INTERNATIONAL/PRIVATE-PUBLIC MULTI-MISSION PAYLOAD AGREEMENTS FOR NEW-GENERATION LUNAR LASER RETROREFLECTORS

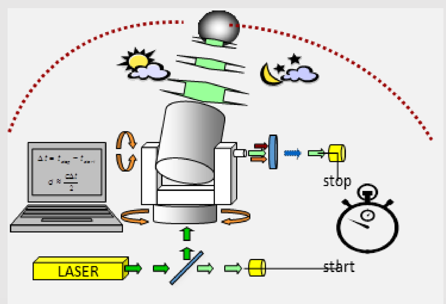
*Since the 1970 **LLR** to the CCRs supplied almost all significant tests of General Relativity. In the 1970s Apollo LLR arrays contributed to a negligible fraction of the ranging error budget. Now because of the lunar librations and the improvement of ground stations, Apollo CCR arrays dominate the error budget. To overcome this limitation, the **SCF_Lab** (at INFN-Frascati) and the University of Maryland (PI of Apollo reflectors) have developed new type of CCR: **MoonLIGHT-2**, a single, large retroreflector unaffected by librations, thus improving the space segment contribution to the overall accuracy of GR tests with respect to old Apollo/Lunokohd arrays. Before launches in the the framework of the GLXP INFN is characterizing the thermal behavior and the optical properties of the payload at the SCF_Lab and also studying the expected GR test improvement with the PEP SW in collaboration with the CfA. INFN-Padova works at ASI-MLRO on improved ground station instrumentation for LLR measurements ond instrument installations. MoonLIGHT is also proposed for the Resource Prospector mission in formulation within NASA.*

*In addition, **INRRI** is an INFN project for a new type of miniaturized CCR array designed to use lander or rover on the Moon and other rocky solar system bodies as long time fixed point for geodesy and GR tests. INRRI has been qualified for ESA ExoMars EDM mission. Using the PEP SW INFN is studying the expected improvement in GR tests using Mars as a test body and a network of INRRIs. The latter is approved for two other Martian missions (**NASA Mars 2020 Rover** & **InSight 2018 lander**) and proposed for CNSA's Chang'E-4 (far side) and for GLXP missions.*

INTRODUCTION

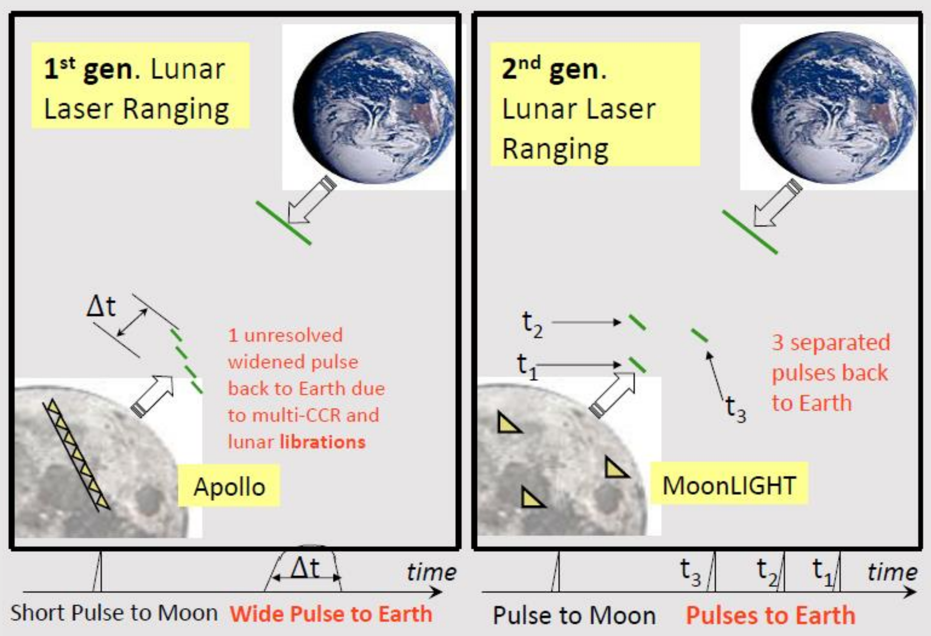
CCR & LLR

- **CCR**s reflect an incoming light beam back in the same direction where it came from
- From the time measurement *t* we can obtain the distance



Libration effect

The Apollo arrays are moved so that one corner of the array is more distant than the opposite corner up to few decimeters. Because the librations tilt the arrays, this increases the width of the LLR pulse coming back to the Earth.



