The Moon and Mars as Laser-ranged Test Bodies for General Relativity

Dell'Agnello Simone, Ciocci E, Contessa S, Delle Monache G, Intaglietta N, Maiello M, Martini M, Mondaini C, Porcelli L, Salvatori L, Tibuzzi M, Vittori R – **INFN-LNF**
Bianco G – **ASI-CGS**, Currie D – **Univ. of Maryland**, Chandler J – **CfA**

ILRS 2016

Potsdam, Germany, Oct. 13, 2016

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

Outline

- INFN-ASI “Joint Laboratory” on laser reflectors/ranging
- INFN *Affiliation* partnership to NASA-SSERVI
  - Solar System Exploration Research Virtual Institute
- Moon & Mars Science Assets to test General Relativity
- Lunar mission opportunities
- Mars mission opportunities
- Outlook

NASA-SSERVI
International Partnerships

Eight international partnerships collaborate with U.S. based SSERVI researchers on a no-exchange-of-funds basis.

Canada
PI: Gordon Osinski,
U. of Western Ontario

Germany
PI: Ralf Jaumann
DLR

Israel
PI: Shlomi Arnon
Ben-Gurion U. at the Negev

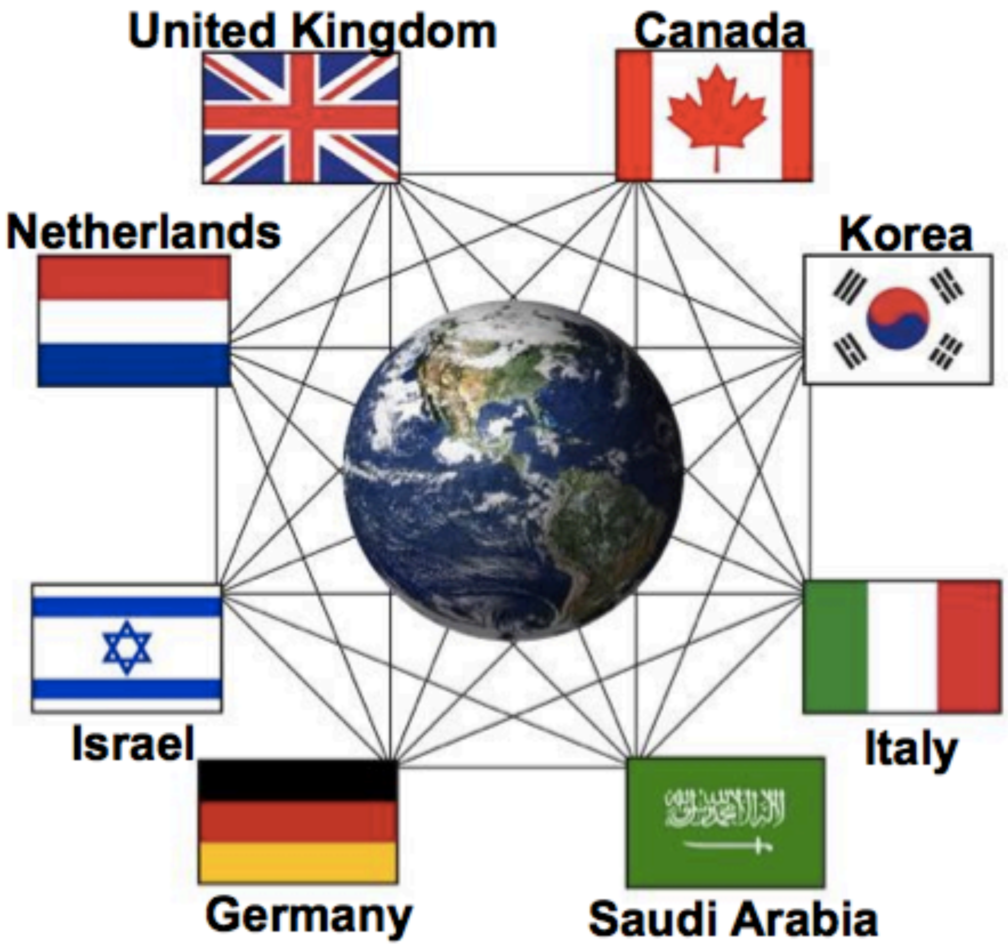
Italy
PI: Simone Dell'Agnello
INFN

Kingdom of Saudi Arabia
PI: Abdulaziz Alothman
King Abdulaziz City for Sci & Tech (KACST)

Korea
PI: Gwangyeok Ju
Korean Aerospace Research Institute (KARI)

Netherlands
PI: Wim van Westrenen
VU U. Amsterdam

United Kingdom
PI: Mahesh Anand,
Open U.



****Additional Partnerships under development include Australia and France***

INFN Affiliation to NASA-SSERVI

Signed in Rome on Sep. 15, 2014
INFN proposal to NASA:
laser retroreflectors for the whole solar system

See also the NASA webpages:

http://sservi.nasa.gov
http://sservi.nasa.gov/internationals/

http://sservi.nasa.gov/articles/nasa-and-infn-sign-affiliate-member-statement/

http://sservi.nasa.gov/articles/infn-laser-retro-reflector-development/

http://sservi.nasa.gov/articles/moon-express-announces-multi-mission-payload-agreement-with-infn-and-university-of-maryland/

INFN Affiliation to NASA-SSERVI

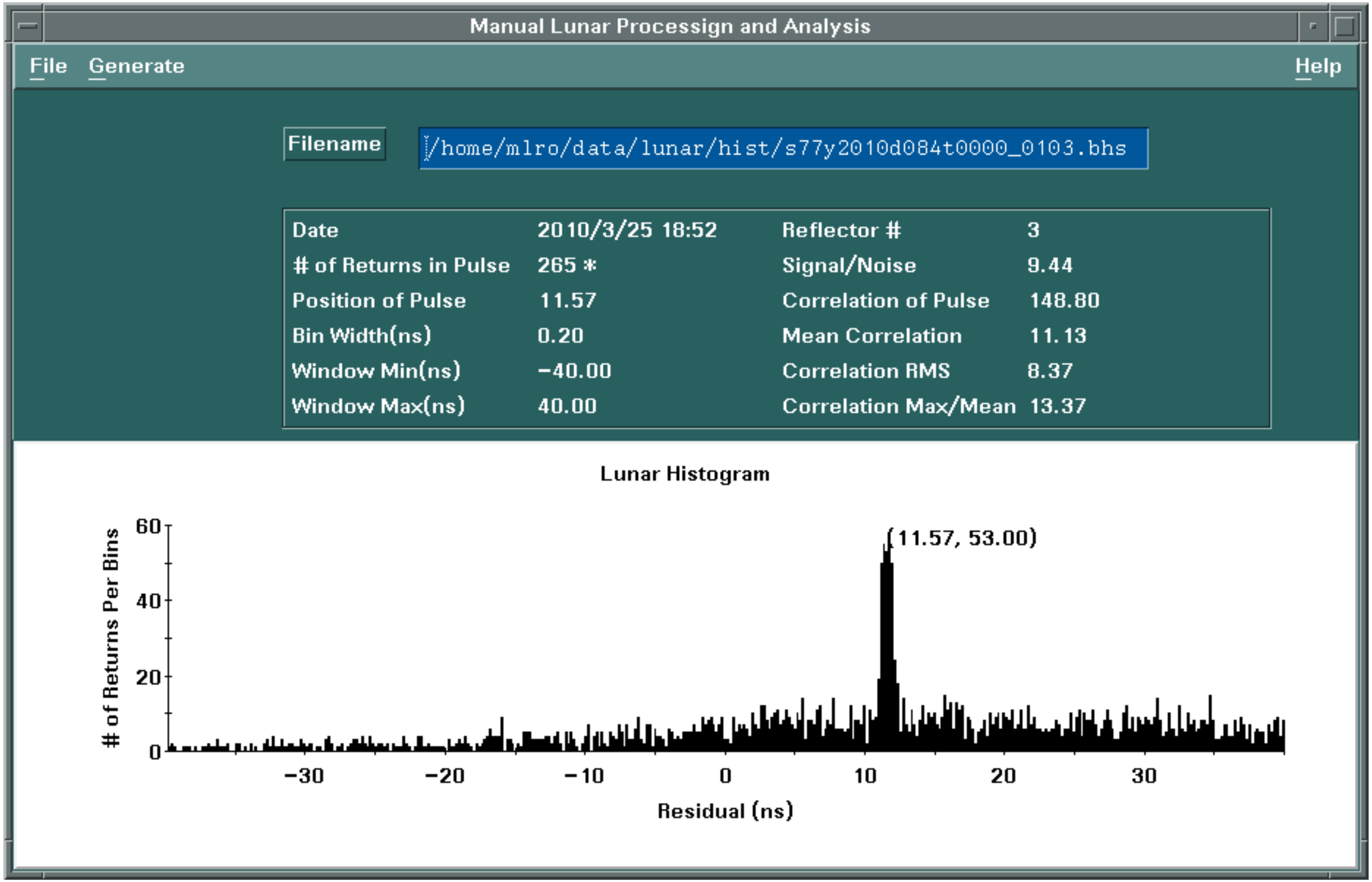
Signed in Rome on Sep. 15, 2014

INFN proposal to NASA: laser retroreflectors for the whole solar system

Right: SSERVI news, visit by C. Elachi (JPL) & E. Flamini (ASI Chief Scientist)


Slide courtesy of G. Bianco
MLRO
Matera Laser Ranging
Observatory
1.5 m telescope
@ASI - CGS

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



Solar system science assets

- MoonLIGHT, the *big* Lunar laser retroreflector
  - Moon Laser Instrumentation for General relativity High accuracy Tests, next-generation lunar (see D. Currie's talk)
- INRRI, the Solar System *micro*reflector
  - Instrument for landing-Roving laser Retroreflector Investigations
- PEP, the Planetary Ephemeris Program *orbital SW*
  - Lunar/Martian positioning data: with PEP, developed in USA at the Harvard-Smithsonian Center for Astrophysics (CfA), by Shapiro, Reasenberg, Chandler since 1960/70s

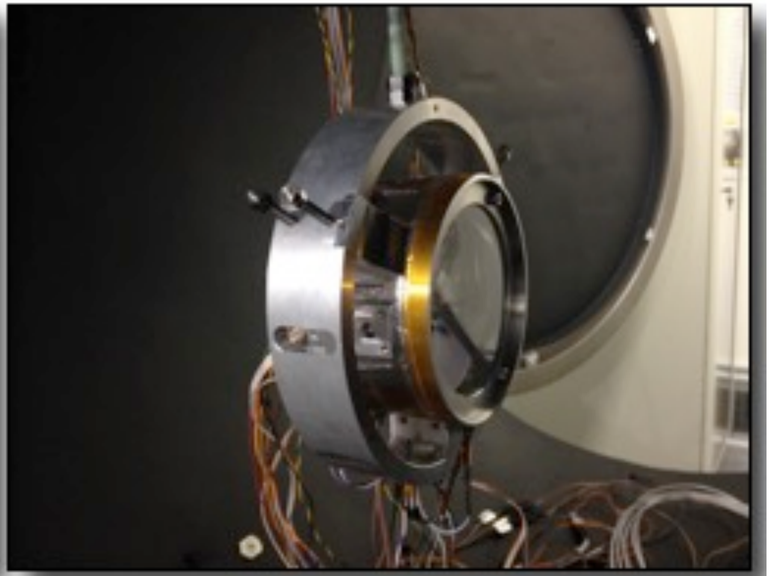
MoonLIGHT / LLRRA21:

Next Generation LLR Reflector (see D. Currie's talk)

