EXPERIMENTAL GRAVITY TESTS IN THE SOLAR SYSTEM

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VULCANO WORKSHOP 2016

Outline

Introduction:

•Science with Satellite/Lunar Laser Ranging

•Tests of General Relativity

Data analysis:

•The "Planetary Ephemeris Program (PEP)"

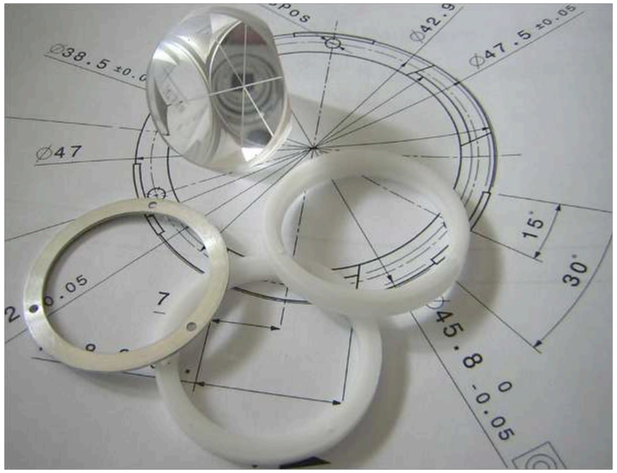
•Physics simulations (Moon/Mars)