SCF_Lab

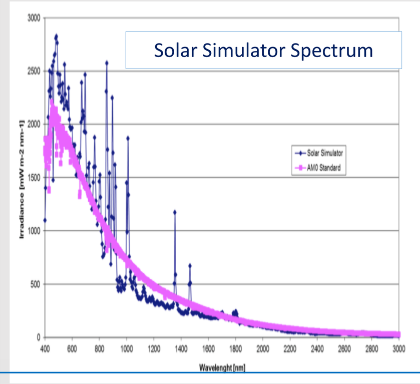
INFN Lab

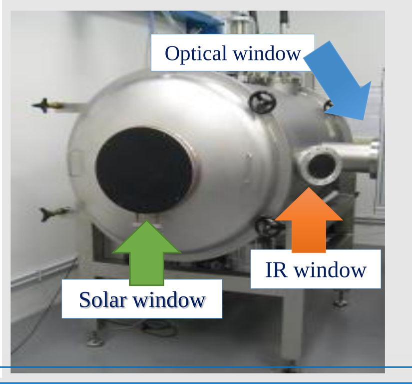
Fully representative space environment:

- Solar Simulator with spectrum AM0
- Payload thermal control, orbit/attitude.

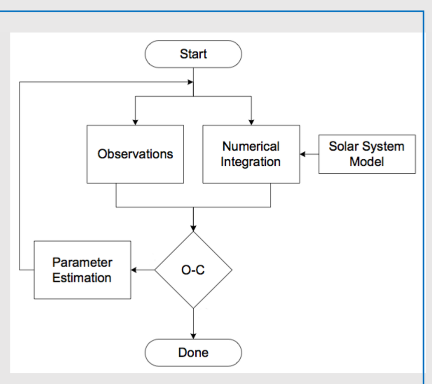
Experimental test, the SCF-TEST:

Thermal IR & Optical FFDP





PEP SW



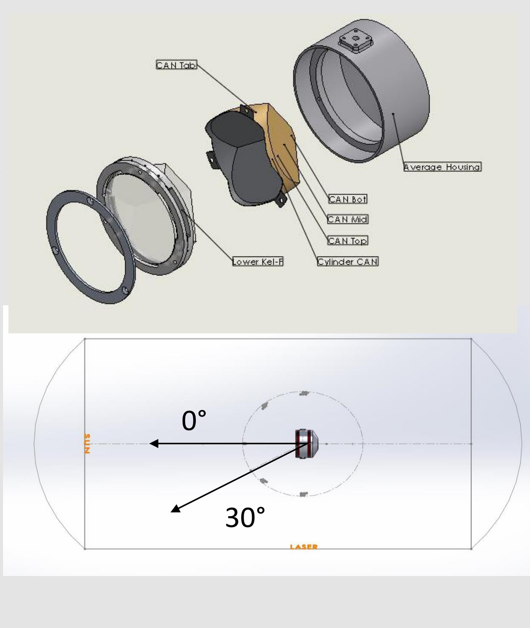
Developed by the CfA, by I. Shapiro et al. starting from 1970s. Include a detailed model of the Solar System. The model parameter estimates are refined by minimizing the residual differences, in a weighted least-squares sense, between observations (O) and model predictions (C, stands for "Computation"), O-C. "Observed" is the measured round-trip time of flight. "Computed" is modeled by the PEP software.

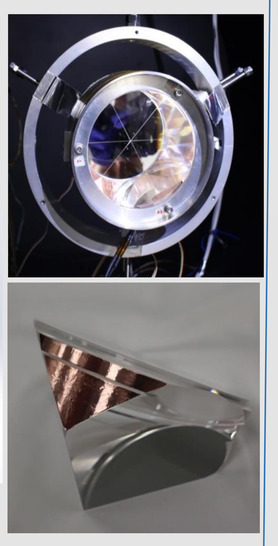
MoonLIGHT-2

SCF-TEST

The aim is to study of the thermal behavior and optical performance in representative space conditions established within the SCF. Test phases:

- 14h SUN ON (facing SS) + 14h SUN OFF (No SS)
- 1 IR every 2 min for all test. FFDP at fixed cadency.
- 3 test campaign setup, 8 different tests along 3y
- Thermal constant and front face gradient analysis
- Optical analysis of FFDP to study the laser return degradation at the Moon velocity aberration





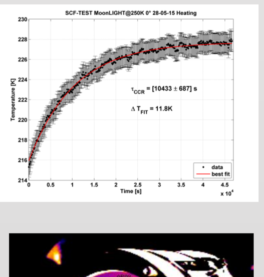
THERMAL ANALYSIS

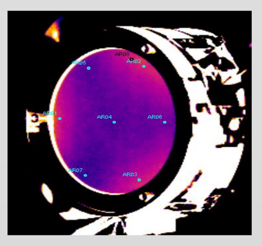
- Long exponential thermal constant will give good isolation from regolith thermal cycle
- Reduced front face gradient in last test, the final configuration, will provide good optical performance

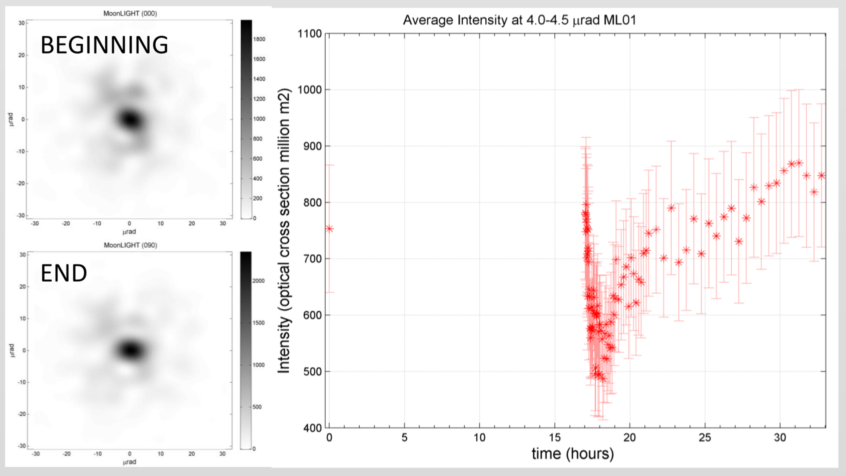
OPTICAL ANALYSIS

- Intensity of laser return at Moon velocity aberration returns to nominal value after SUN OFF and is in agreement with simulations
- No major differences in FFDP at beginning and end of test

Test Campaigns	SCF TEST		τ_{CCR} [10^3 sec]			Maximum ΔT [K]		
	Housing Temp [K]	SUN inclination	Heating phase	Cooling phase	Average	Heating phase	Cooling phase	Average
1st With Can No tape (11-12/2014)	300	0°	11.9 ± 0.8	13.3 ± 0.9	12.6 ± 1.0	3.6 ± 1.0	3.6 ± 1.0	3.6 ± 1.4
	300	30°	11.5 ± 0.7	14.4 ± 0.9	13.2 ± 2.1	5.8 ± 1.0	5.4 ± 1.0	5.6 ± 1.4
2nd With Can With tape (05-09/2015)	300	0°	15.1 ± 1.0	16.5 ± 1.1	15.8 ± 1.0	3.1 ± 1.0	2.9 ± 1.0	3.0 ± 1.4
	250	0°	10.4 ± 0.7	10.7 ± 0.7	10.5 ± 0.2	4.7 ± 1.0	4.1 ± 1.0	4.4 ± 1.4
	330	0°	15.6 ± 1.1	16.1 ± 1.1	15.9 ± 1.5	3.1 ± 1.0	3.4 ± 1.0	3.3 ± 1.4
3rd No Can With tape (12/2015)	300	0°	12.2 ± 0.8	13.6 ± 0.9	13.0 ± 1.2	2.9 ± 1.0	2.8 ± 1.0	2.9 ± 1.4
	300	30°	11.1 ± 0.7	13.2 ± 0.8	12.1 ± 1.1	3.3 ± 1.0	2.7 ± 1.0	3.0 ± 1.4