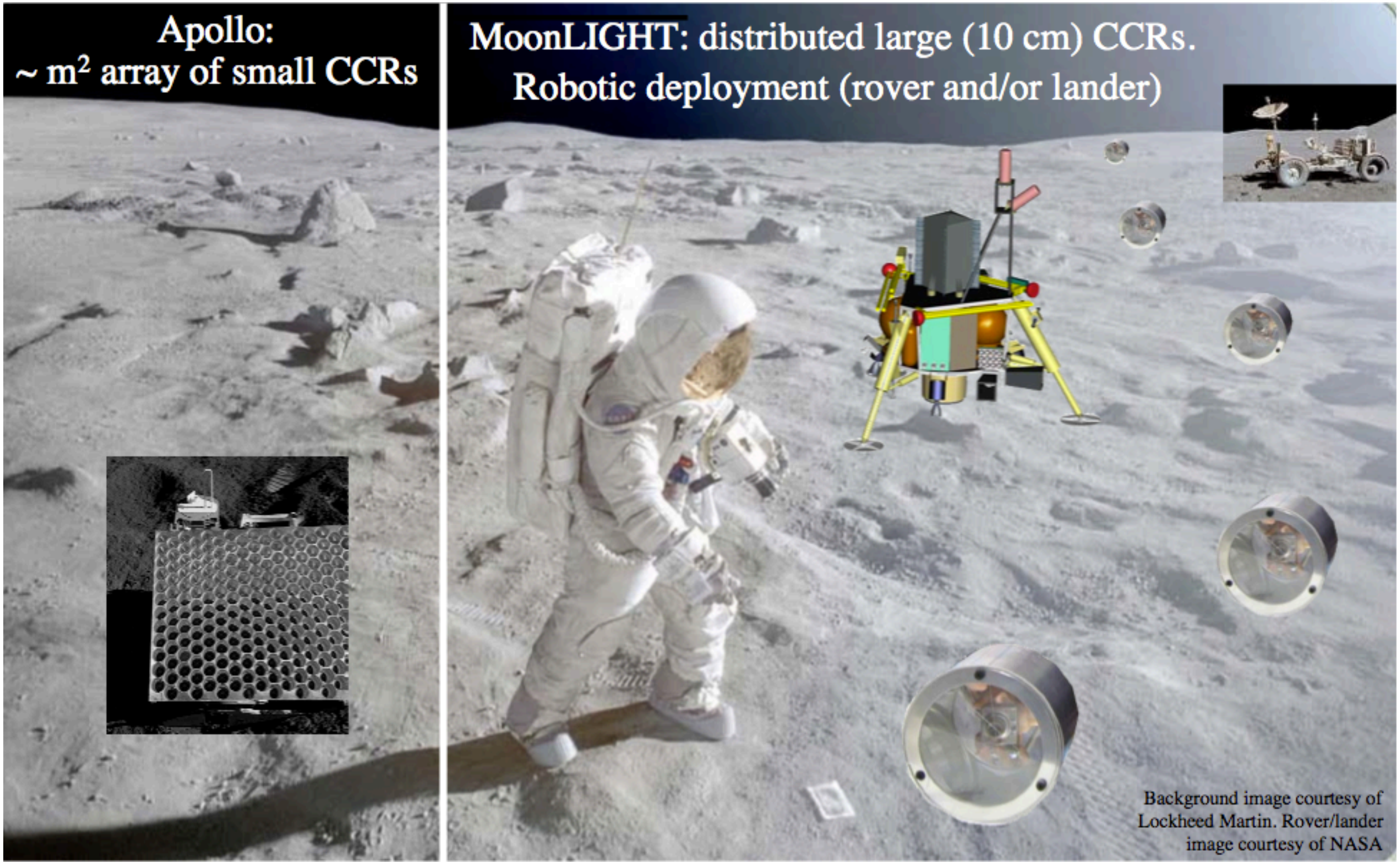
- Collaboration
  - INFN-Frascati, U. Maryland, INFN/Univ. Padua
  - Lunar stations: ASI-MLRO (Italy), APOLLO (US), OCR (Fr.)

MoonLIGHT (100 mm) **GNSS (33 mm)**

MoonLIGHT package



MoonLIGHT (next-generation reflector)



Lunar Laser Ranging test of General Relativity

- Improvements of the space segment up to ×100 with MoonLIGHTs on near side in addition to 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 et al Plan. & Space Sci. 74 (2012) 276–282; M. Martini PhD thesis 2016

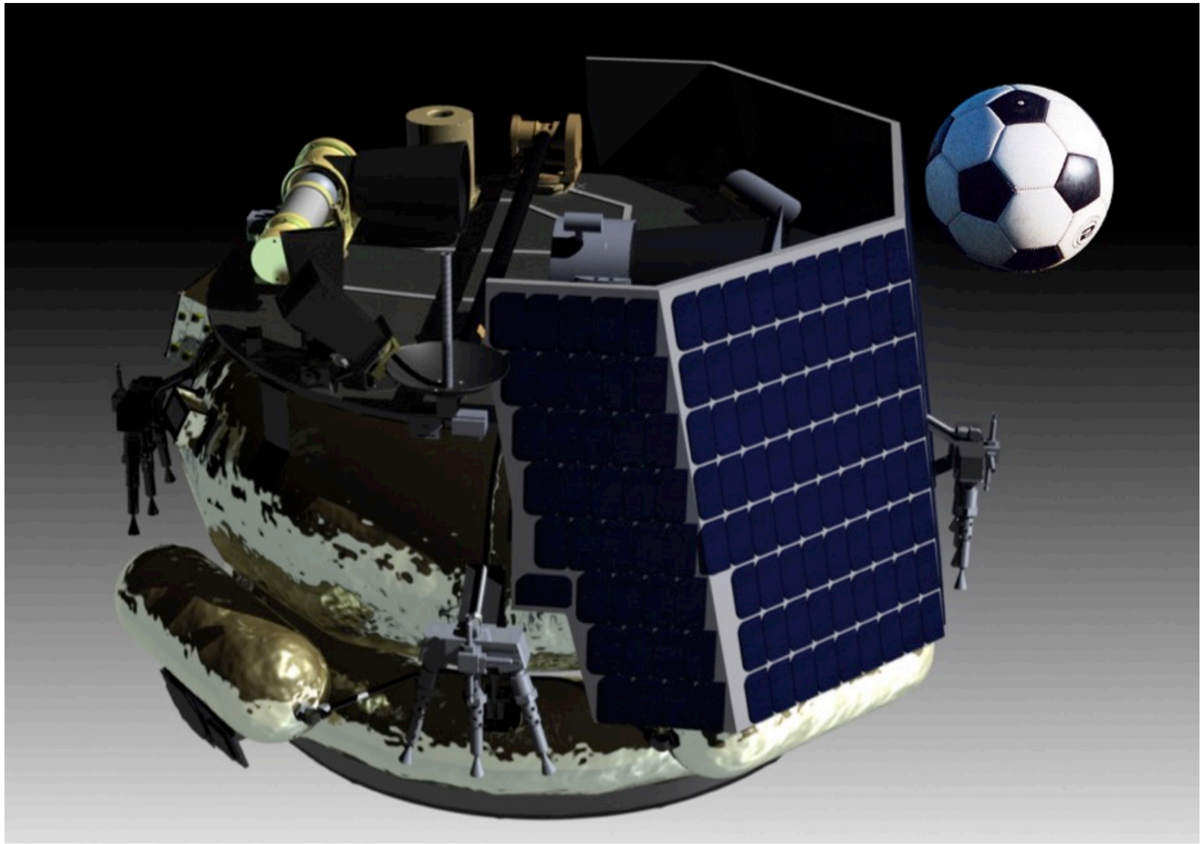
MoonLIGHT + INRRI on the Moon

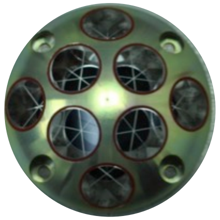
Commercial mission: Moon Express 1 (US, end 2017- start 2018)

MEX-INFN-UMD agreement: on 15/5/15 in Frascati

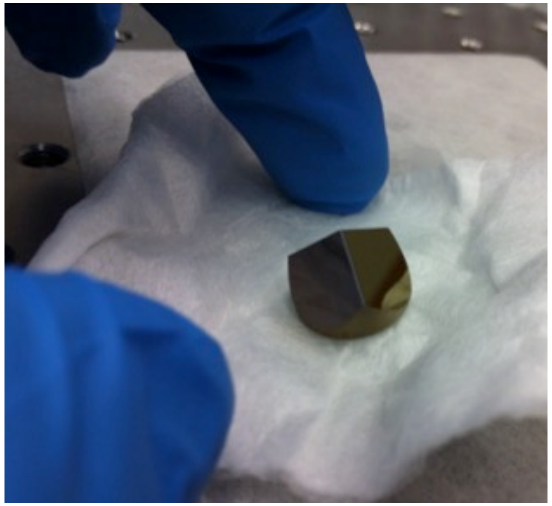
Competing also for Google Lunar X Prize

Note: the INRRI microreflector is an INFN-only payload

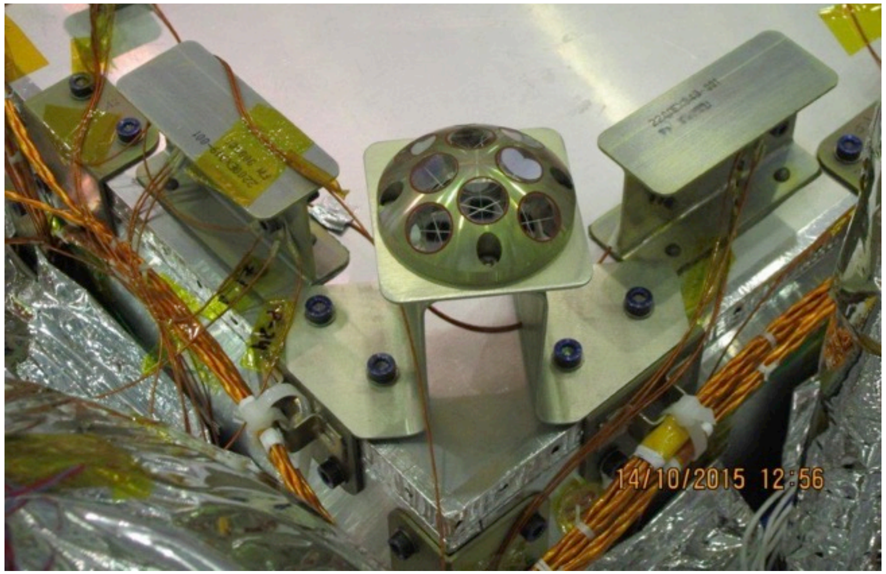




INRRI qualification/integration for ExoMars



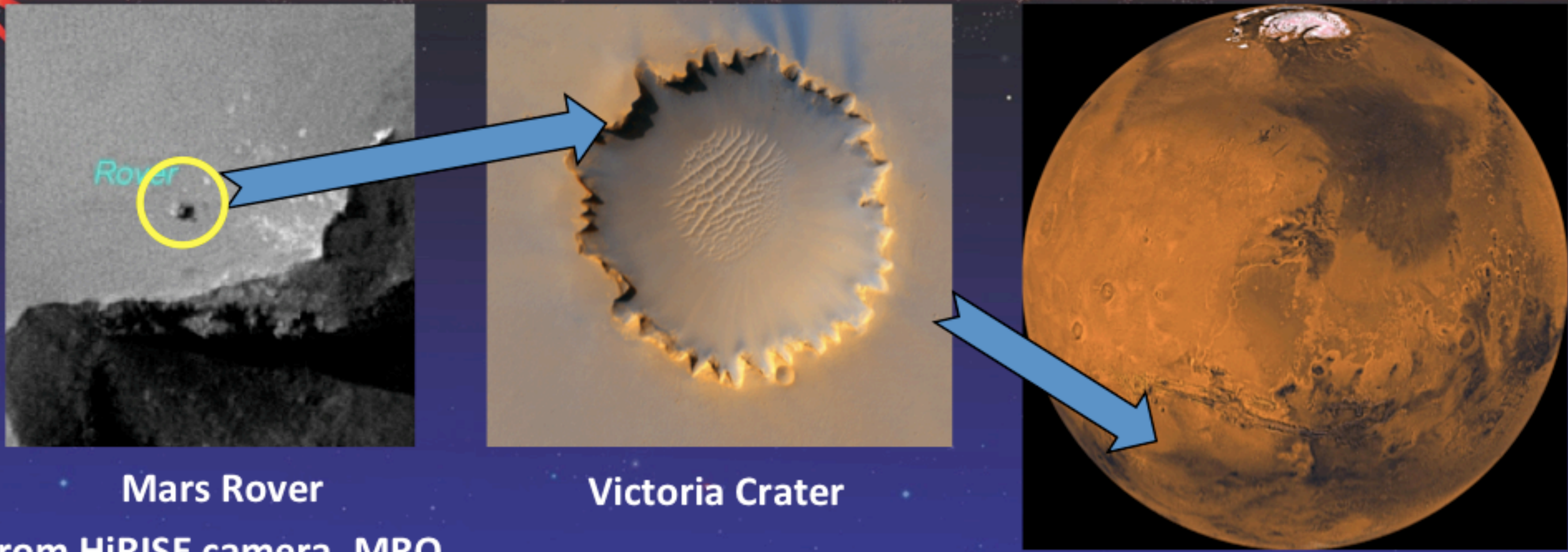
- Eight ½ inch microreflectors
- Reflector load/peel test
- TVT (158-328 K)
- Vibe/shock (Proton rocket)
- Repeat load/peel test
- Mass loss check (none)
- *INRRI: 25 gr < ½ Pyramid weight = 60 gr*