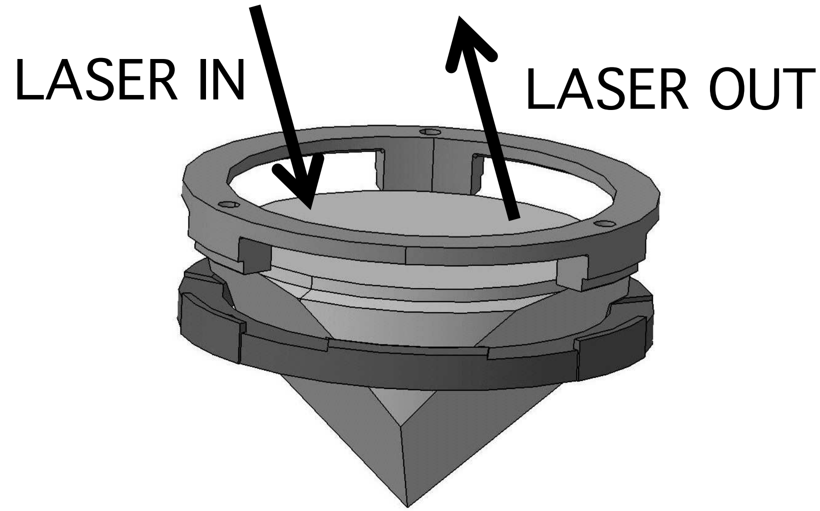
•Results

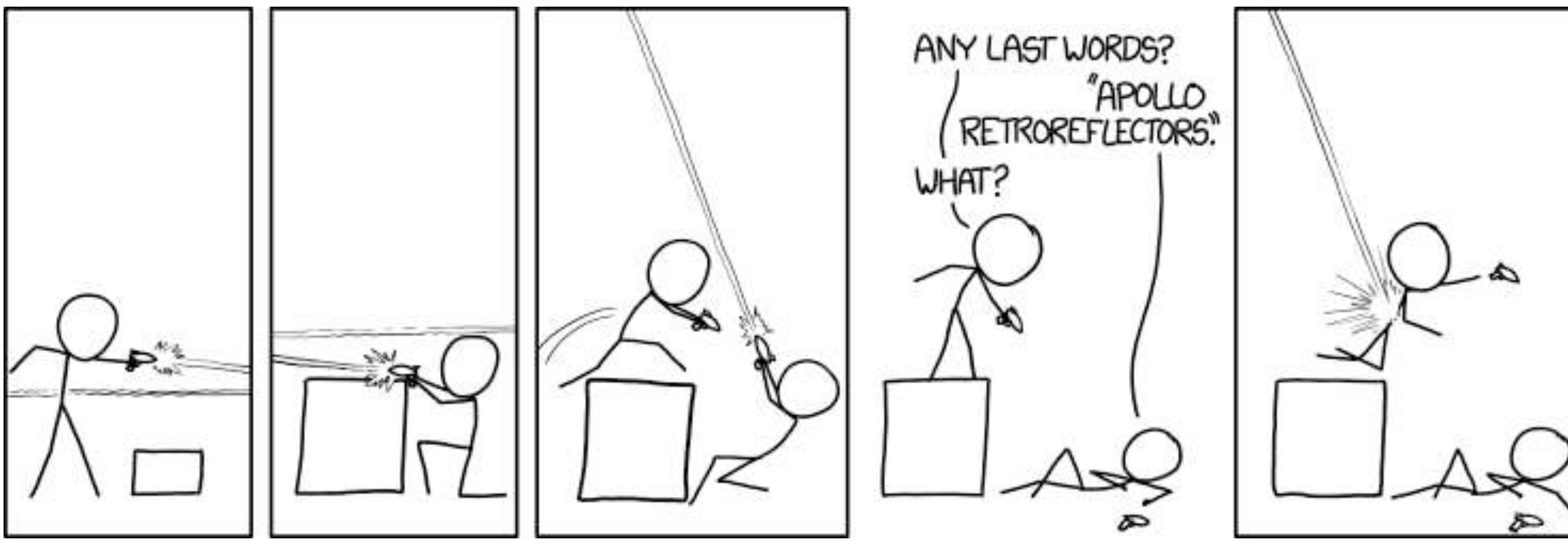
Conclusions and prospects

Introduction

Corner Cube Retroreflector

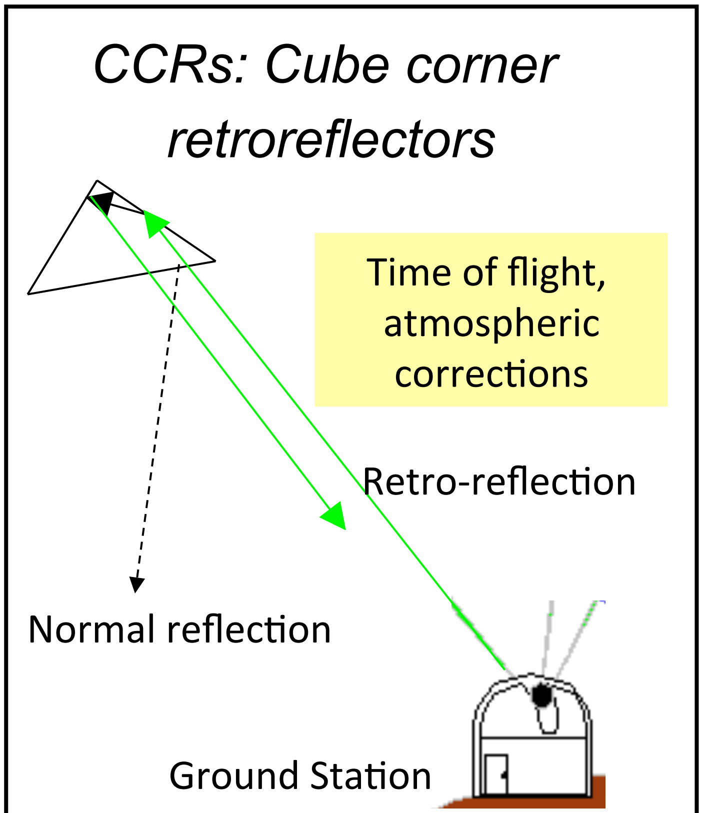


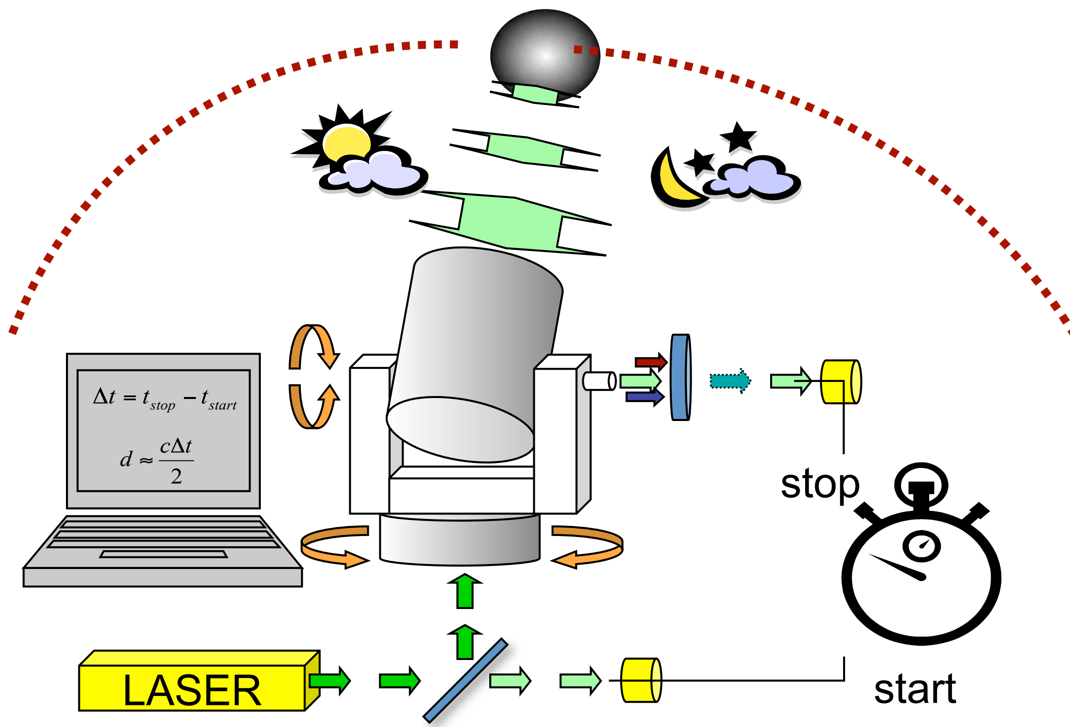




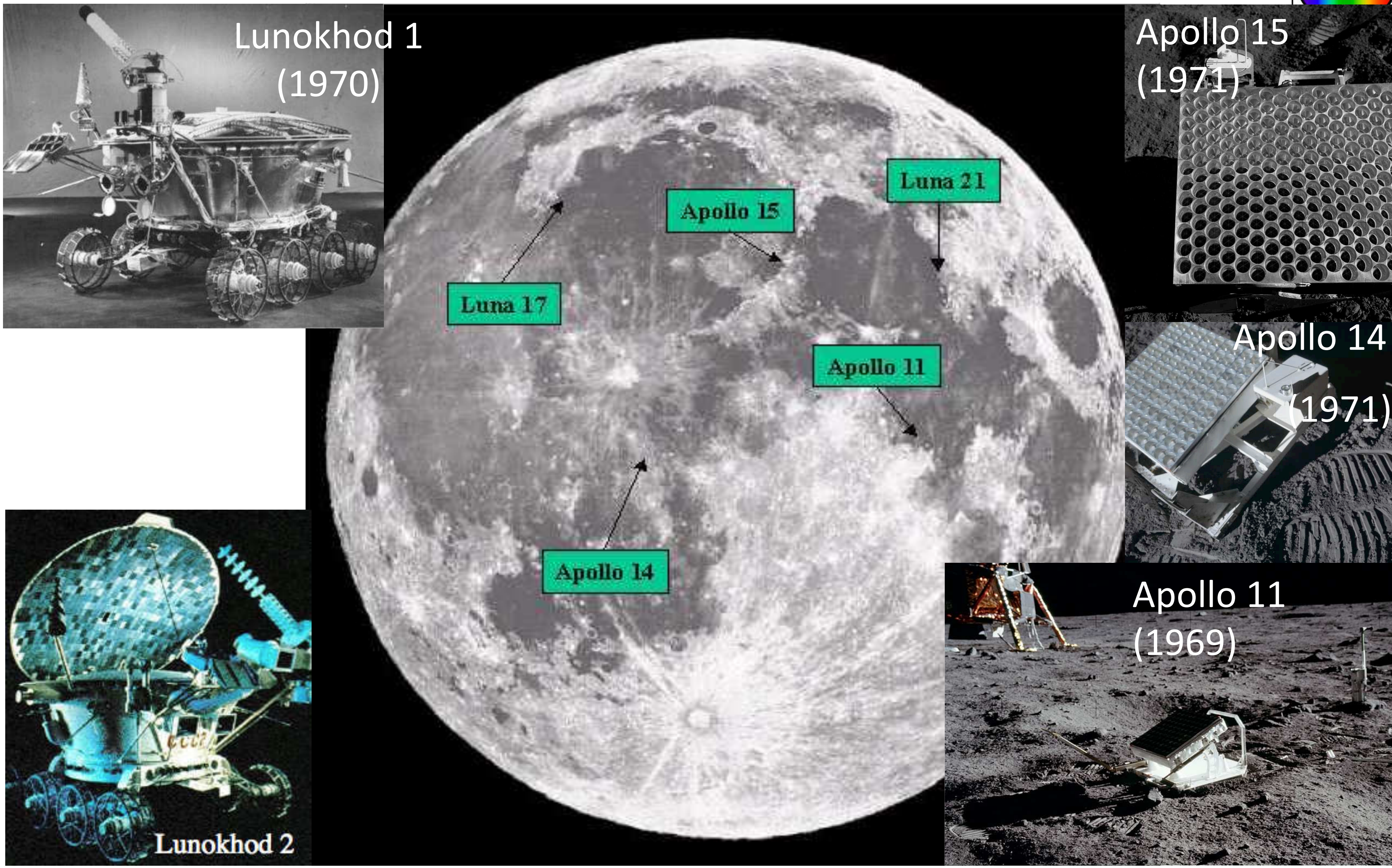
Satellite/Lunar Laser Ranging

- An observatory on Earth transmits a short pulse towards a CCR array on Satellite/Moon.
- The CCR reflect the pulse back to the observatory.
- Time of flight measurement → Distance
- Track Satellite/Moon orbit and obtain orbit parameter





Lunar Laser Ranging



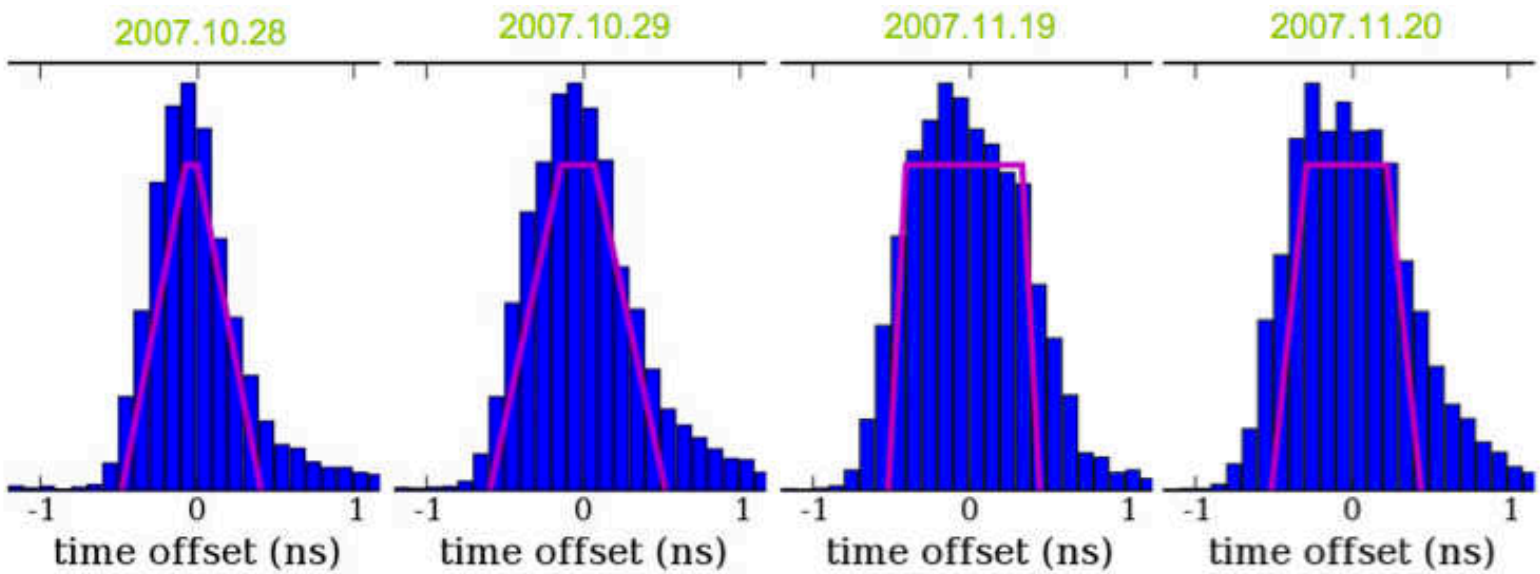
Tests of General Relativity

- Measurement of relativistic geodetic precession of lunar orbit, a true three-body effect (~3m / lunar orbit)
- Time variation of universal gravitational constant G
- Violation of Weak and Strong Equivalence Principle (WEP/SEP)
- Parametrized Post-Newtonian (PPN) parameter β: measures the non-linearity of gravity

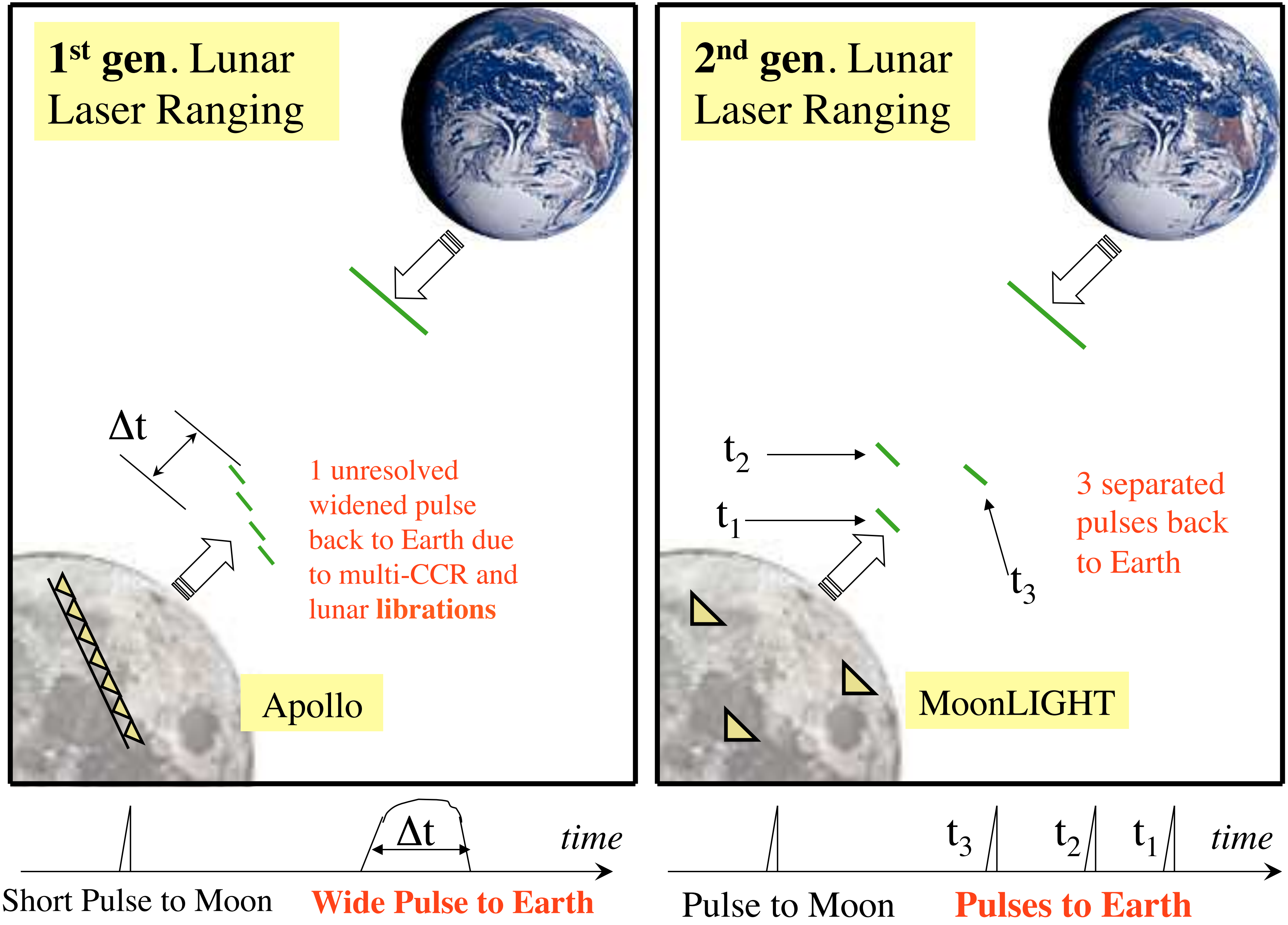
Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod few cm accuracy*
Parameterized Post-Newtonian (PPN) β	$\|\beta-1\|<1.1\times10^{-4}$
Weak Equivalence Principle (WEP)	$\|\Delta a/a\|<1.4\times10^{-13}$
Strong Equivalence Principle (SEP)	$\|\eta\|<4.4\times10^{-4}$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

Librations: the main limitation of Apollo/Lunokhod

Effect of multi-CCR array orientation due to lunar librations



Due to this phenomenon the Apollo arrays are moved so that one corner of the array is more distant than the opposite corner by a few decimeters. Because of this libration tilt, the arrays broaden the LLR pulse back to Earth.