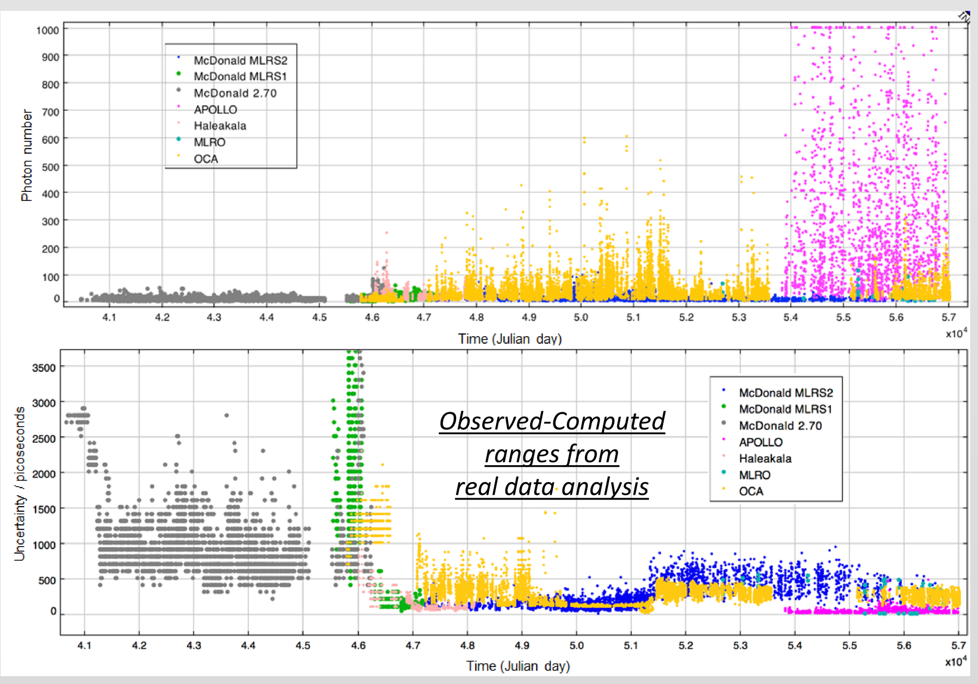


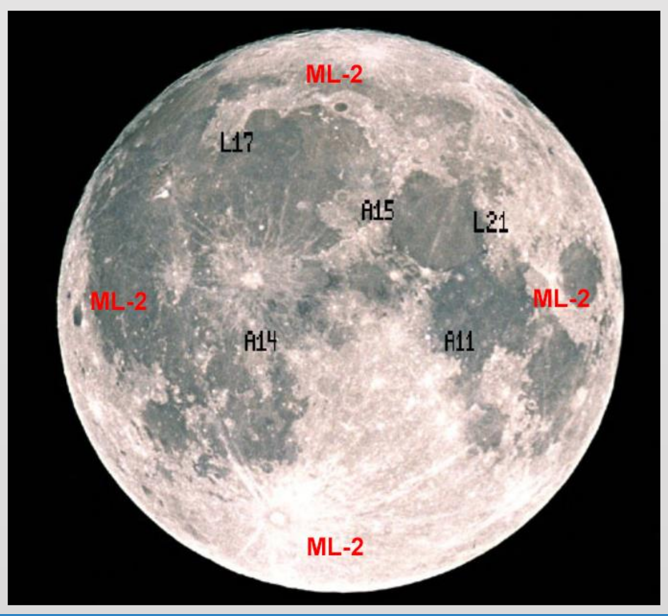
GR TEST and ILRS stations

Study the improvement in GR using 4 MoonLIGHT reflectors:

- Analyze all real LLR data available until now
- Simulate up to 15y of LLR data of 4 MoonLIGHTs plus Apollo/Lunokhod reflectors
- ILRS improvements à la APOLLO station

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





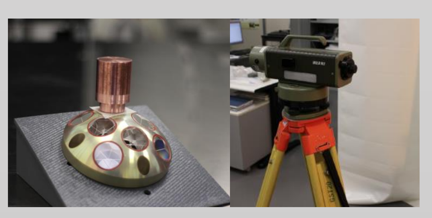
QUALIFICATION TEST

Compact array of 8 CCR fixed to an aluminum alloy frame through the use of silicon rubber suitable for space applications.

- Dimensions: 5.4 cm x 2 cm. Mass: 25 g.
- CCR front face diameter = 1/2 inch.

We qualified INRRI for the ExoMars EDM mission:

1) Quasi-static load and 'peel' test on each CCR



Check that silicon rubber ultimate performances were not reached. The test aimed at determining differences in elastic properties of the bonding before and after TVT and dynamic tests.