Laser microreflectors for *whole* solar system

- Positioning and/or geodetic targets (ground "truth" georeferencing). Observed locally, by laser orbiters
  - Laser altimetry (NASA LRO, ESA AIM); dedicated laser ranging
  - Lasercom (like NASA's LADEE mission, Mars 2022 orbiter)
    - Lasercom: slides by D. Cornwell, Head NASA Optical Division
    - 2022 orbiter: Slides by E. Stofan, Chief Scientist of NASA-HQ
- Supports mm-positioning w/single shot to single reflector
  - Supports VIS to NIR (~2000 nm)
- Laser-tracking supports retrieval, redirection, deflection …
- Laser-guide directed forms of energy and interceptors

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



Mars Rover

From HiRISE camera, MRO
Approx 30 cm resolution

Victoria Crater

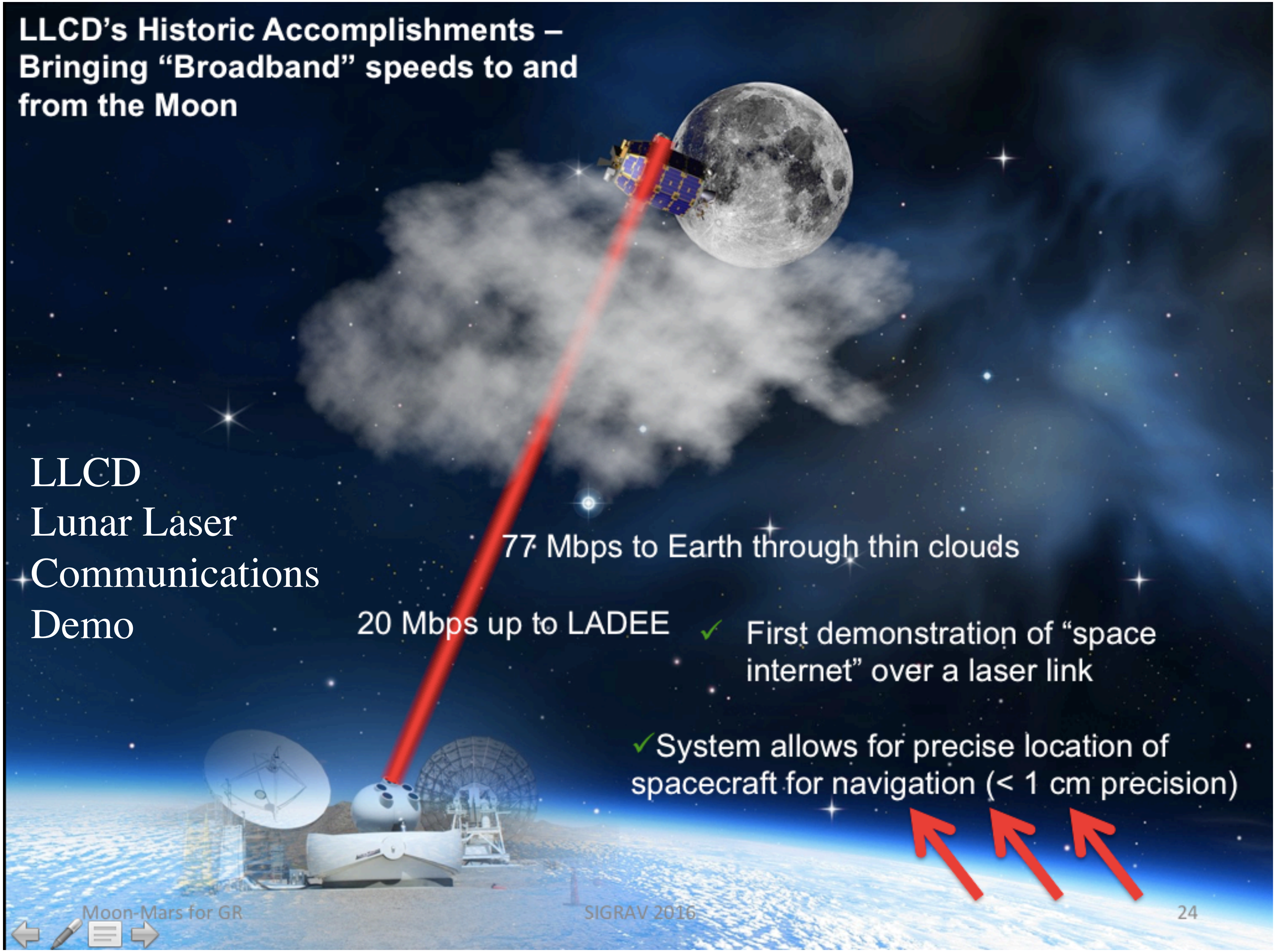
Mars

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

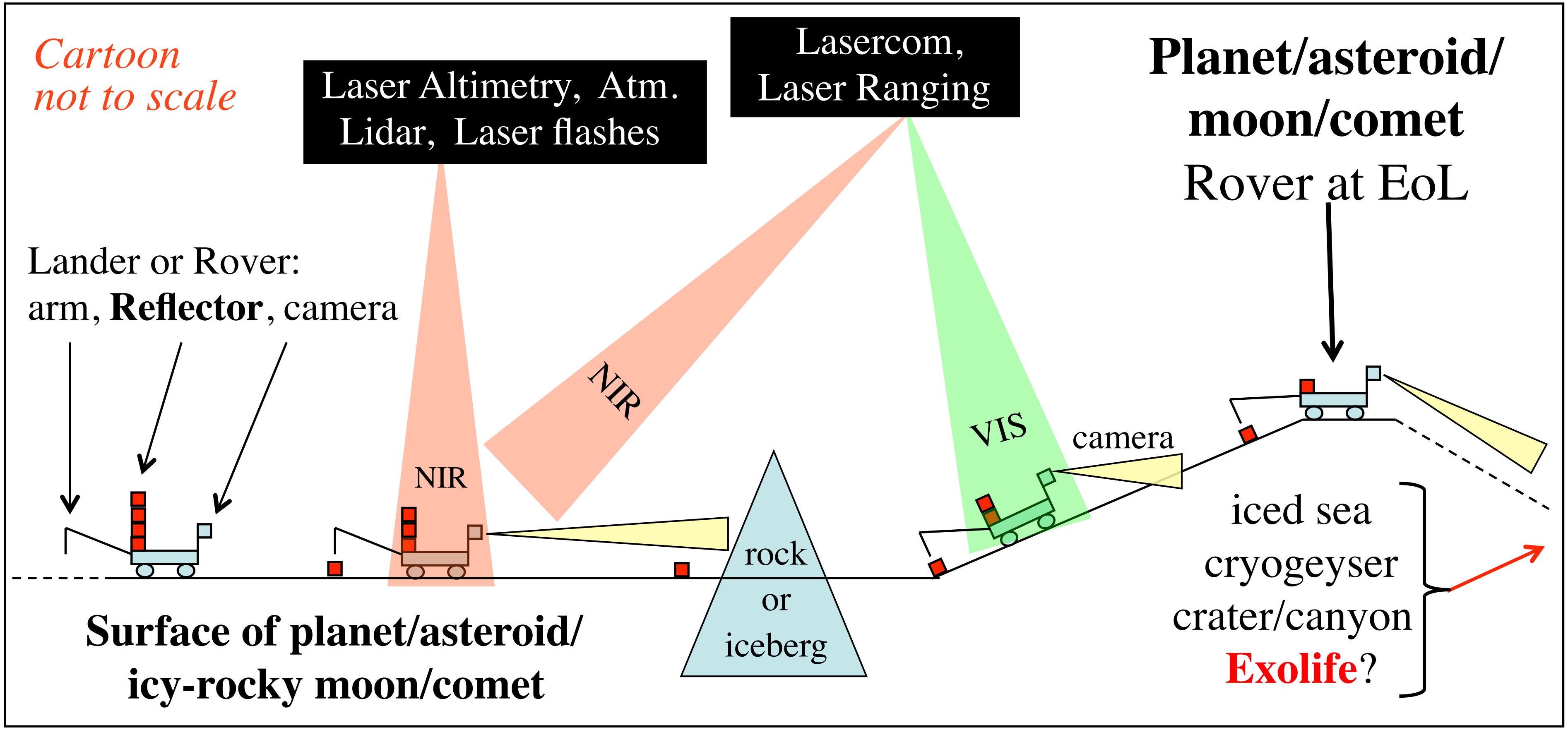
- at 1 bit / pixel:
- 6 Mbps requires 9 years (best Ka-band)
- 250 Mbps requires 9 weeks (JPL's DOT)

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

Chart courtesy of Don Boroson, MIT Lincoln Laboratory


LLCD's Historic Accomplishments – Bringing "Broadband" speeds to and from the Moon
LLCD
Lunar Laser
Communications
Demo
77 Mbps to Earth through thin clouds
20 Mbps up to LADEE
✓ First demonstration of "space internet" over a laser link
✓System allows for precise location of spacecraft for navigation (< 1 cm precision)
Moon-Mars for GR
SIGRAV 2016
24