1st gen. Lunar Laser Ranging
Δt
1 unresolved widened pulse back to Earth due to multi-CCR and lunar librations
Apollo
Δt
time
Short Pulse to Moon
Wide Pulse to Earth
2nd gen. Lunar Laser Ranging
t2
t1
t3
3 separated pulses back to Earth
MoonLIGHT
t3
t2
t1
time
Pulse to Moon
Pulses to Earth

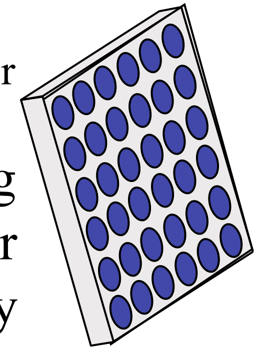
MoonLIGHT-2 reflector

Libration rotations up to ~8°
(effect of *e* and *i* of Moon orbit).
Current accuracy of ~ 2 cm

Laser Pulse

far corner

Librating
Multi-reflector
array



near corner

Past
(Apollo)

fat laser pulse:
return uncertainty
dominated by pulse

Present
(APOLLO)

medium laser pulse:
return uncertainty
dominated by array libration

Future
(MoonLIGHT)

short laser pulse:
return uncertainty
dominated by pulse
Shorter pulses can be done

Data Analysis

Planetary Ephemeris Program

In order to analyze LLR data we used the PEP software, developed by the CfA, by I. Shapiro et al. starting from 1970s.

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.

Generating Predictions

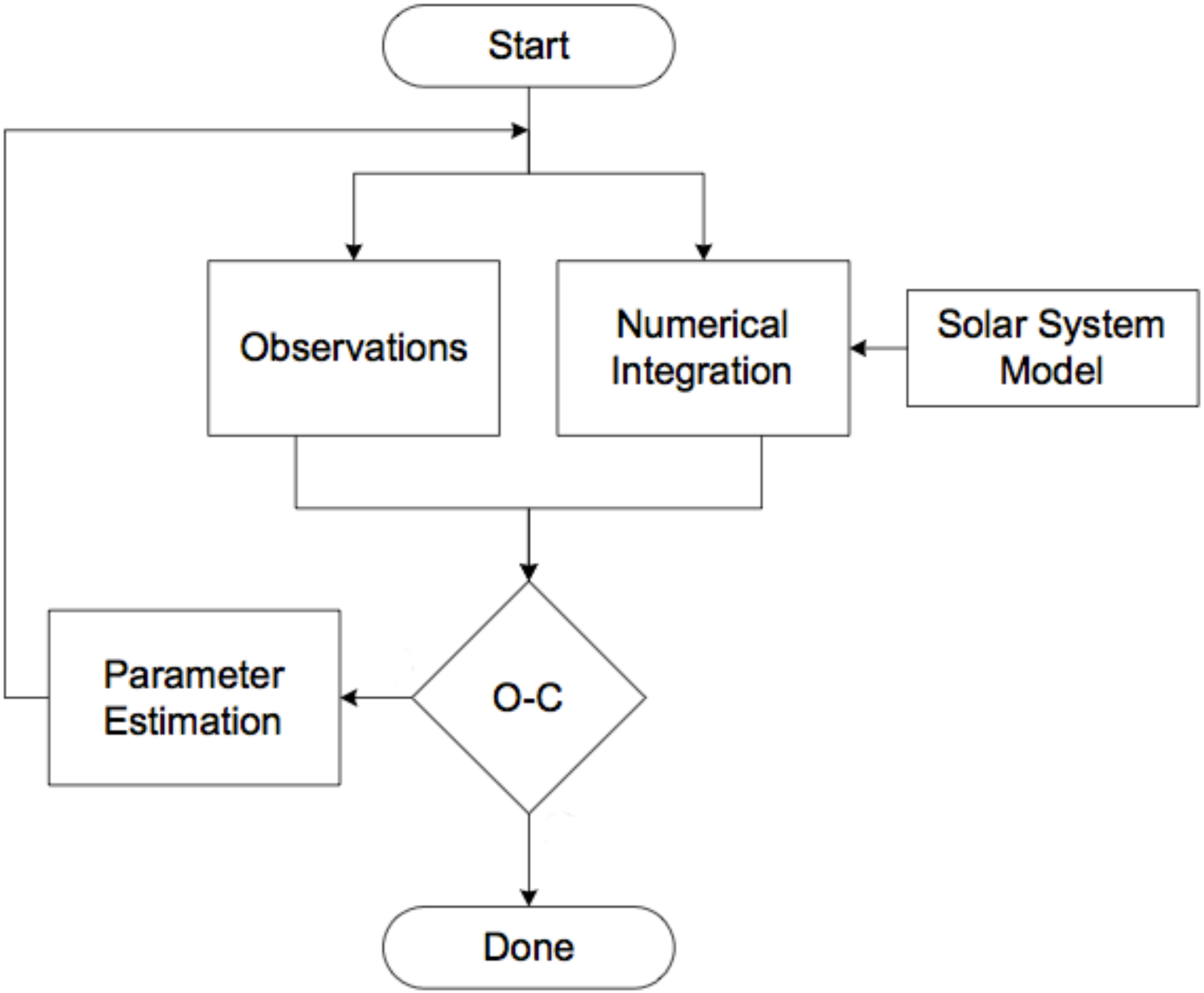
How does one can generate an ephemeris?

- Must obtain accurate observations;

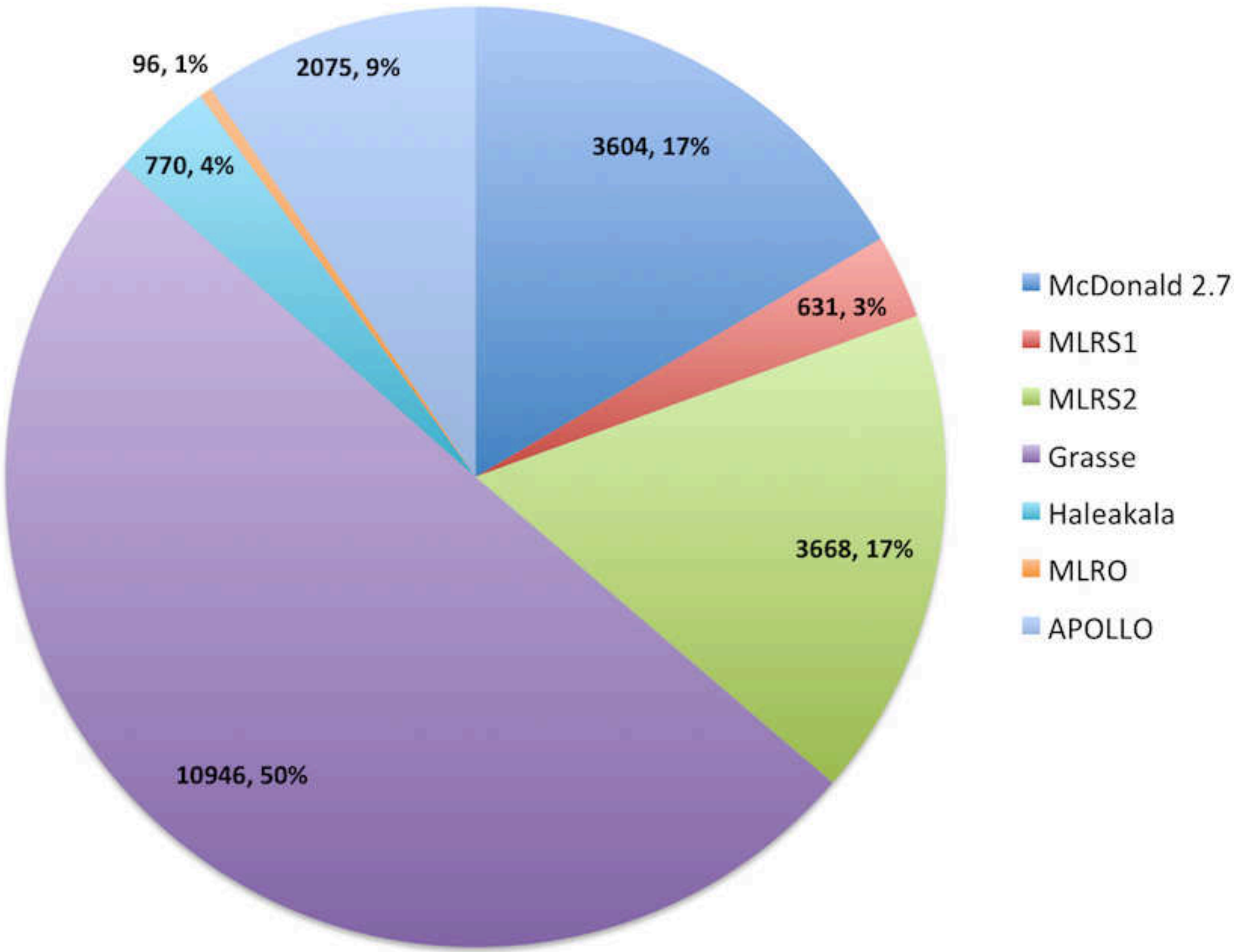
- Develop a comprehensive solar system model that we then integrate numerically (including complications, such as planetary rotation dynamics and lunar motion);

- Simultaneously fit all of these model parameters to the available observations (from asteroids and interplanetary probes, etc.).

Generating Predictions



Data Analysis LLR Normal Points



Normal Point Data

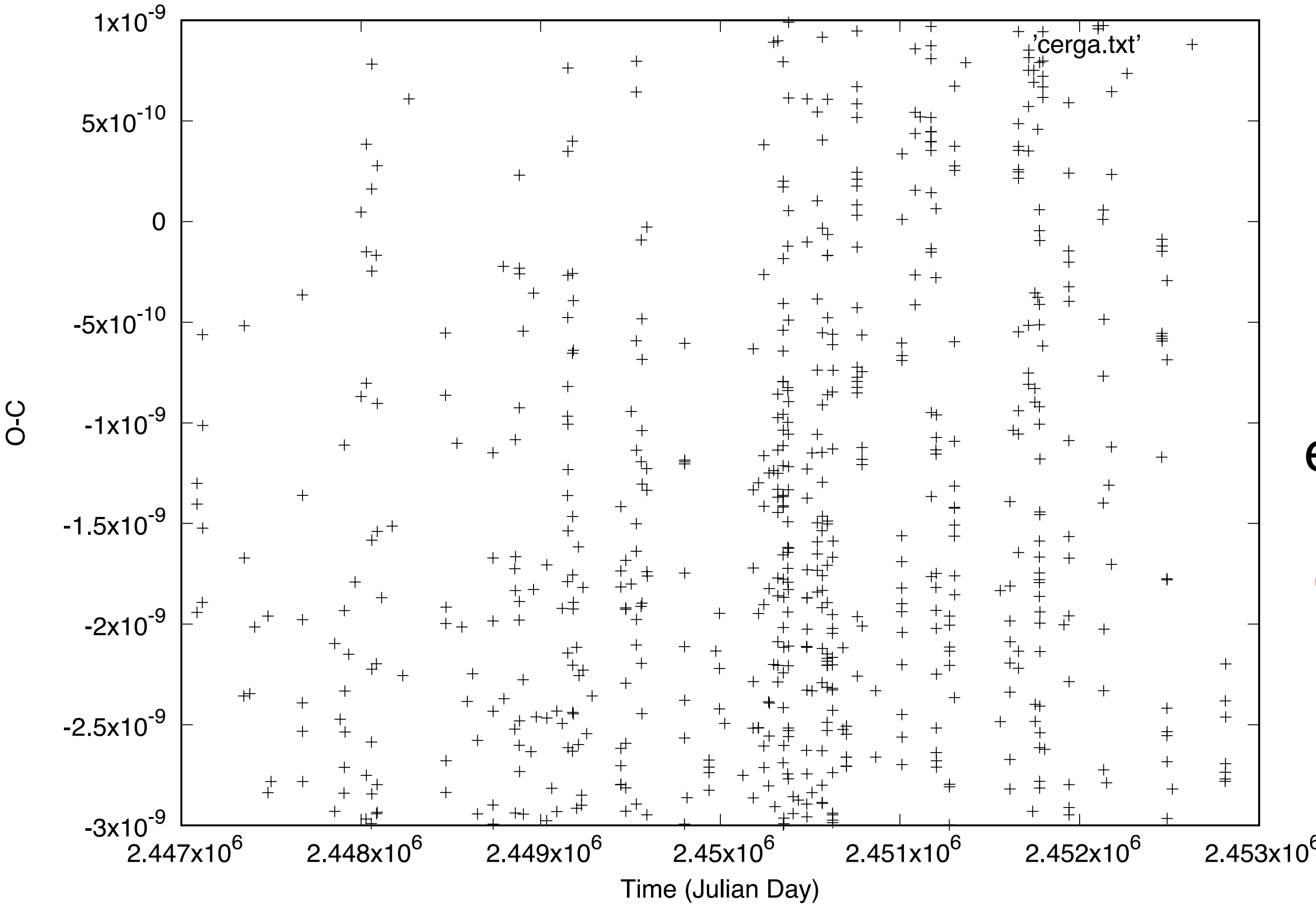
```
512008 330123950000000026170710379889370610207 317312B 72439 -5134 5320A 250A
```

