kaichang Di (dikc@radi.ac.cn), Beijing
- Test GR with Lunar Laser Ranging (and Laser Altimetry) & Lunar Radio Ranging to laser retroreflectors and radio transponders on Chang'E landers (& rovers). Re-do also Shapiro time delay !
- Gravity tests in the Sun-Earth-Moon system (& Mars)
- Also collaboration on PEP sw upgrade: improved modeling of the interior structure of the Moon


CNSA
Chang'E landers/rovers
(figure courtesy of Wang Qian, LESEC-CNSA)

Conclusions & prospects

- Three major missions landing/roving Mars soon
- Passive, laser retroreflector-based

  Lunar / Mars Geo-Physics Networks (LGN / MGN)
  - MoonLIGHT reflector
    - ~ 1.2 kg/15 cm (fixed pointing)
  - Microreflector
    - 25 gram, ~ 5 cm x 2 cm size
- Geo-reference exploration (landing accuracy, roving)
- Accurate test of General Relativity and its extensions
- Selenodesy, Mars geodesy