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

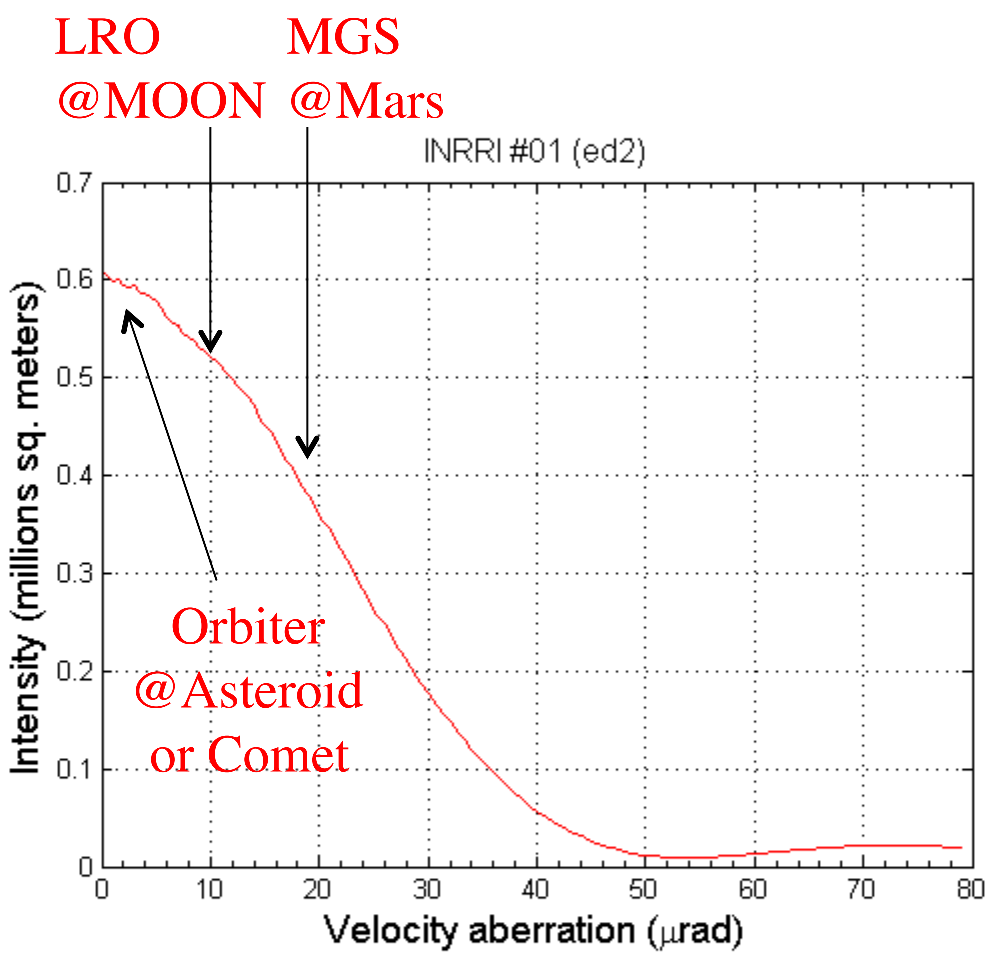


Laser-locate Rover/Lander w/reflector from orbiters. Moon far side

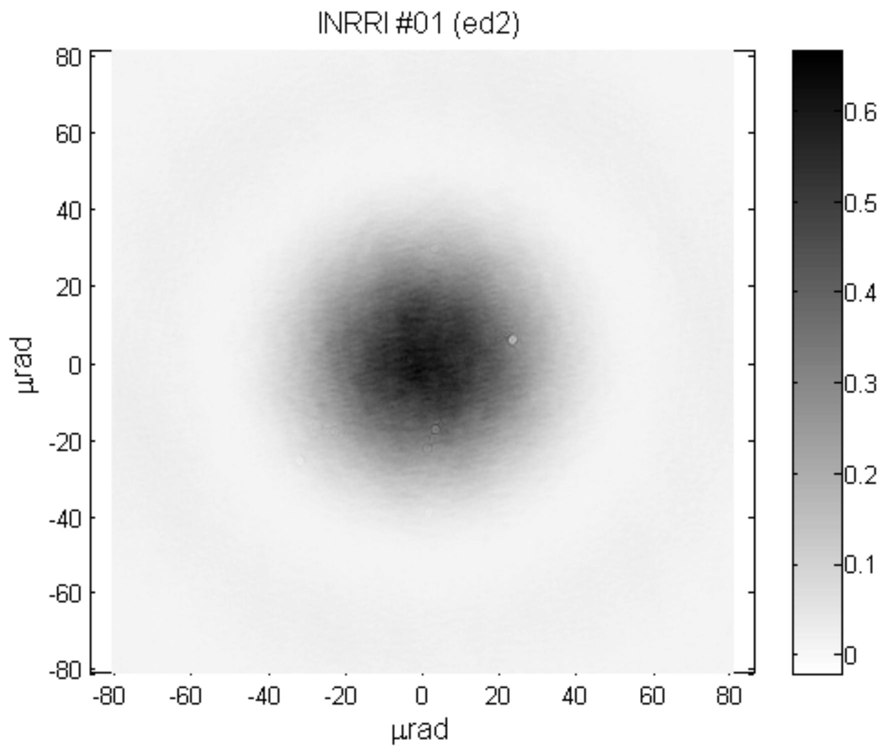
Global and local reflector networks to serve Exploration, Planetary Science, Geodesy and test Fundamental Gravity

INRRI laser location by orbiters

Measured laser return, or *lidar optical cross section* (msqm, μrad) units at 532 nm. Adequate to observe INRRI

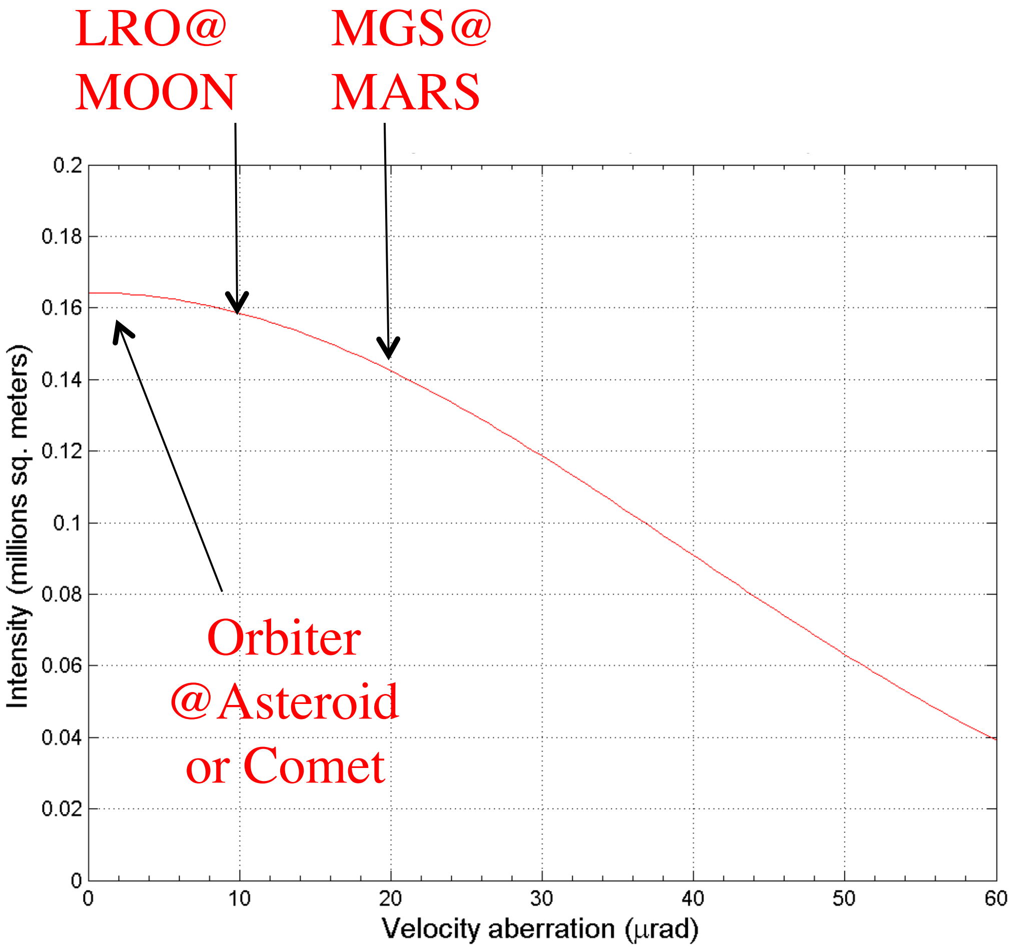


INRRI coated reflector (Airy) far field diffraction pattern

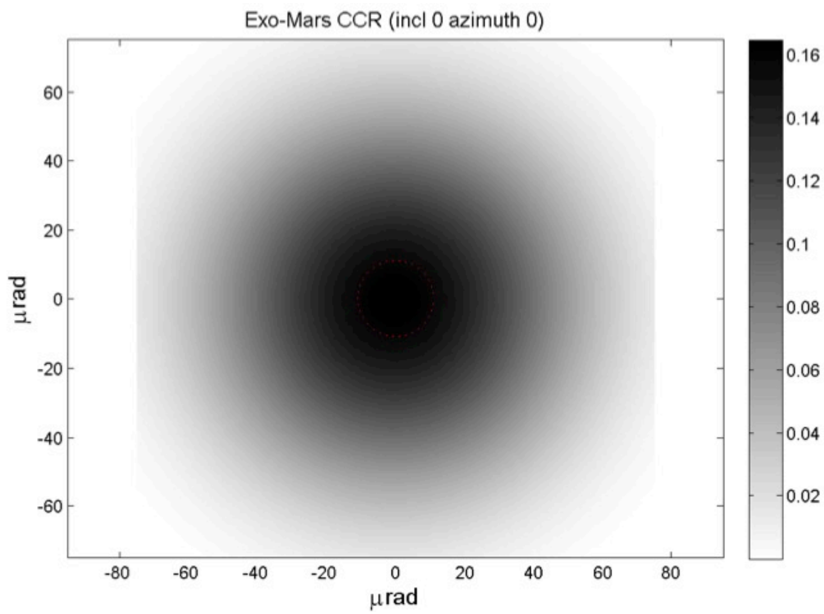


INRRI laser location by orbiters

Simulated laser return (CodeV), or *lidar optical cross section*, (msqm, μrad) nits at 1064 nm (LOLA, MOLA). Airy peak even wider at 1550 nm (LLCD). Adequate to observe INRRI



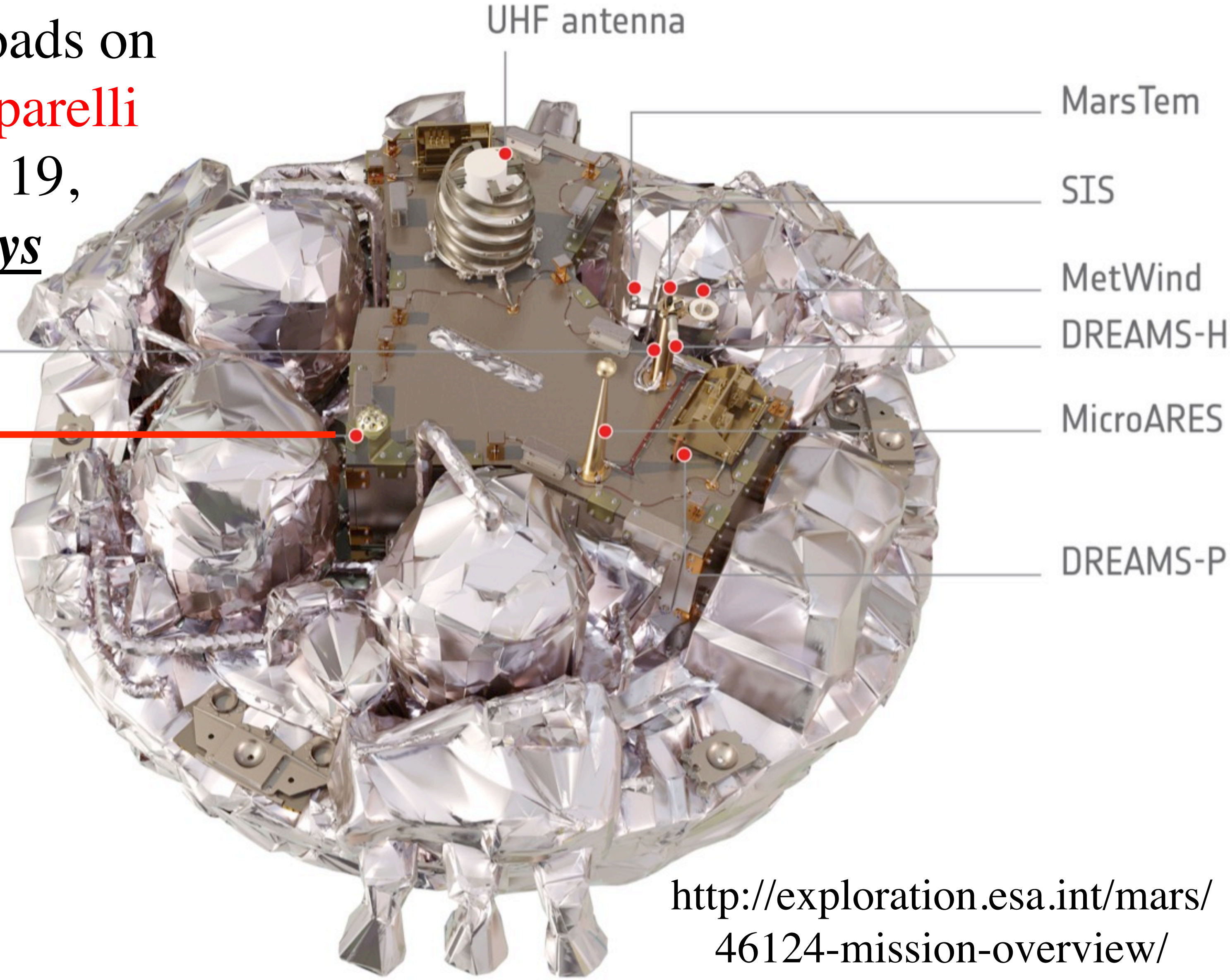
INRRI coated reflector (Airy) far field diffraction pattern