The fields are:

field	width	represents	this example	notes
51	2	?	51	
2008	4	year	2008	time is UTC launch time
3	2	Month	March	
30	2	Day	30th	
12	2	Hour	12 h	
39	2	Monute	39 m	
500000000	9	10^{-7} seconds	50.0000000 s	
26170710379889	14	round trip time, 10^{-13} seconds	2.6170710379889 s	measured round trip
3	1	reflector number	Apollo 15 (#3)	0=A11; 1=L1; 2=A14; 3=A15; 4=L2
70610	5	station ID	Apache Point	
207	3	# photons in NP	207 photons	saturates at 999
317	6	uncert in 0.1 ps	31.7 ps	
312	3	10×SNR	31.2	saturates at 99.9
B	1	data quality grade	B	A, B, C, D
72439	6	pressure, 0.01 mbar	724.39 mbar	
-51	4	temperature, 0.1°C	-5.1°C	
34	2	% relative humidity	34%	
5320	5	wavelength, angstroms	5320 angstrom	
A	1	?	A	
250	4	NP duration, sec	250 sec	
A	1	?	A	

A normal point contains several information e.g. date of observation, atmospheric conditions, as well as time of flight, data quality and CCR arrays

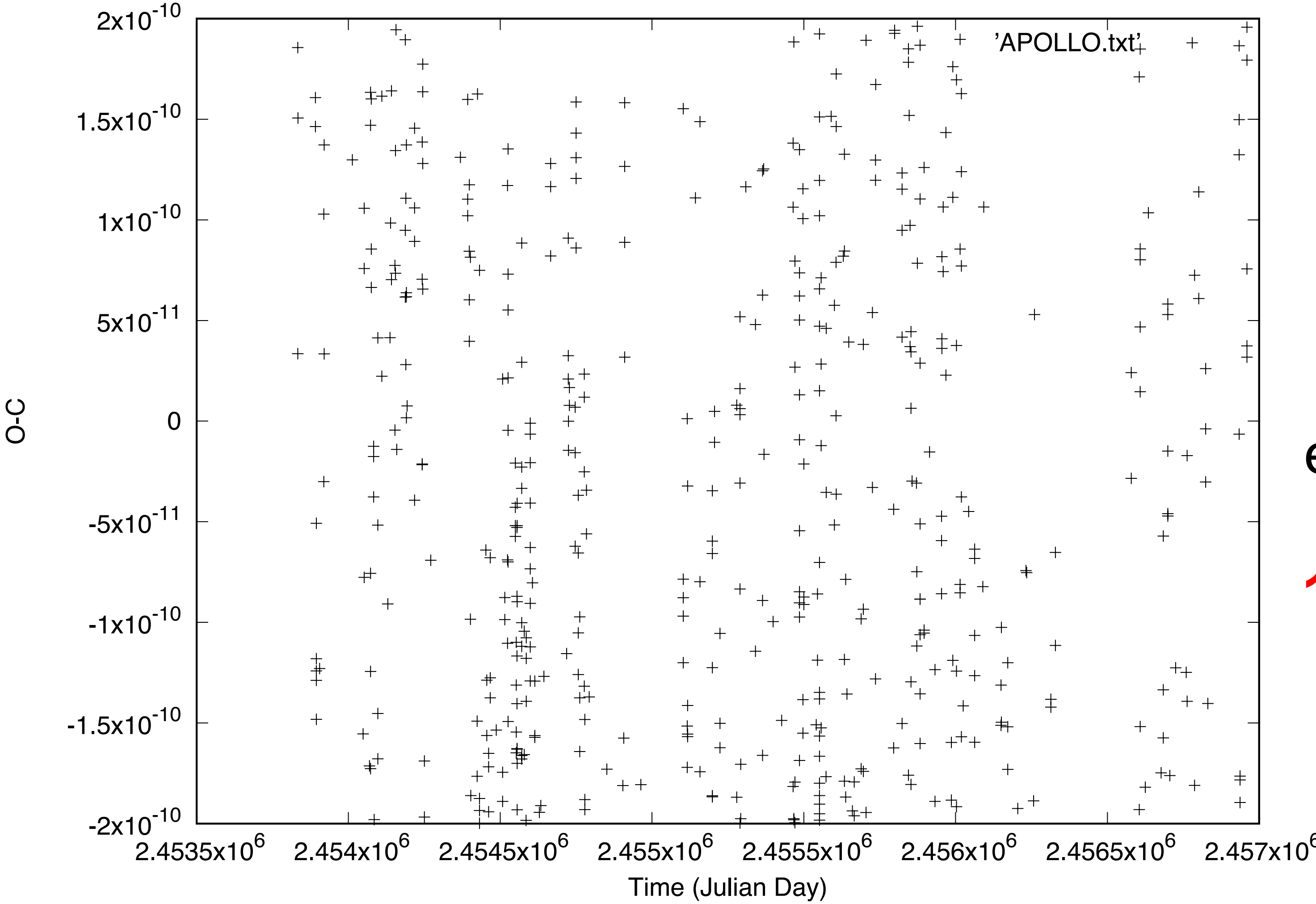
O-C residual analysis with PEP



CERGA
on
existing CCRs

10^{-9} seconds

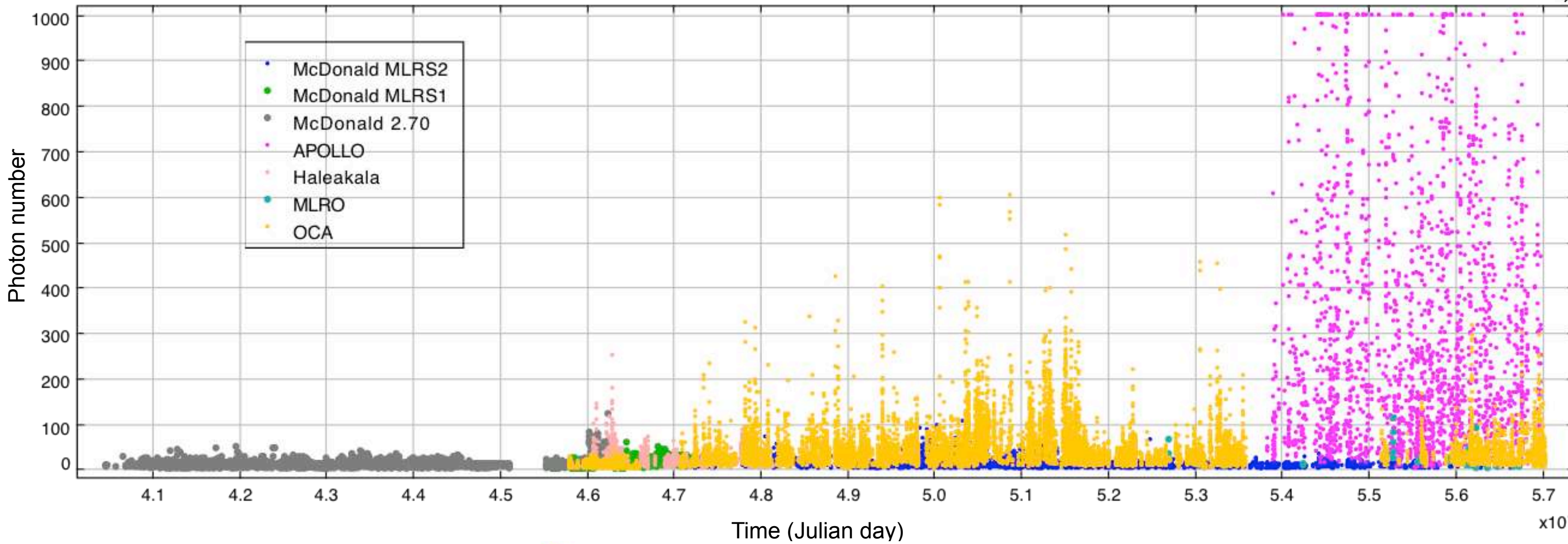
O-C residual analysis with PEP

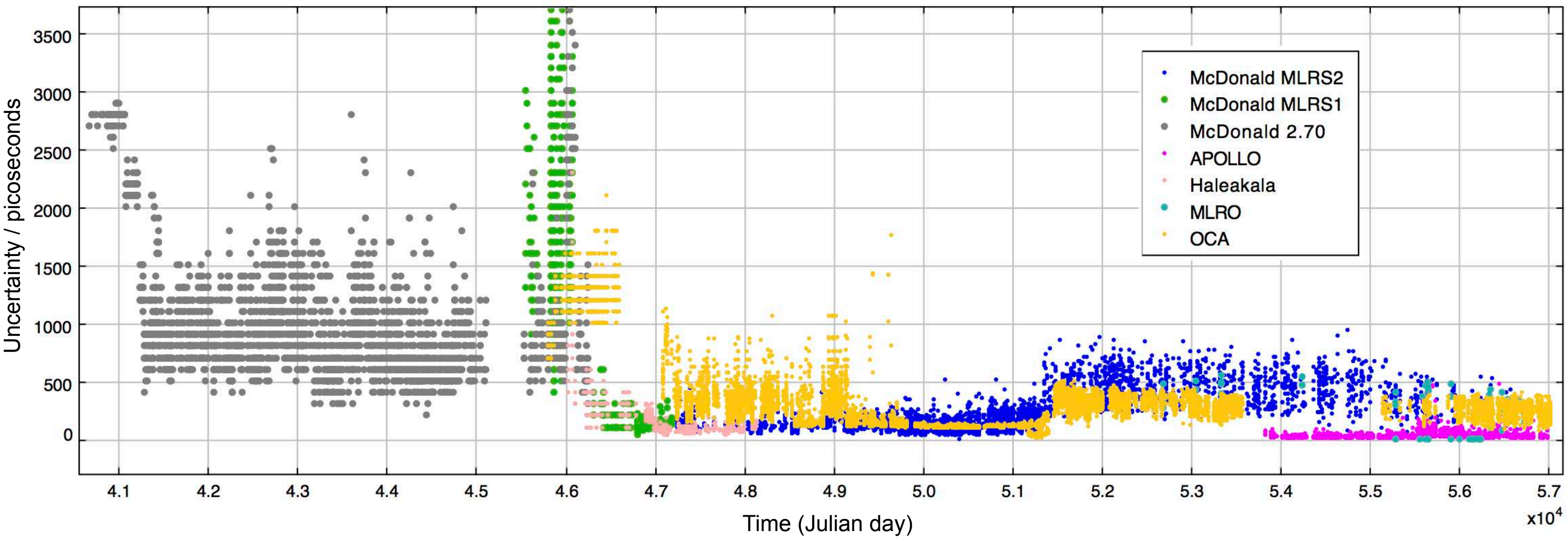


APOLLO
on
existing CCRs

10^{-10} seconds

O-C residual analysis with PEP





LLR tests of General Relativity (GR)

Due to librations a major improvement in LLR efficiency and precision and, therefore, on GR tests can and must be obtained only by going from arrays to single retroreflectors.