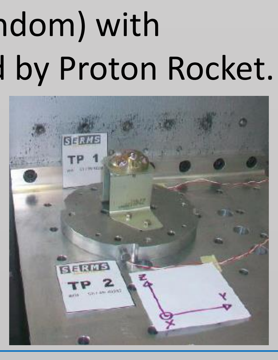
3) Dynamic load (at SERMS s.r.l.)

Sine/random environment:

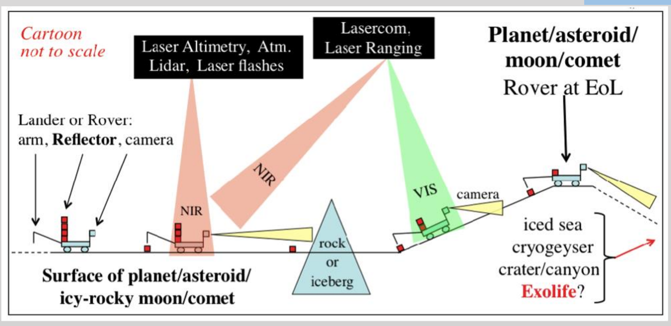
- Shock along the three axes (sine/random) with vibration characteristics determined by Proton Rocket.

Pyroshock test:

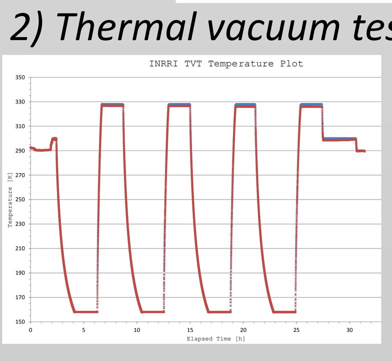
- Reproduction of rocket stage separations.
- Limit characteristics determined by mission profile.