ExoMars 2016: 1st laser retroreflector on Mars

Science payloads on Lander Schiaparelli

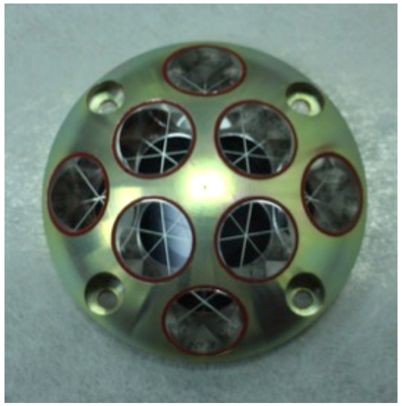
Landing: Oct 19, 2016, ***in 6 days***



INRRI

25 gr

~5cm×2cm



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

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

S. Dell'Agnello[a], G. Delle Monache[a], L. Porcelli[a,*], A. Boni[a], S. Contessa[a], E. Ciocci[a], M. Martini[a], M. Tibuzzi[a], N. Intaglietta[a], L. Salvatori[a], P. Tuscano[a], G. Patrizi[a], C. Mondaini[a], C. Lops[a], R. Vittori[b,a], M. Maiello[a], E. Flamini[c], E. Marchetti[c], G. Bianco[d,a], R. Mugnuolo[d], C. Cantone[a]

[a]*Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF), Via E. Fermi 40, 00044, Frascati, Rome, Italy.*
[b]*Aeronautica Militare Italiana (AMI), Viale dell'Università 4, 00185, Rome, Italy.*
[c]*Agenzia Spaziale Italiana - Headquarters (ASI-HQ), Via del Politecnico snc, 00133, Rome, Italy.*
[d]*Agenzia Spaziale Italiana - Centro di Geodesia Spaziale Giuseppe Colombo (ASI-CGS), Località Terlecchia, P.O. Box ADP, 75100, Matera, Italy.*

Accepted by Advances in Space Research

Abstract

During Summer 2015 the SCF_Lab[1] (Satellite/lunar/GNSS laser ranging/altimetry and cube/microsat Characterization Facilities Laboratory) Team of INFN-LNF, with support by ASI, carried out an intense activity of final design, manufacturing and testing in order to construct, space qualify and finally integrate INRRI-EDM/2016 on ESA's ExoMars EDM spacecraft (also dubbed 'Schiaparelli'), which was successfully launched on March 14, 2016. INRRI (INstrument for landing-Roving laser Retroreflector Investigation) for the EDM (Entry descent and landing Demonstration Module) 2016 mission is a compact, lightweight, passive, maintenance-free array of eight cube corner laser retroreflectors fixed to an aluminium alloy frame through the use of silicon rubber suitable for space applications. INRRI was installed on the top panel of the EDM Central Bay on October 14, 2015. It will enable the EDM to be laser-located from Mars orbiters, through laser ranging and altimetry, lidar atmospheric observations from orbit, laser flashes emitted by orbiters, and lasercom. One or all of the above means of observation can be supported by INRRI when there is an active, laser-equipped orbiter, es-

INRRI exploration/science goals on Mars

http://exploration.esa.int/mars/48898-edm-science-payload/

http://exploration.esa.int/mars/57466-retroreflector-for-exomars-schiaparelli/

- Accurate positioning of landing-roving
- Improved definition of Meridian 0 (*Mars Greenwich*) better than current Airy 0 crater (200 m accuracy)
- Test of General Relativity and its extensions
- Lidar-based/aided landing (return to lander/rover site)
- Atmospheric trace species detection by lidar on orbiter
- Atmospheric dust measurement by lidar on orbiter?
- Lasercomm test & diagnostics

Ultimately: Mars Geo/physical Network (MGN)

National Aeronautics and Space Administration

Headquarters
Washington, DC 20546-0001

July 14, 2016

SMD/Mars Exploration Program

MAJOR NEWS

Dr. Enrico Flamini
Chief Scientist
Agenzia Spaziale Italiana
Via del Politecnico snc
00133 Rome
Italy

Sincerely,

James G. Watzin
Director, Mars Exploration Program

Dear Dr. Flamini:

NASA is agreeable to hosting the Agenzia Spaziale Italiana (ASI) Laser Retroreflector Array (LRA) on the Mars 2020 rover, as we see the instrument to be of mutual benefit, holding the potential to improve the accuracy of geospatial maps that the scientific community has been building for the last several decades. We are also exploring the possibility of including an ASI LRA on NASA's Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission.

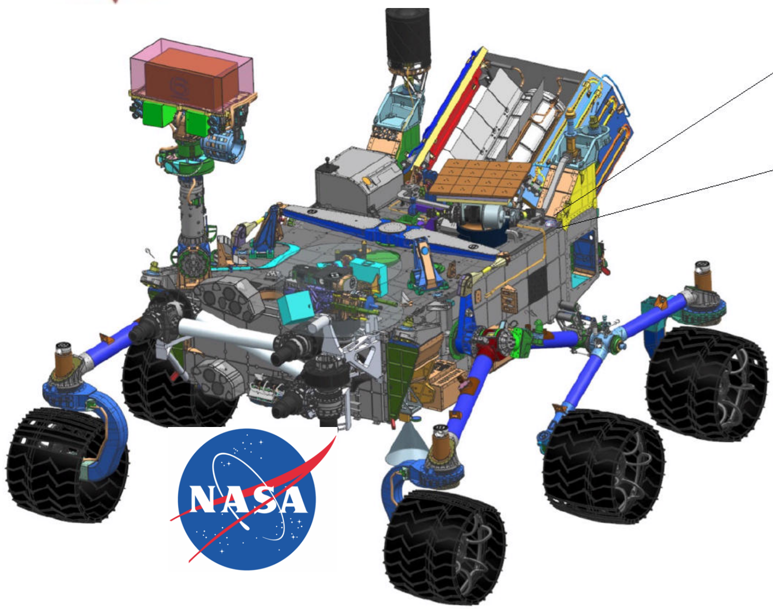
Mars Geo/physical Network (MGN) of INRRIs

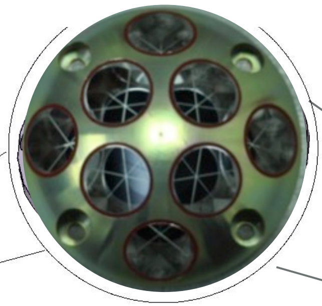
ExM 2016 Schiaparelli ≡ 1st MGN node ≡ Mars *Greenwich*

NASA/ASI: Mars 2020, Insight 2018?

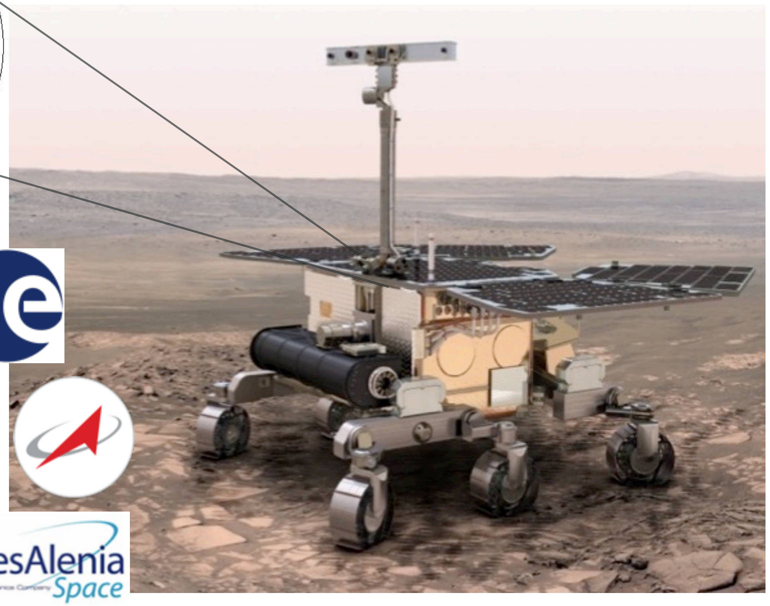
ESA/ASI: ExoMars 2016, ExoMars 2020

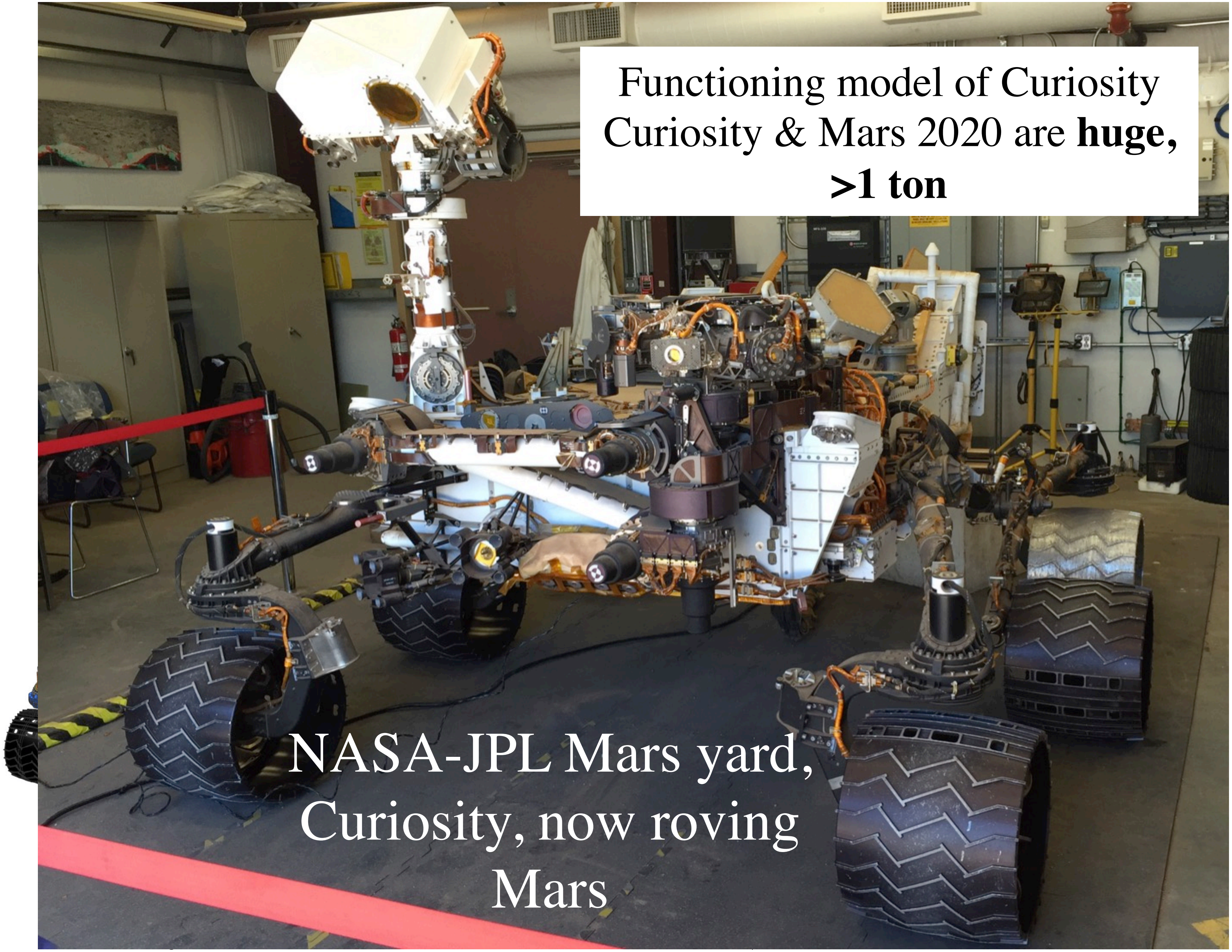
Mars 2020 (NASA)