It is a pre-requisite (condicio sine qua non)

Efficiency (# returns to make a normal point) of single, large reflector: few thousands times larger than reflector arrays

State of the art measurements

Precision test of violation of GR	Apollo/Lunokhod JPL	Apollo/Lunokhod PEP
Geodetic Precession	$\lvert K_{gp}\rvert < 6.4\times10^{-3}$	$\lvert K_{gp}\rvert < 7.9\times10^{-3}$
Time Variation of the Gravitational Constant	$\lvert \dot{G}/G\rvert < 9\times10^{-13} yr^{-1}$	$\lvert \dot{G}/G\rvert < 9.8\times10^{-13} yr^{-1}$
Parametrized Post-Newtonian, β	$\lvert \beta-1\rvert < 1.1\times10^{-4}$	$\lvert \beta-1\rvert < 4.0\times10^{-4}$

Simulated observations

Simulation to optimize MoonLIGHT for the first deploying (2018) using all real LLR data taken until now from Apollo and Lunokhod

CCR Array	Data Type	Time Span	Sites	Stations	Accuracy
Apollo + Lunokhod	Dummy	2015 2030	11-14-15 Lunokhod1-2	APOLLO	0,5 cm
				CERGA	1,0 cm
				MLRS	
				MLRO	
MoonLIGHT with and without Sun Shade	Dummy	2018 2030	80°N, 0°W 80°S, 0°E 0°N, 80°E 0°N, 80°W	APOLLO	0,1 cm
				CERGA	0,2 cm
				MLRS	
				MLRO	

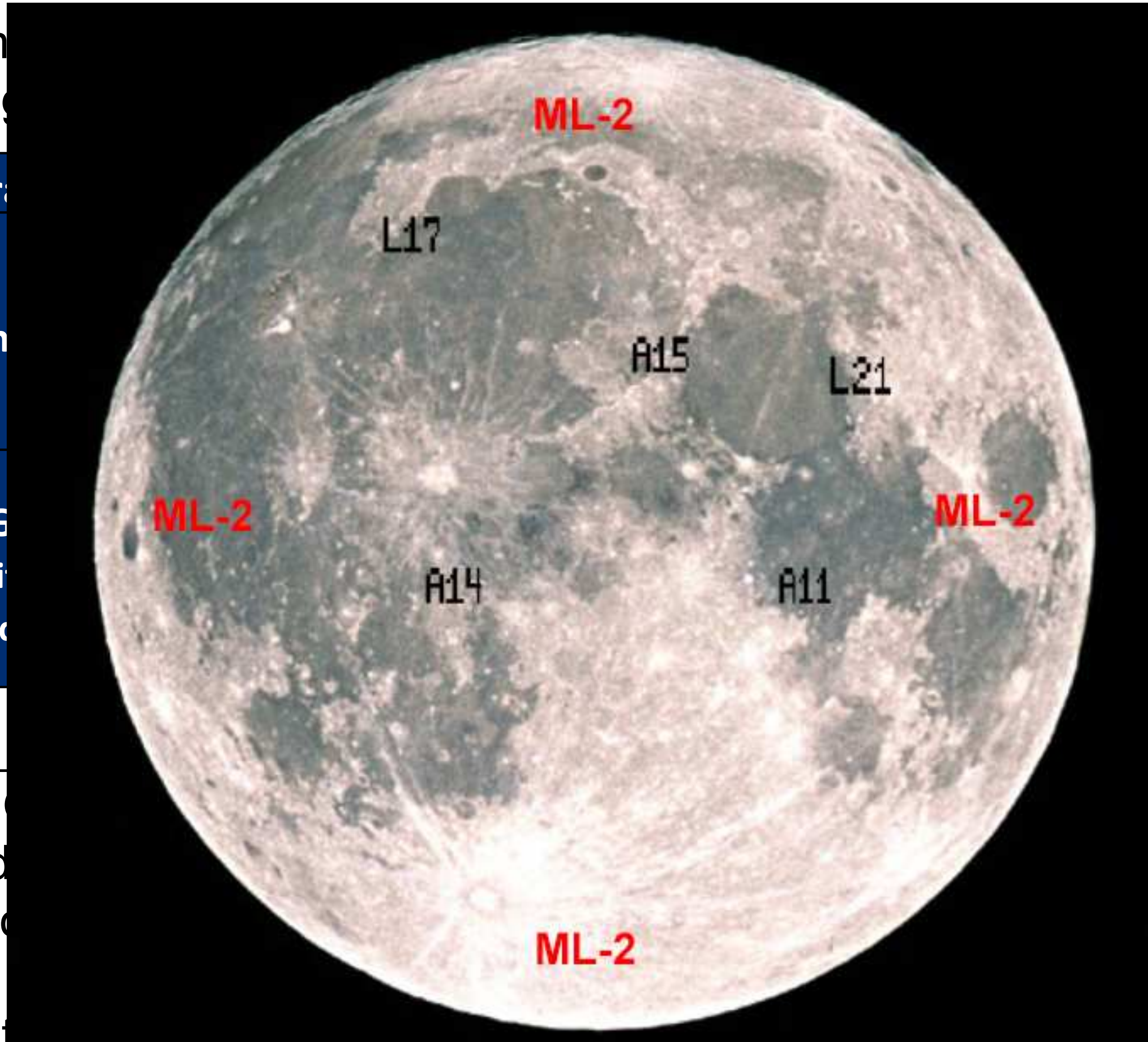
➢ **<u>GR tests expected improvement</u>:**

- 4 MoonLIGHT-2 (starting from 2018, one per year) plus any other Apollo/ Lunokhod
- 15 years of simulations starting from 2015.
- Accuracy simulation of Optimal design as “STD”
- 3 different accuracy value set: STD, double STD and half of STD.

Simulated observations

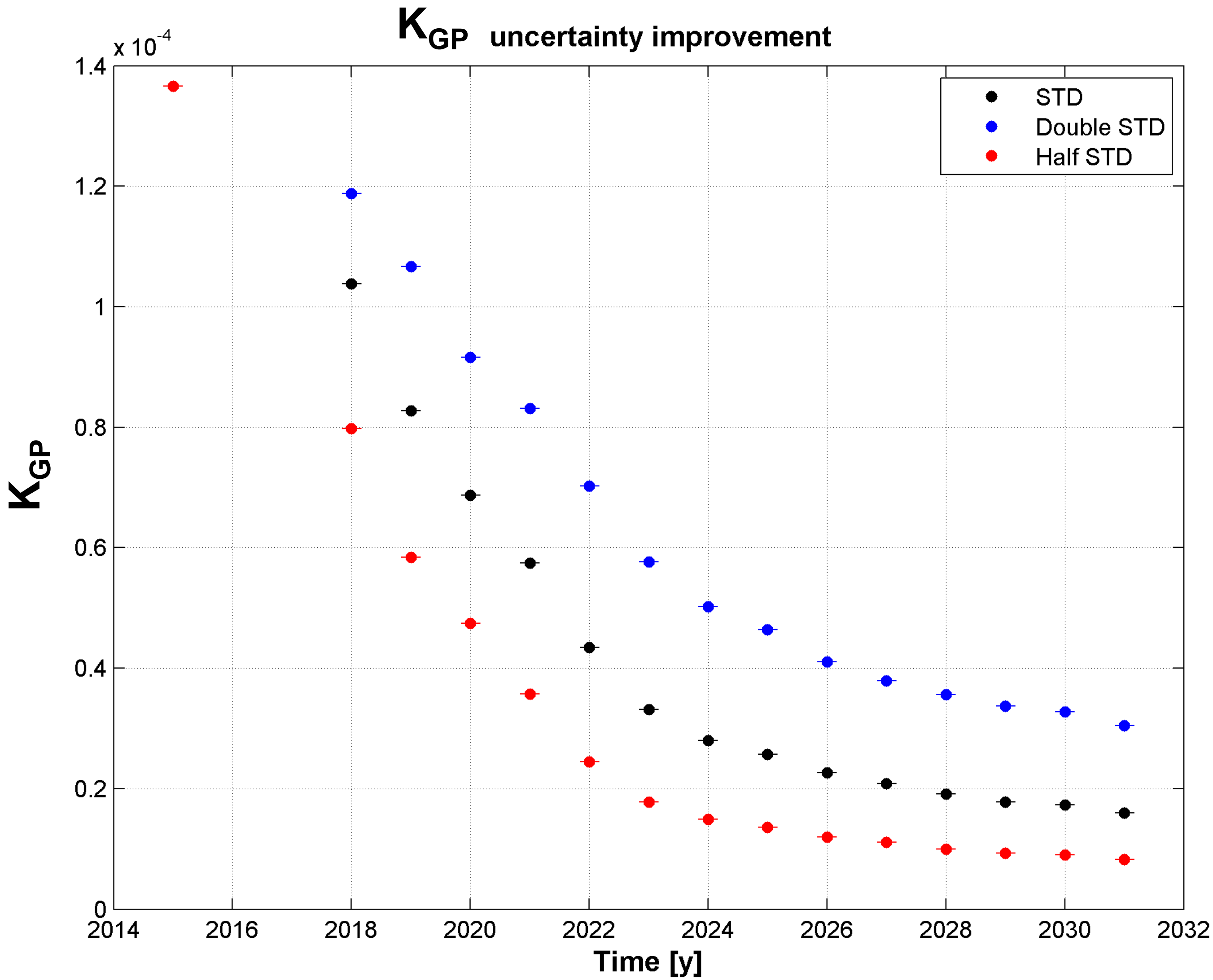
Sim … 2018)
usin … okhod

CCR Arr…	…	Accuracy
Apollo + Lun…		0,5 cm
		1,0 cm
MoonLIG… with and wi… Sun Shad…		0,1 cm
		0,2 cm