INRRI



2) Thermal vacuum testing

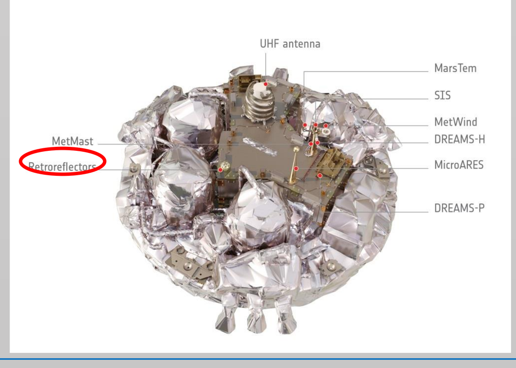


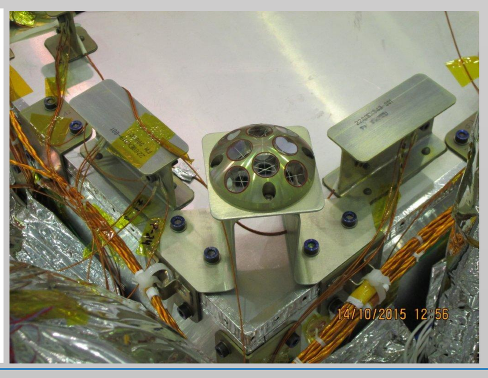
With INRRI thermally controlled

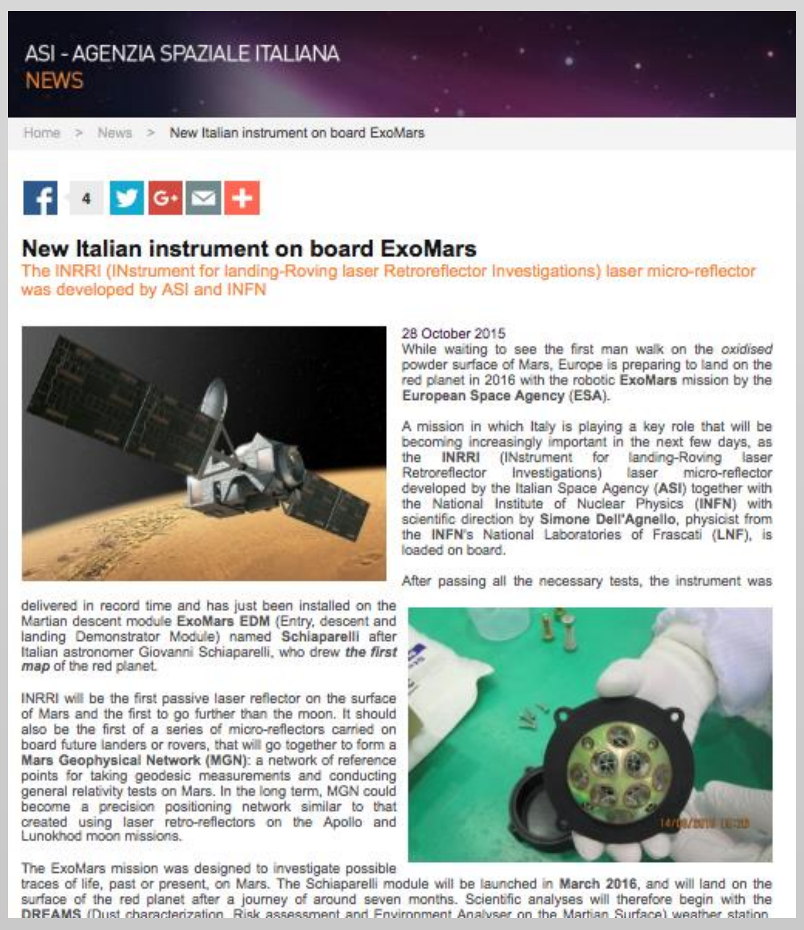
4 cycles with:

T dwell

4) Accepted & launched w/ExoMars EDM on 14/03/2016







New Italian instrument on board ExoMars

The INRRI (INstrument for landing-Roving laser Retroreflector Investigations) laser micro-reflector was developed by ASI and INFN

28 October 2015

While waiting to see the first man walk on the *oxidised* powder surface of Mars, Europe is preparing to land on the red planet in 2016 with the robotic **ExoMars** mission by the **European Space Agency (ESA)**.

A mission in which Italy is playing a key role that will be becoming increasingly important in the next few days, as the **INRRI** (INstrument for landing-Roving laser Retroreflector Investigations) laser micro-reflector developed by the Italian Space Agency (**ASI**) together with the National Institute of Nuclear Physics (**INFN**) with scientific direction by **Simone Dell'Agnello**, physicist from the **INFN**'s National Laboratories of Frascati (**LNF**), is loaded on board.

After passing all the necessary tests, the instrument was delivered in record time and has just been installed on the Martian descent module **ExoMars EDM** (Entry, descent and landing Demonstrator Module) named **Schiaparelli** after Italian astronomer Giovanni Schiaparelli, who drew ***the first map*** of the red planet.

INRRI will be the first passive laser reflector on the surface of Mars and the first to go further than the moon. It should also be the first of a series of micro-reflectors carried on board future landers or rovers, that will go together to form a **Mars Geophysical Network (MGN)**: a network of reference points for taking geodesic measurements and conducting general relativity tests on Mars. In the long term, MGN could become a precision positioning network similar to that created using laser retro-reflectors on the Apollo and Lunokhod moon missions.

The ExoMars mission was designed to investigate possible traces of life, past or present, on Mars. The Schiaparelli module will be launched in **March 2016**, and will land on the surface of the red planet after a journey of around seven months. Scientific analyses will therefore begin with the **DREAMS** (Dust characterization, Risk assessment and Environment Analyser on the Martian Surface) weather station

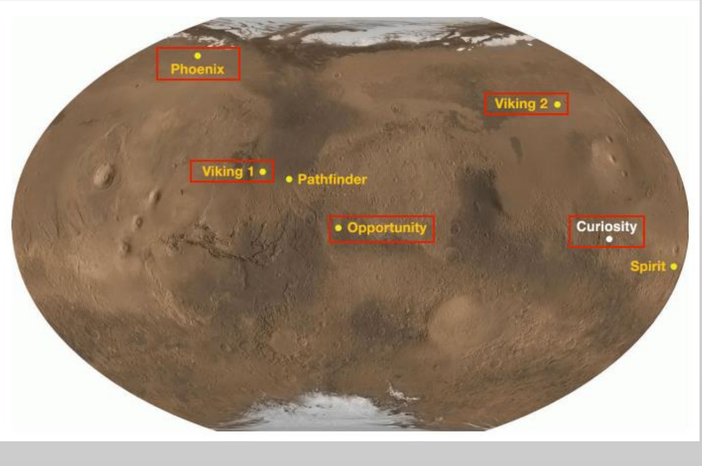
GR SIMULATIONS

We started to study the expected improvements in GR tests with an INRRI network on Mars.