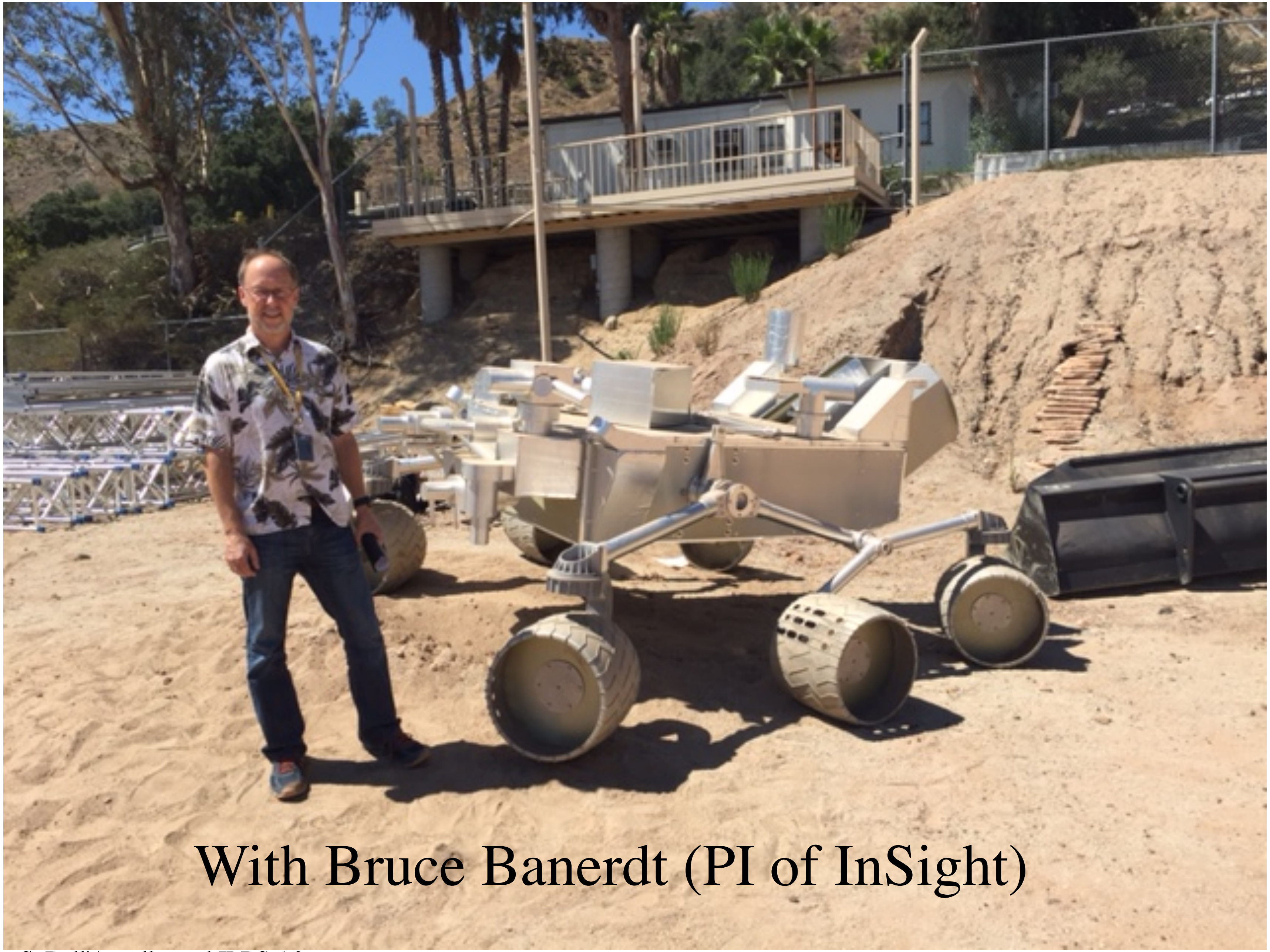


ExoMars 2020

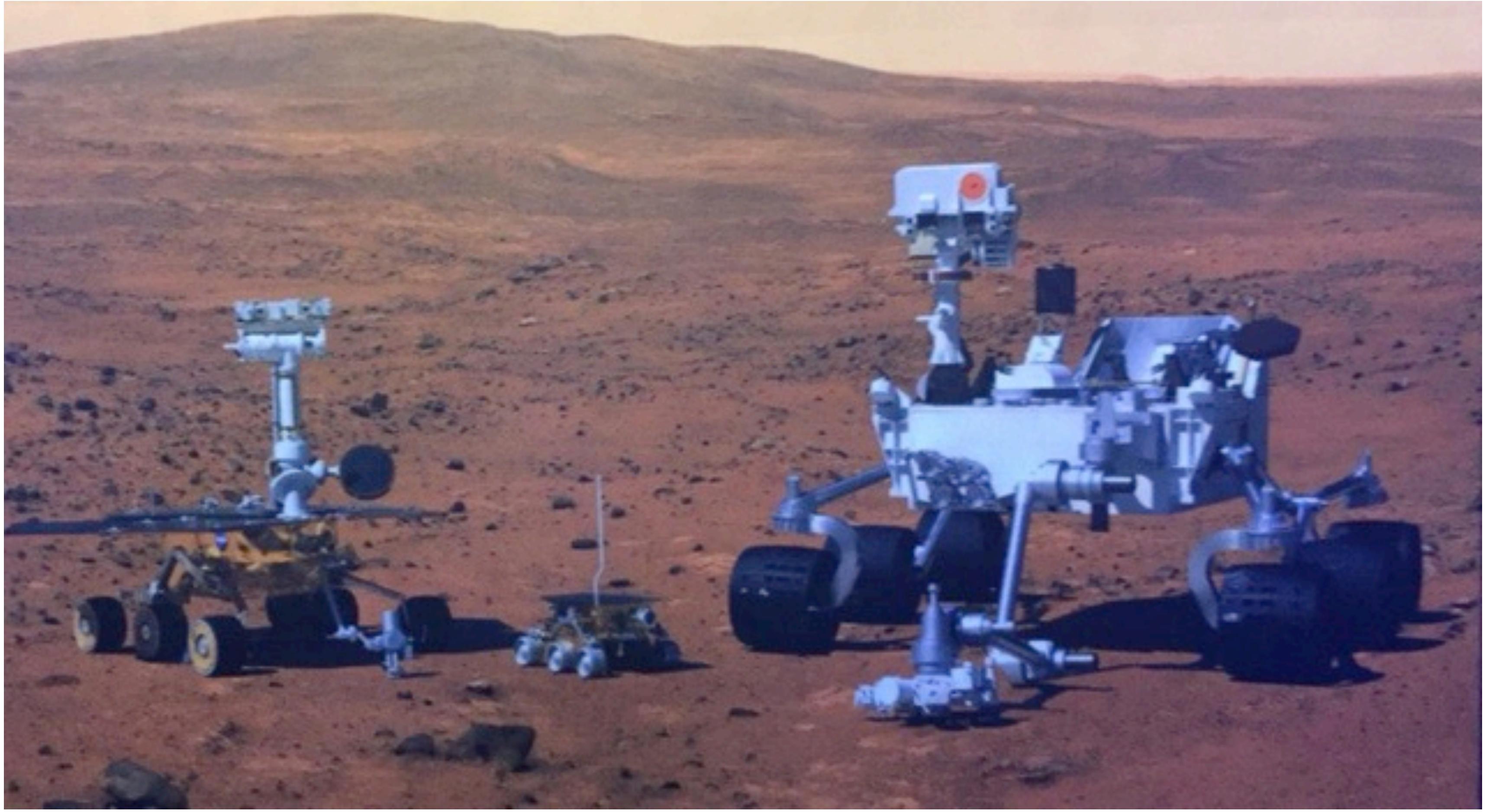



Functioning model of Curiosity
Curiosity & Mars 2020 are **huge, >1 ton**
NASA-JPL Mars yard, Curiosity, now roving Mars

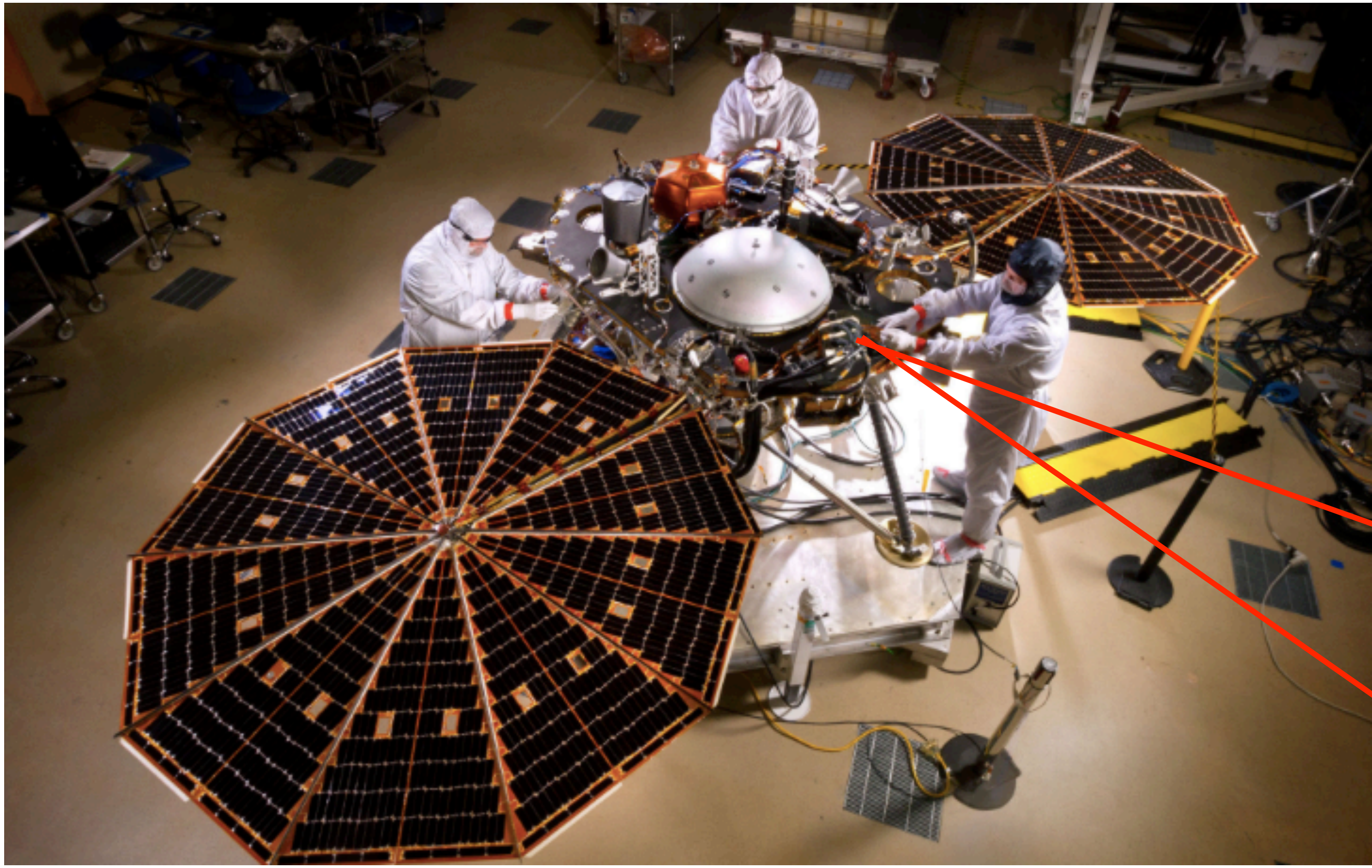
NASA-JPL Mars yard, Curiosity mockup



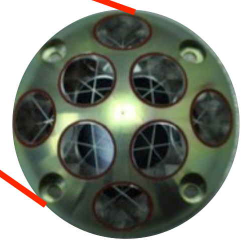
Spirit/Opportunity (left), **Sojourner** (cnt), **Curiosity** (right)
Three generation of Mars Rovers



NASA’s InSight Lander (May 2018 launch)



Dr. W. Bruce Banerdt
Principal Investigator



“InSight's investigation of the Red Planet's interior is designed to increase understanding of how all rocky planets, including Earth, formed and evolved,” said Bruce Banerdt, InSight Principal Investigator at NASA’s Jet Propulsion Laboratory (JPL), Pasadena,