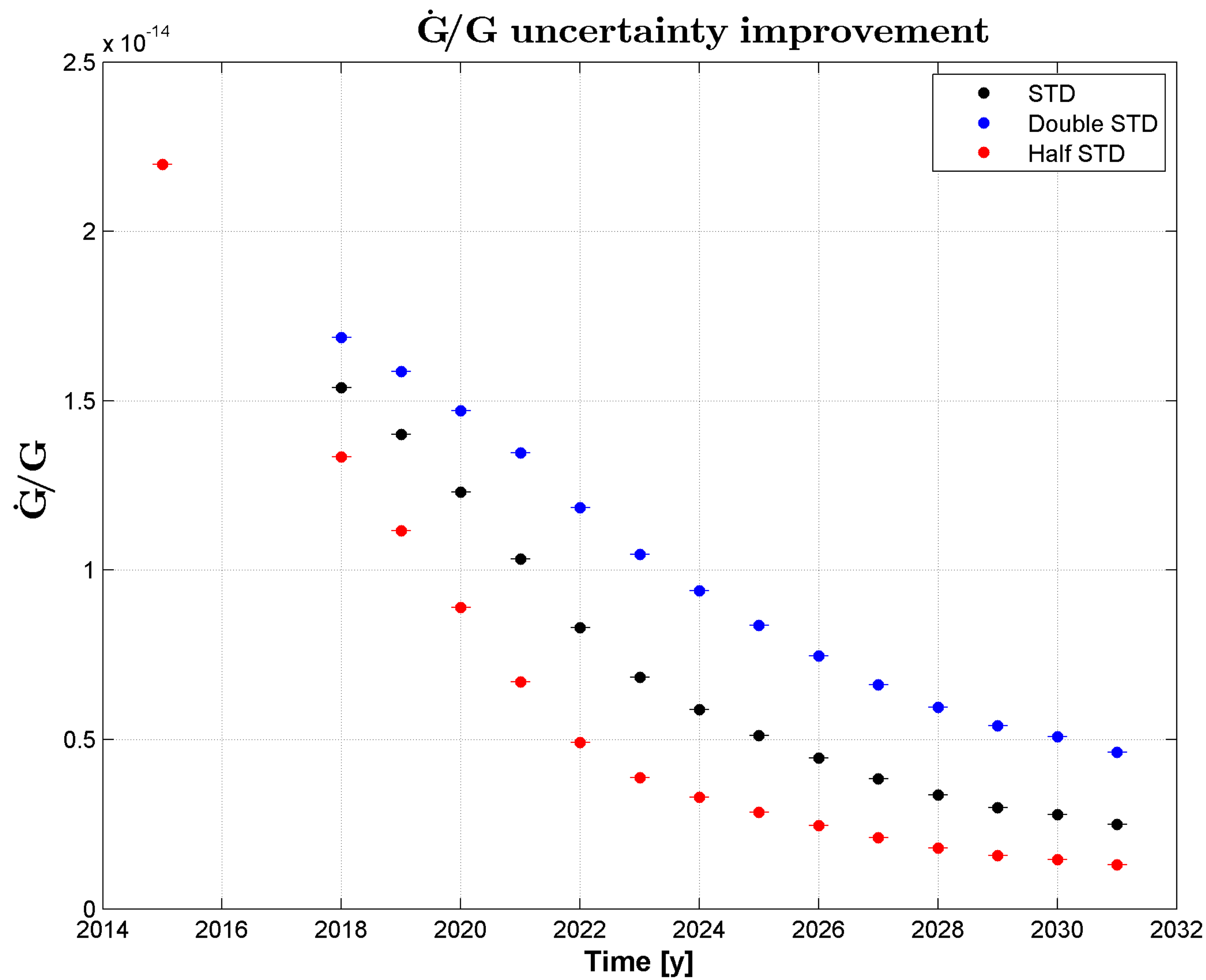


➢ **GR tests** …
- 4 MoonLI… …r Apollo/ Lunokhod…
- 15 years …
- Accuracy …
- 3 different… ….

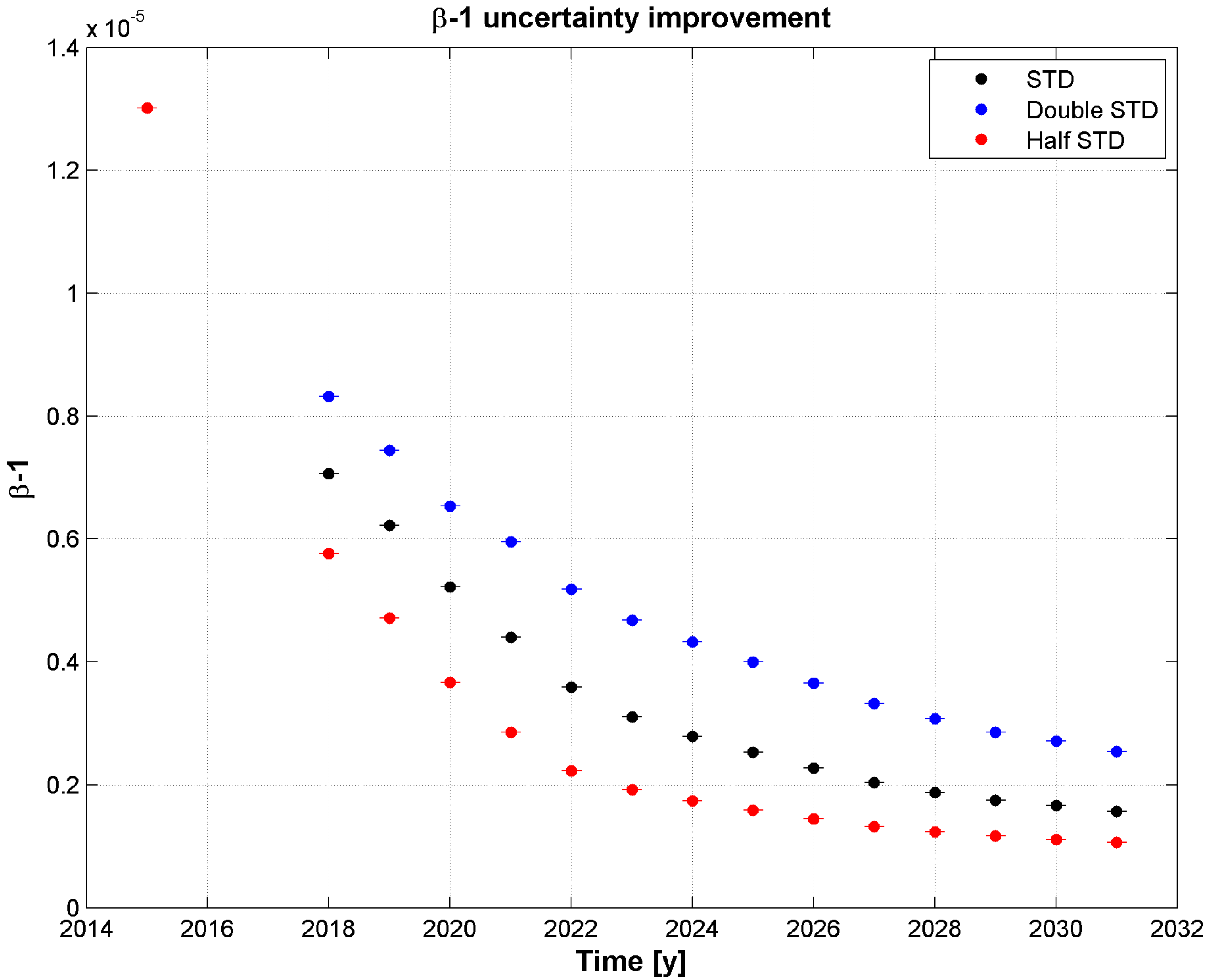
GR test improvement: Simulated observations



GR test improvement: Simulated observations



GR test improvement: Simulated observations

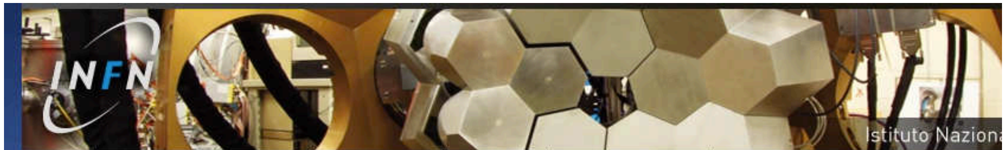


Results

- We, in Italy, developed new reflectors, and we have agreements for new lunar missions to deploy them
- Using simulation by PEP *as-is* we will improve the test of General Relativity by a factor ~10 with new reflectors and new missions (not including improved stations/software)
  - *Lots of new data from new reflectors/missions WILL HELP improve PEP*
  - *Improvement of PEP software (better modeling of effect included in PEP, addition of effects not yet implemented) will follow the improvement due to new reflectors.*

Precision test of violation of GR	Improvement STD	Improvement H-STD
Time Variation of the Gravitational Constant	× 8.8	× 16.9
Geodetic Precession	× 8.6	× 16.6
Parametrized Post-Newtonian, β	× 8.2	× 12.3

Fly me to the Moon…and beyond



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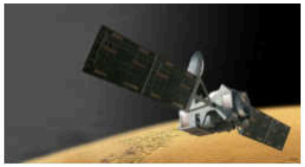
EXOMARS, A BORDO NUOVO STRUMENTO ITALIANO TARGATO ASI E INFN

Pubblicato Mercoledì, 28 Ottobre 2015



In attesa di vedere il primo uomo saltellare sulla polvere
prepara a sbarcare sul Pianeta Rosso, nel 2016, con la
dell'*European Space Agency* (ESA). Una missione in cui l'I
si arricchisce ulteriormente in questi giorni. Sale, infatti, a
INRRI (*INstrument for landing-Roving laser Retroreflecto*
Spaziale Italiana (ASI) e dell'Istituto Nazionale di Fisica Nu
la supervisione scientifica di Simone Dell'Agnello, fisico
Frascati (LNF) dell'INFN.

Dopo aver superato con successo tutti i test previsti, lo strumento è stato consegnato a tempo di record
sul modulo di discesa marziano ExoMars EDM (*Entry, descent and landing Demonstrator Module*) batte
dell'astronomo italiano Giovanni Schiaparelli, che disegnò la prima mappa del Pianeta Rosso. INRRI dive
passivo sulla superficie marziana e il primo oltre la Luna. Dovrebbe inoltre essere l'antesignano di una se
futuri Lander o Rover, che assieme formeranno un *Mars Geo/physics Network* (MGN): una rete di punt
geodesia di Marte e test di Relatività Generale. A lungo termine, MGN potrebbe diventare una rete di
simile a quella dei retroriflettori laser delle missioni Apollo e Lunokhod sulla Luna.

La missione ExoMars è stata ideata per indagare eventuali tracce di vita, passata o presente, su Marte
lanciato nel mese di marzo del 2016 e, dopo un viaggio di circa 7 mesi, si poserà sulla superficie del Pian

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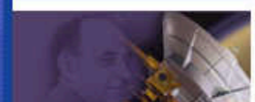

Half a century of italian space missions.
The Space history in Italy since 1964.

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4

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).