- Use current GR test as benchmark
- Simulate up to 15y of data of 5 INRRI (starting from 2017, one new payload every 2 year).

INRRIs sites:

- Phoenix
- Viking 1/2
- Curiosity
- Opportunity



Preliminary results

Precision test of violation of GR	Positioning accuracy: 10 m	Positioning accuracy: 1m
Time variation of Gravitational constant	×5.6	×33.4
Parametrized Post-Newtonian β	×2.4	×9.9

PUBLICATIONS

Paper published on international peer review journal:

- Journal of Applied Mathematics and Physics, 2015, 3, 218-227, "Advanced Laser Retroreflectors for Astrophysics and Space Science"
- "INRRI-EDM/2016: the first laser retroreflector on the surface of Mars" for Advances in Space ResearchAdvances in Space Research, 2017, Vol. 59, 645-655

Paper submitted on international peer review journal:

- "Test of General Relativity using Lunar Laser Ranging Data and the Planetary Ephemeris" [to be submitted]
- Vulcano Workshop 2016, "Gravity Session", "Experimental gravity tests in the solar system"
- "Fourteenth Marcel Grossmann Meeting" (Rome 2015), "Next-generation Laser Retroreflectors for Precision Tests of General Relativity" [submitted]
- MetroAerospace 2015 (Benevento 2015), "Laser ranging positioning metrology for Galileo and the Moon", DOI 10.1109/MetroAeroSpace.2015.7180630
- 19th International Workshop on Laser Ranging 2014 (Annapolis, USA), "Test of general relativity using lunar laser ranging data and the planetary ephemeris program (PEP)"
- International Conference on Space Optics 2014 (Tenerife, Spain), Next-Generation Laser Retroreflectors for GNSS, Solar System Exploration, Geodesy, Gravitational Physics and Earth Observation
- AOGS 2015 in Singapore 06/2015. title: "Next-Generation Laser Retroreflectors for Lunar Science and Exploration"
- Congresso Nazionale di Scienze Planetarie, Bornio 02/2016. "INRRI-EDM/2016: the first laser retroreflector on the surface of Mars"

Posters:

- LNF Mini-Workshop Series: Fundamental and Quantum Physics with Lasers , Frascati 2014, title: "SCF_Lab: TEST OF GENERAL RELATIVITY USING LUNAR LASER RANGING DATA AND THE PLANETARY EPHEMERIS PROGRAM"
- ASI, Workshop Componentistica 01/2016. title:" INRRI-EDM/2016: The first laser retroreflector payload on Mars"

***AM0** = Air Mass 0*
***APOLLO** = Apache Point Observatory Lunar Laser ranging Operation*
***ASI** = Agenzia Spaziale Italiana*
***CCR** = Cube Corner Retroflector*
***CfA** = Center for Astrophysics*
***FFDP** = Far Field Diffraction Pattern*
***GLXP** = Google Lunar X Prize*
***GR** = General Relativity*
***ILRS** = International Laser Ranging Service*
***IR** = InfraRed*
***INFN** = Istituto Nazionale di Fisica Nucleare*
***INRRI** = INstrument for landing-Roving laser ranging/altimetry Retroreflector Investigations*
***LLR** = Lunar Laser Ranging*
***MLRO** = Matera Laser Ranging Observatory*
***MoonLIGHT** = Moon Laser Instrumentation for General relativity High-accuracy Tests*
***PEP** = Planetary Ephemeris Program*
***SERMS** = Studio degli Effetti delle Radiazioni sui Materiali per lo Spazio*
***SCF/SCF-G**= Satellite/lunar/GNSS laser ranging/altimetry and Cube/microsat Characterization Facilities / SCF Galileo optimized*
***SCF_Lab** = Satellite/lunar/GNSS laser ranging/altimetry and Cube/microsat Characterization Facilities Laboratory*

The MoonLIGHT-2 Collaboration.
MoonLIGHT-2 is an approved experiment of INFN-CSN2 (Commissione Scientifica Nazionale n. 2)
Poster Authors: SCF_Lab Research Group:
http://www.lnf.infn.it/esforimenti/etrusco/