Meeting with NASA's InSight Lander PI

If equipped w/INRRI, **InSight** (Interior exploration using Seismic Investigations, Geodesy and Heat Transport) will become the 2nd *node* of the Mars Geo/physical Network. Bruce is a promoter of both Lunar & Mars Geo/physical Networks

GR tests with Mars – PEP simulations

- MGN, Mars Geo/physics Network of INRRIs
- Test of non-ideal MGN (~all north, weather/accuracy limitations)

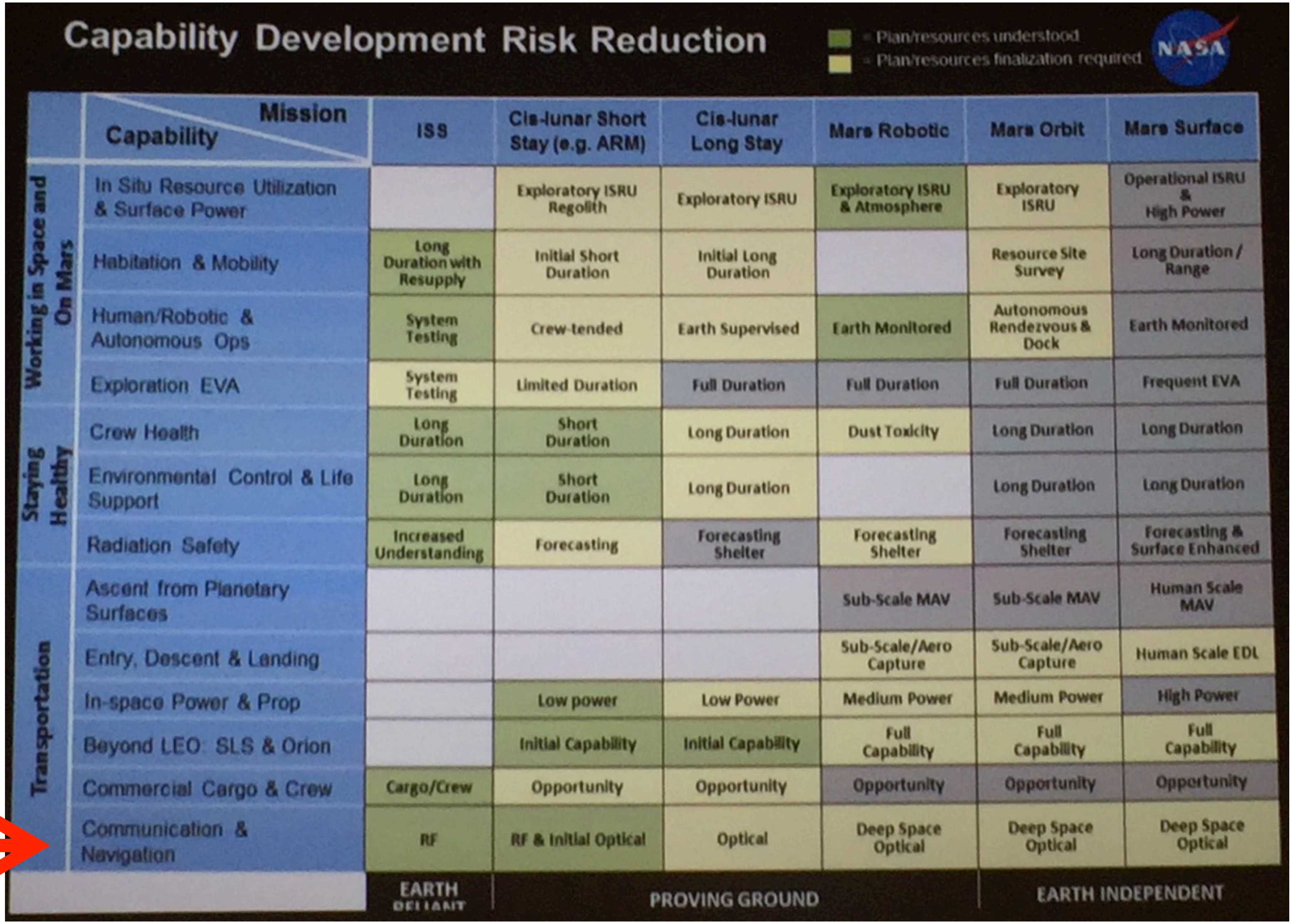
  Phoenix Lander (68N, 234E), Curiosity Rover (4S, 137E), Opportunity Rover (2S, 354E), Viking1 lander (22N, 50W), Viking 2 Lander (48N, 258W)
- Data: 1 laser normal point (NP) every 7 Sols for 10 years
  - Or >1 NP every 7 Sols for < 10 years
- Preliminary, but based on consolidated lunar PEP analysis
- Accuracy: 10cm–10m (current ephemeris ~50m)

INRRI: Time/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 *Analysis group*	**1 x E-04** Lunar Laser Ranging *JPL, Harvard-INFN*	**2.3 x E-05** Cassini *Bertotti et al*	**9 x E-13** Lunar Laser Ranging *JPL, Harvard-INFN*

Lasercom/altimetry (2022), Journey to Mars (2030)

Talk by Ellen Stofan @ASI-HQ, Rome, June 2016

From ASI: lasercom and laser altimeter on the orbiter



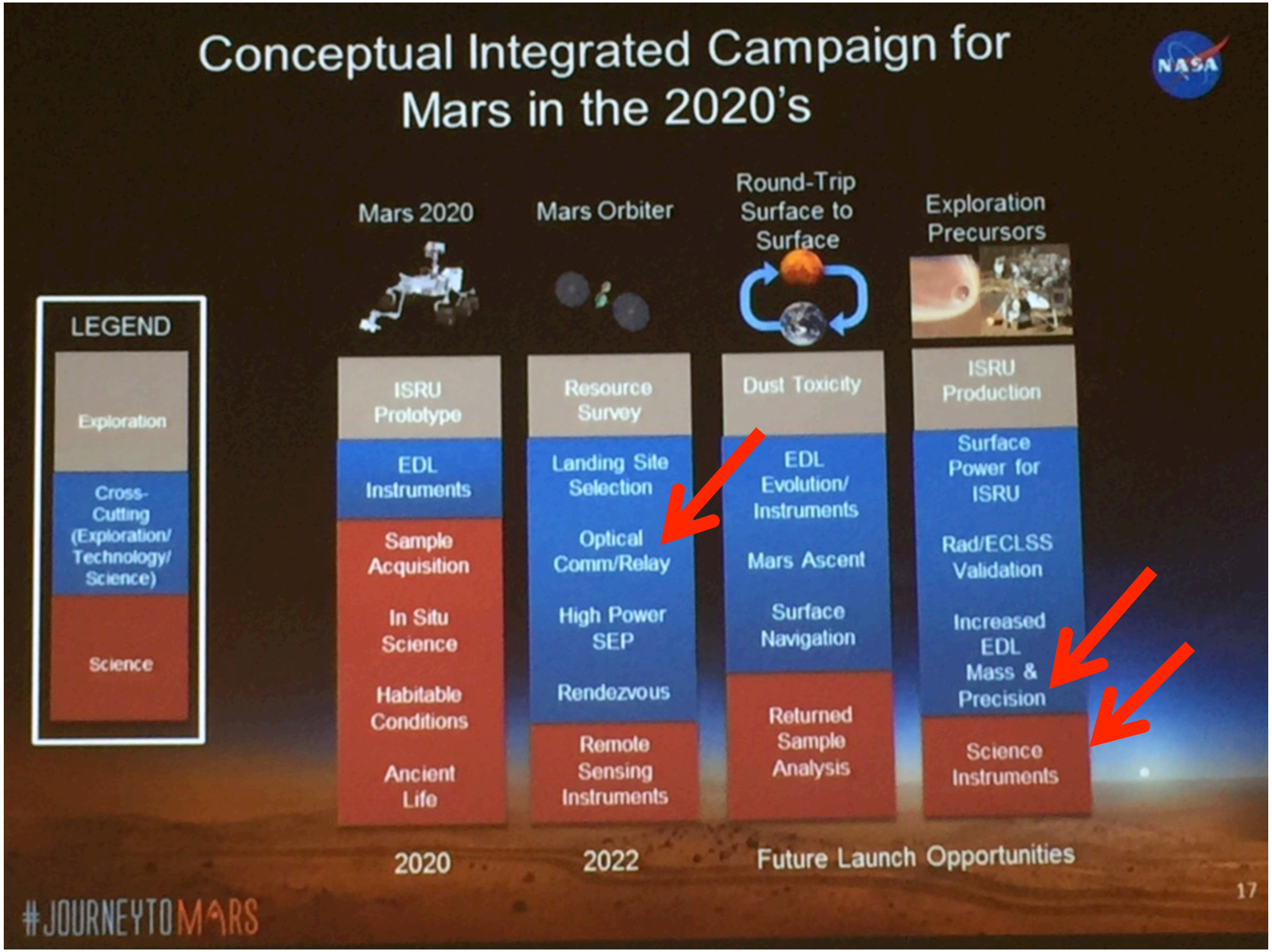
Capability Development Risk Reduction

- Plan/resources understood
- Plan/resources finalization required

	Capability / Mission	ISS	Cis-lunar Short Stay (e.g. ARM)	Cis-lunar Long Stay	Mars Robotic	Mars Orbit	Mars Surface
Working in Space and On Mars	In Situ Resource Utilization & Surface Power		Exploratory ISRU Regolith	Exploratory ISRU	Exploratory ISRU & Atmosphere	Exploratory ISRU	Operational ISRU & High Power
	Habitation & Mobility	Long Duration with Resupply	Initial Short Duration	Initial Long Duration		Resource Site Survey	Long Duration / Range
	Human/Robotic & Autonomous Ops	System Testing	Crew-tended	Earth Supervised	Earth Monitored	Autonomous Rendezvous & Dock	Earth Monitored
	Exploration EVA	System Testing	Limited Duration	Full Duration	Full Duration	Full Duration	Frequent EVA
Staying Healthy	Crew Health	Long Duration	Short Duration	Long Duration	Dust Toxicity	Long Duration	Long Duration
	Environmental Control & Life Support	Long Duration	Short Duration	Long Duration		Long Duration	Long Duration
	Radiation Safety	Increased Understanding	Forecasting	Forecasting Shelter	Forecasting Shelter	Forecasting Shelter	Forecasting & Surface Enhanced
Transportation	Ascent from Planetary Surfaces				Sub-Scale MAV	Sub-Scale MAV	Human Scale MAV
	Entry, Descent & Landing				Sub-Scale/Aero Capture	Sub-Scale/Aero Capture	Human Scale EDL
	In-space Power & Prop		Low power	Low Power	Medium Power	Medium Power	High Power
	Beyond LEO: SLS & Orion		Initial Capability	Initial Capability	Full Capability	Full Capability	Full Capability
	Commercial Cargo & Crew	Cargo/Crew	Opportunity	Opportunity	Opportunity	Opportunity	Opportunity
	Communication & Navigation	RF	RF & Initial Optical	Optical	Deep Space Optical	Deep Space Optical	Deep Space Optical
		EARTH RELIANT	PROVING GROUND			EARTH INDEPENDENT	