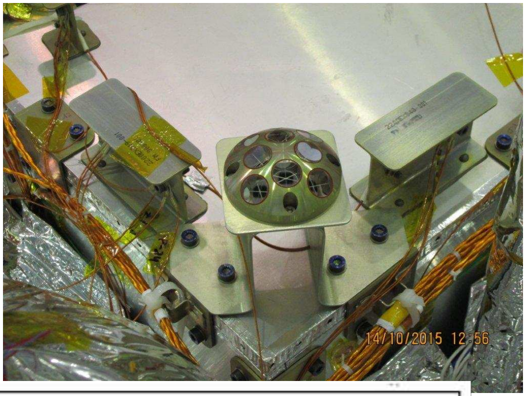
A mission in which Italy is playing a key role that will be becoming increasingly important in the next few days, as the **INRRI** (INstrument for landing-Roving laser Retroreflector Investigations) laser micro-reflector developed by the Italian Space Agency (**ASI**) together with the National Institute 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.

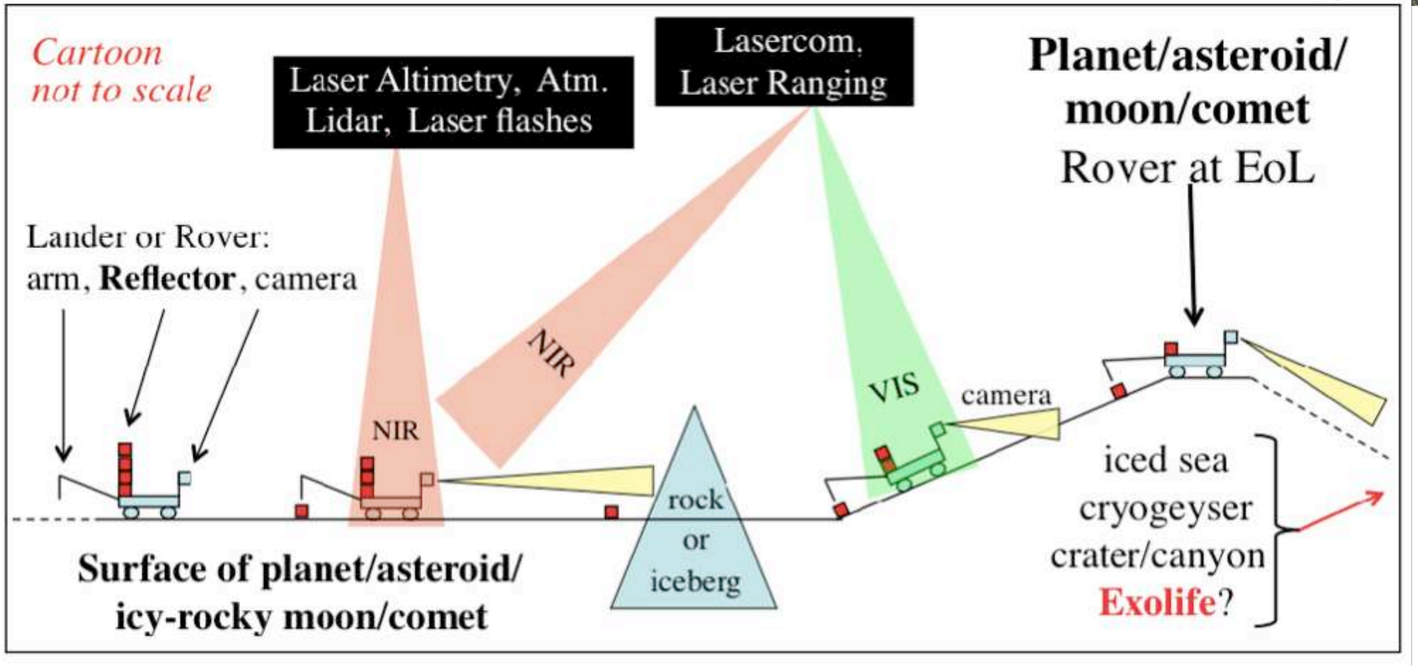
After passing all the necessary tests, the instrument was delivered in record time and has just been installed on the Martian descent module **ExoMars EDM** (Entry, descent and landing Demonstrator Module) named **Schiaparelli** after Italian astronomer Giovanni Schiaparelli, who drew ***the first map***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

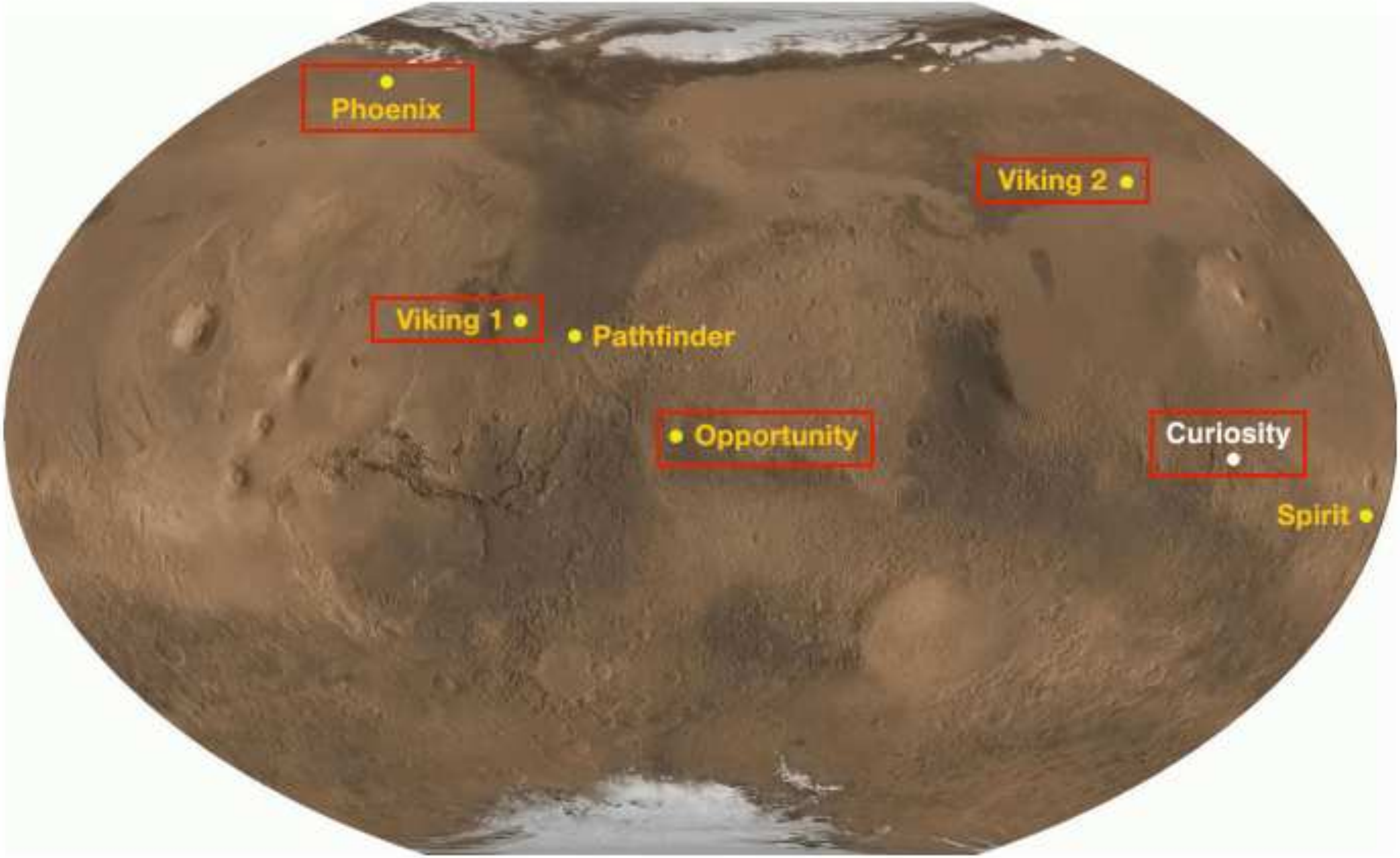
INRRI the first laser retroreflector on Mars



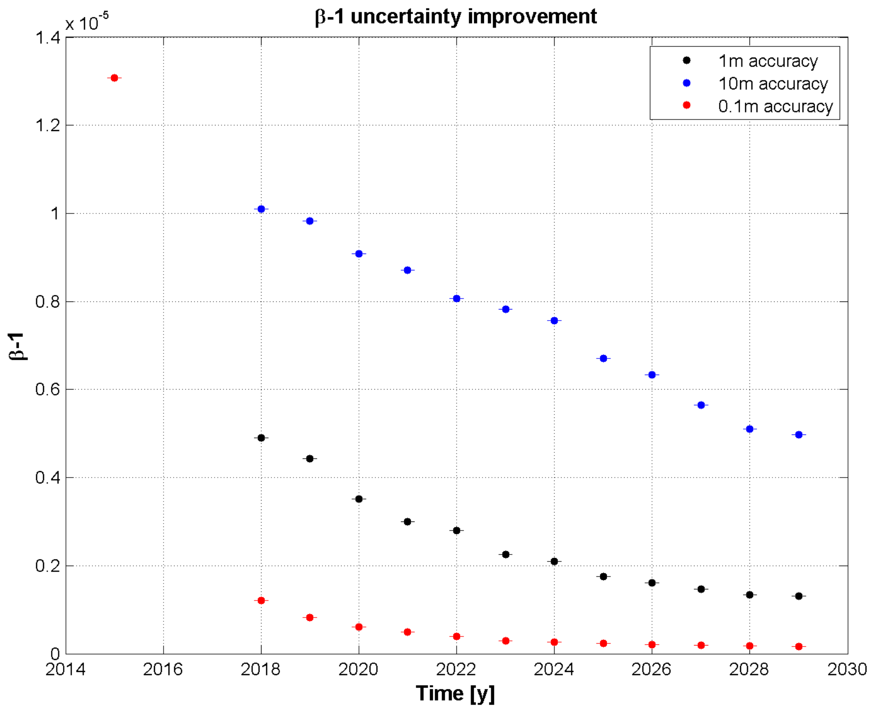


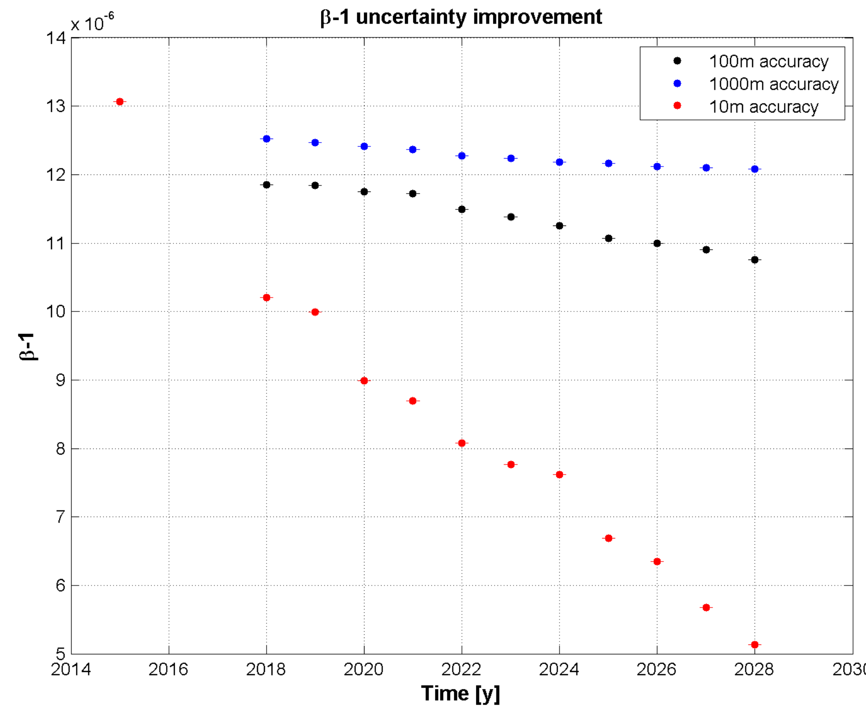
INstrument for landing-**R**oving laser ranging/altimetry **R**etroreflector **I**nvestigations