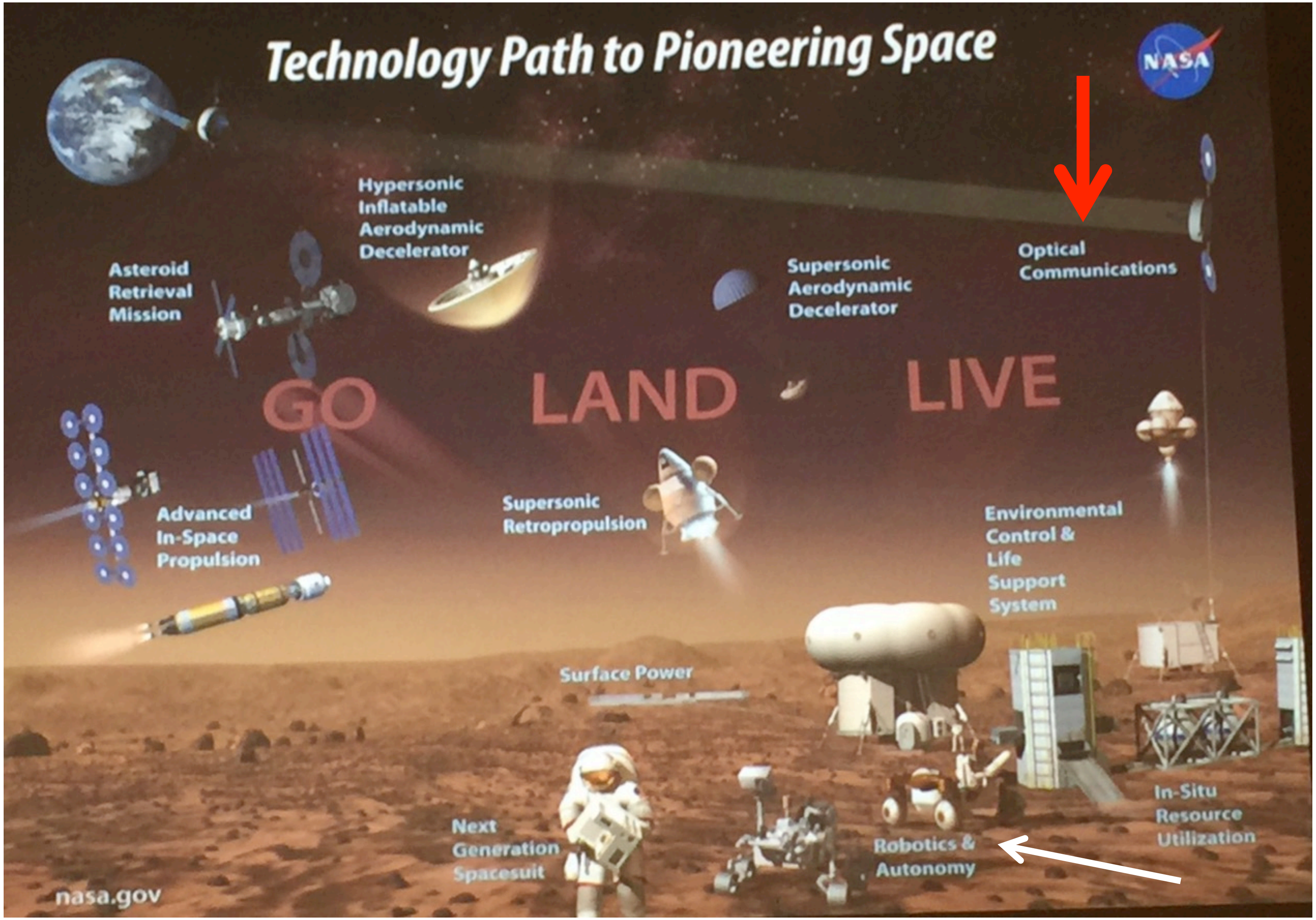
Lasercom/altimetry (2022), Journey to Mars (2030)

Talk by Ellen Stofan @ASI-HQ, Rome, June 2016



Lasercom/altimetry (2022), Journey to Mars (2030)

Talk by Ellen Stofan @ASI-HQ, Rome, June 2016



Outlook

- Quote by JFK in 1960's (my modest additions in *italics*):
  - "We (*ILRS, too*) are going (*landing/roving*) to the Moon (*& Mars*), not because it is easy ... (*but*) because it is hard
- New and strong wave of Mars/Moon landing/roving science, exploration, mining, ISRU, search for exolife ...
- All the above mean great opportunities to test GR and New Physics of gravity; and for Solar System Geodesy
  - GLXP: Moon Express ...
  - ESA: ExoMars Lander (Oct 19, 2016, **in 6 days**) & Rover (2020)
  - NASA: Mars 2020 Rover. InSight lander (2108)?
  - NASA's Journey to Mars, Optical communications and relay orbiter. With ASI collaboration
- *Future of ILRS? (Also) To the Moon, Mars & beyond*

MOON EXPRESS

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

UNIVERSITY OF MARYLAND 1856

MEDIA RELEASE

Daven Maharaj / 650-241-8577
media@moonexpress.com

FOR RELEASE: May 15th, 2015 @ 2:00PM GMT

Moon Express Announces First International Multi-Mission Payload Agreement with The INFN National Laboratories of Frascati and the University of Maryland

"MoonLIGHT" Lunar Laser Ranging Array Will Bring New Insights into General Relativity

Frascati, Italy (May 15th, 2015) – Moon Express, Inc. (MoonEx) has announced a multi-mission payload agreement with The National Laboratories of Frascati (INFN-LNF) and the University of Maryland to deliver a new generation of lunar laser ranging arrays to the Moon. Under the agreement, "MoonLIGHT" instruments will be carried on the first four Moon Express missions and used in conjunction with Apollo Cube Corner (CCR) Retroreflector arrays to test principles of Einstein's General Relativity theory, add to international scientific knowledge of the Moon, and increase lunar mapping precision that will support the company's future lander missions.

"MoonLIGHT" Payload Agreement Announcement in Frascati, Italy. L-R: Jack Burns, CU; Doug Currie, UMD; Simone Dell'Agnello, INFN-LNF; Bob Richards, Moon Express

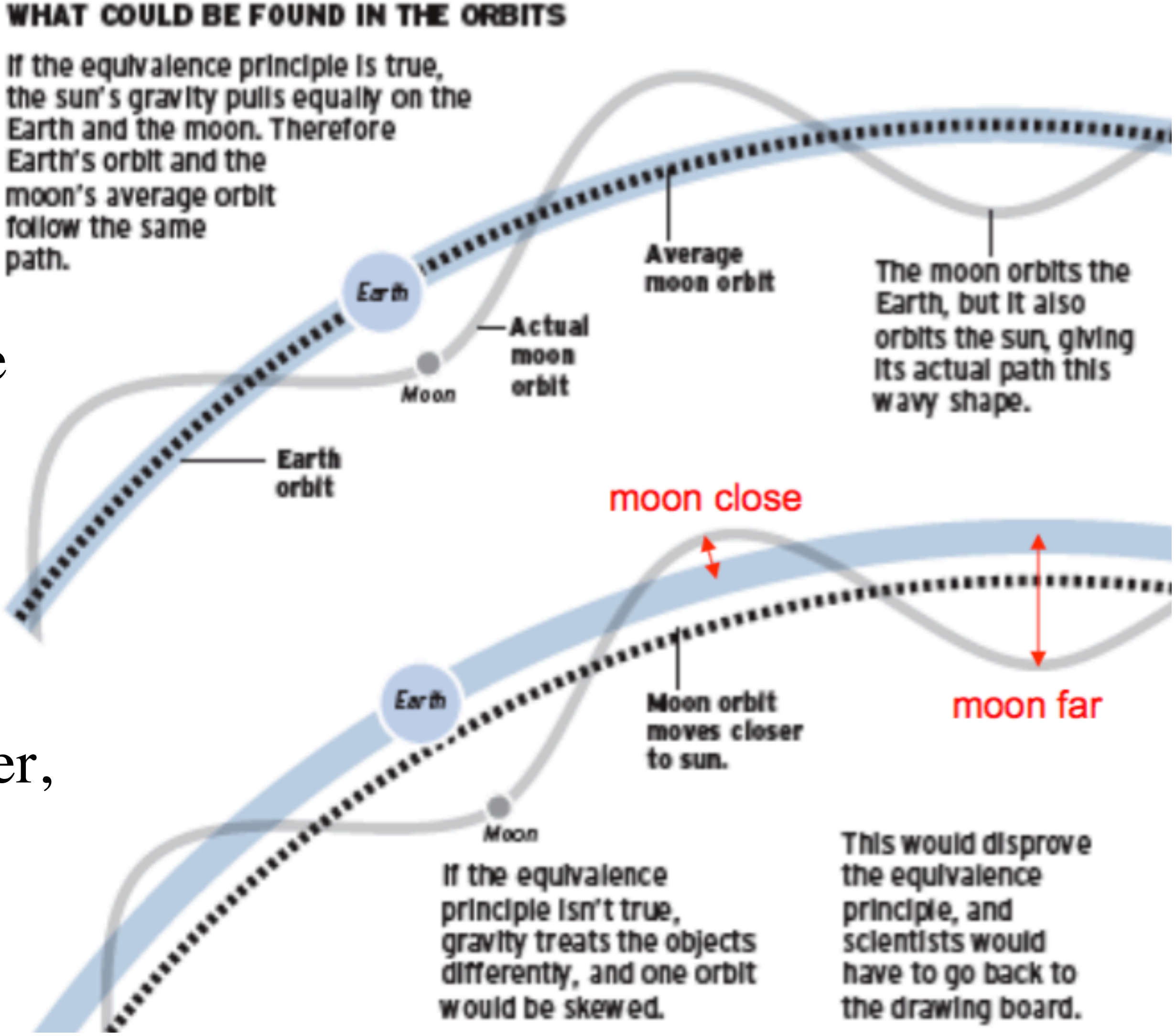
The payload announcement was made today in Frascati, Italy, right after the European Lunar Symposium, during a Global Exploration Roadmap workshop of the International Space Exploration Coordination Group (ISECG), attended by officials

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 ∝ 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:

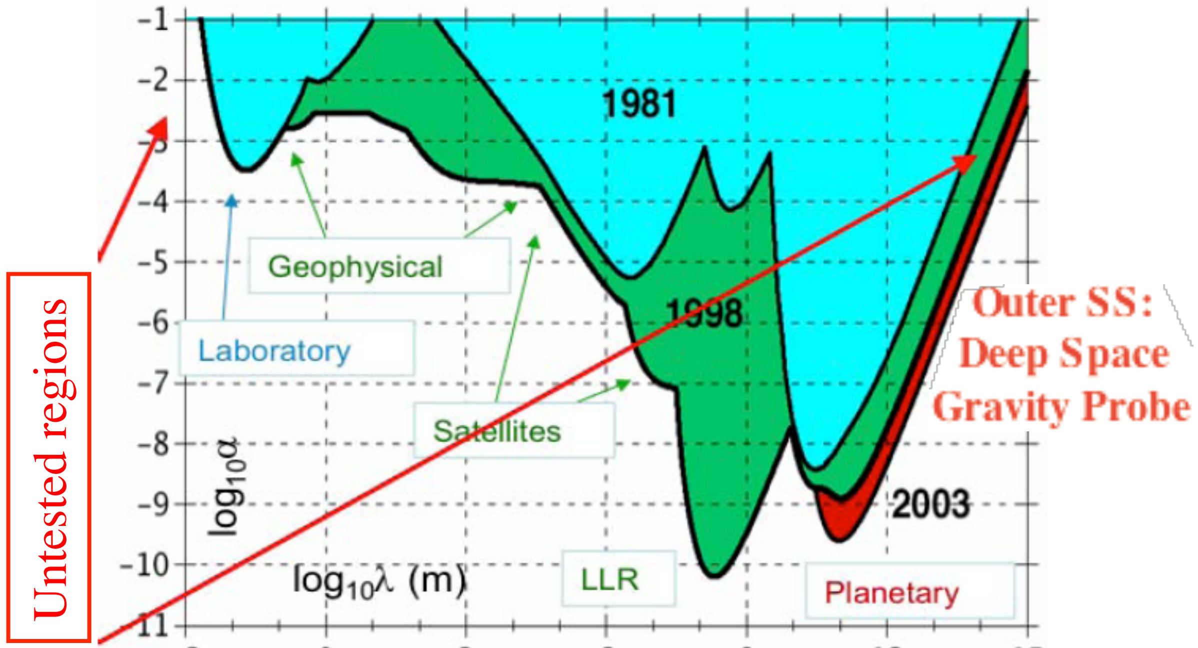
$$\boldsymbol{\beta - 1 = (1.2 \pm 1.1) \times 10^{-4}}$$

High accuracy η and β measurements

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

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 **$\alpha \sim 3\times10^{-11}$ down to $<10^{-12}$ at scales $\lambda \sim$ million km**



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