Simulated observations

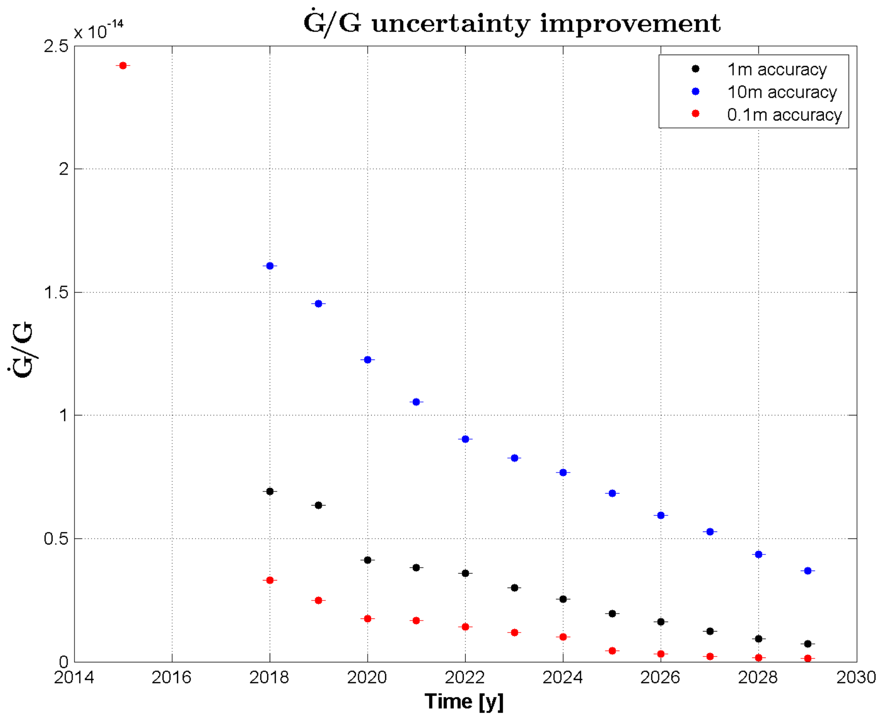


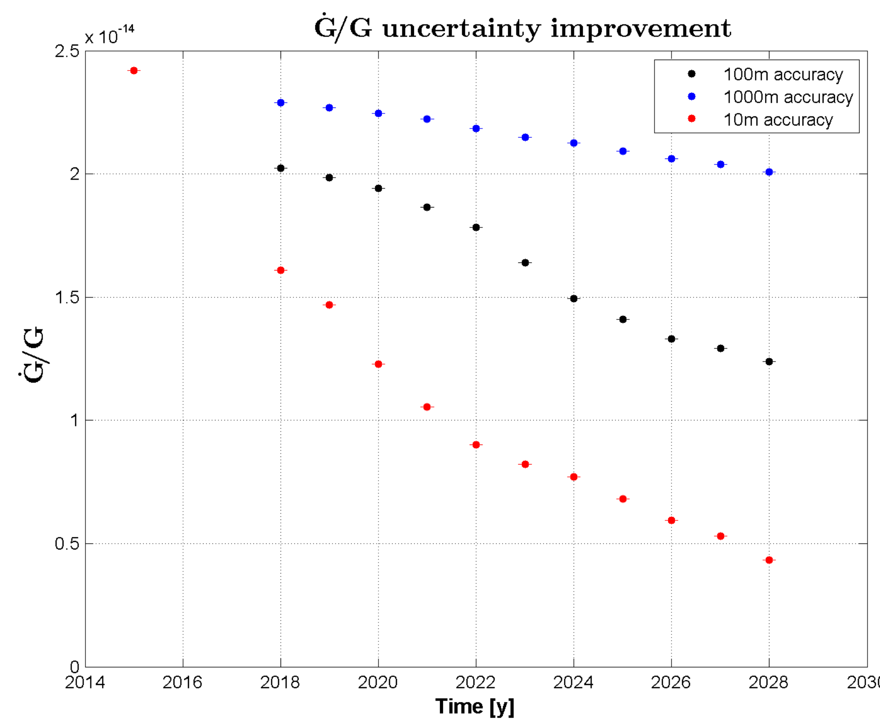
Preliminary Results





Preliminary Results





Conclusions and Prospects

We have developed and built, **MoonLIGHT**, a unique next-generation lunar laser retroreflector payload and validated its performance with a unique facility and an innovative industry-standard laboratory test

The improvements shown by simulations are important and represent the most pessimistic case where we do not consider **LLR station upgrades** or **any software updates**

We are currently simulating INRRI performance for Mars missions of ESA/ASI and NASA. **To the Moon and beyond …**

Further prospects

- Continue to refine our knowledge of data and software to better estimate (and reduce) the measurement uncertainty on geodetic precession, Gdot/G and on other GR parameters.

- After the ExoMARS landing we can also develop future General Relativity tests with Mars.

- We have the option to implement the equations of motion of new gravity theories (like SPACE-TIME TORSION and NON-MINIMALLY COUPLED GRAVITY) inside PEP and study <u>not only the secular variation</u> of the geodetic precession , but also <u>periodic signatures</u> of NEW PHYSICS on the geodetic precession and on other PPN parameters

Publications

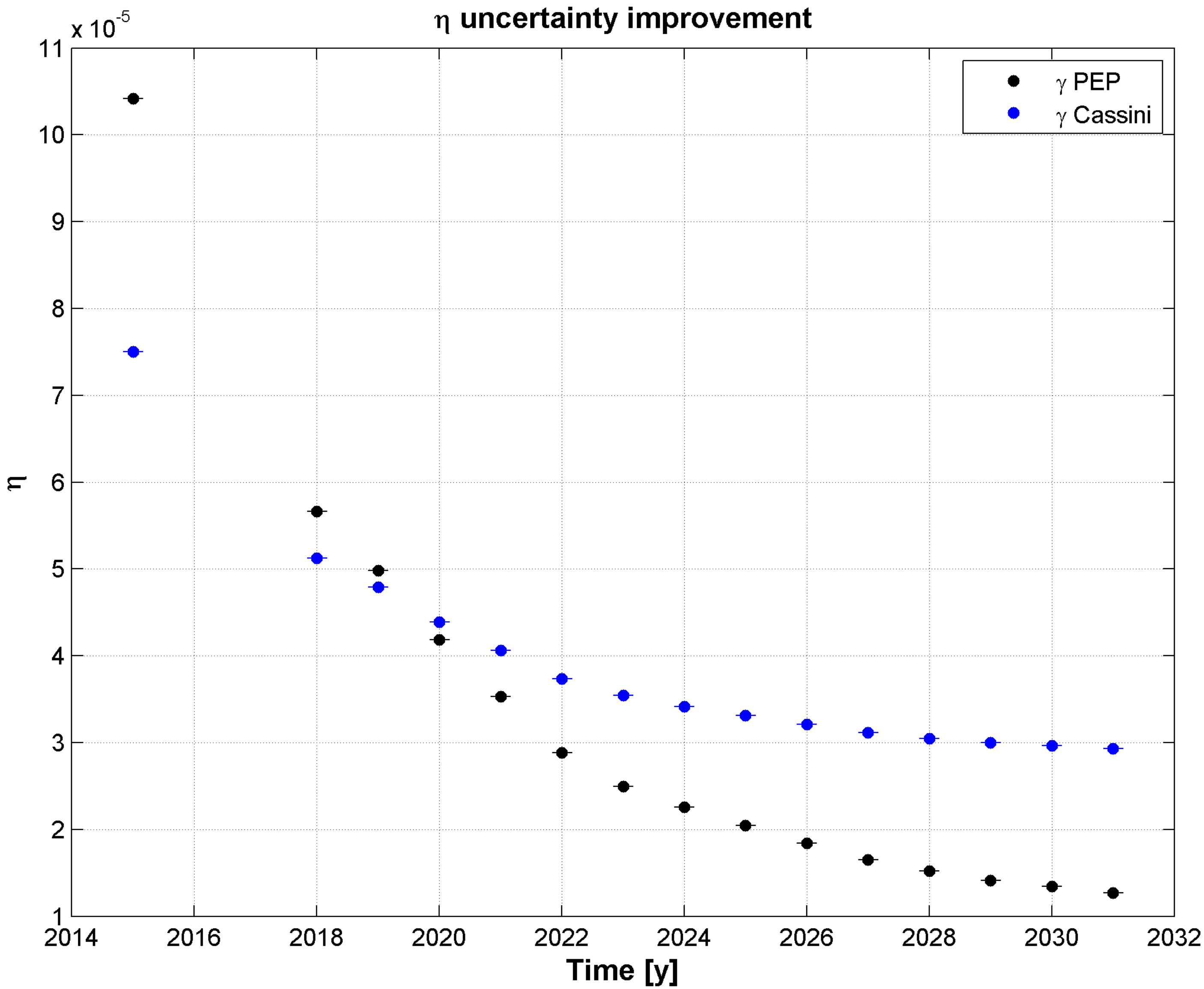
- M. Martini et al, Moonlight: A new lunar laser ranging retroreflector and the lunar geodetic precession, *Acta Polytechnica* **53**(Supplement):746–749, 2013, DOI: 10.14311/AP.2013.53.0746
- M. Martini et al, MoonLIGHT: A USA–Italy lunar laser ranging retroreflector array for the 21st century, Planetary and Space Science 74 (2012) 276–282.
- M. Martini et al, Laser ranging positioning metrology for Galileo and the Moon, Metrology for Aerospace, 2015 IEEE, DOI: 10.1109/MetroAeroSpace. 2015.7180630
- S. Dell'Agnello et al, Advanced Laser Retroreflectors for Astrophysics and Space Science, *Journal of Applied Mathematics and Physics*, 3, 218-227, 2015
- M. Martini and S. Dell'Agnello, Probing gravity with next generation lunar laser ranging, Chapter in the book: R. Peron et al. (eds.), *Gravity: Where Do We Stand?*, DOI 10.1007/978-3-319-20224-2_5, Springer International Publishing, Switzerland, 2016.
- INRRI-EDM/2016: the first laser retroreflector on the surface of Mars, submitted to *Advances in Space Research, 2016*
- *M. Martini et al, PRL* in preparation

THANK YOU
FOR YOUR ATTENTION

ANY COMMENTS/QUESTIONS?

SPARES

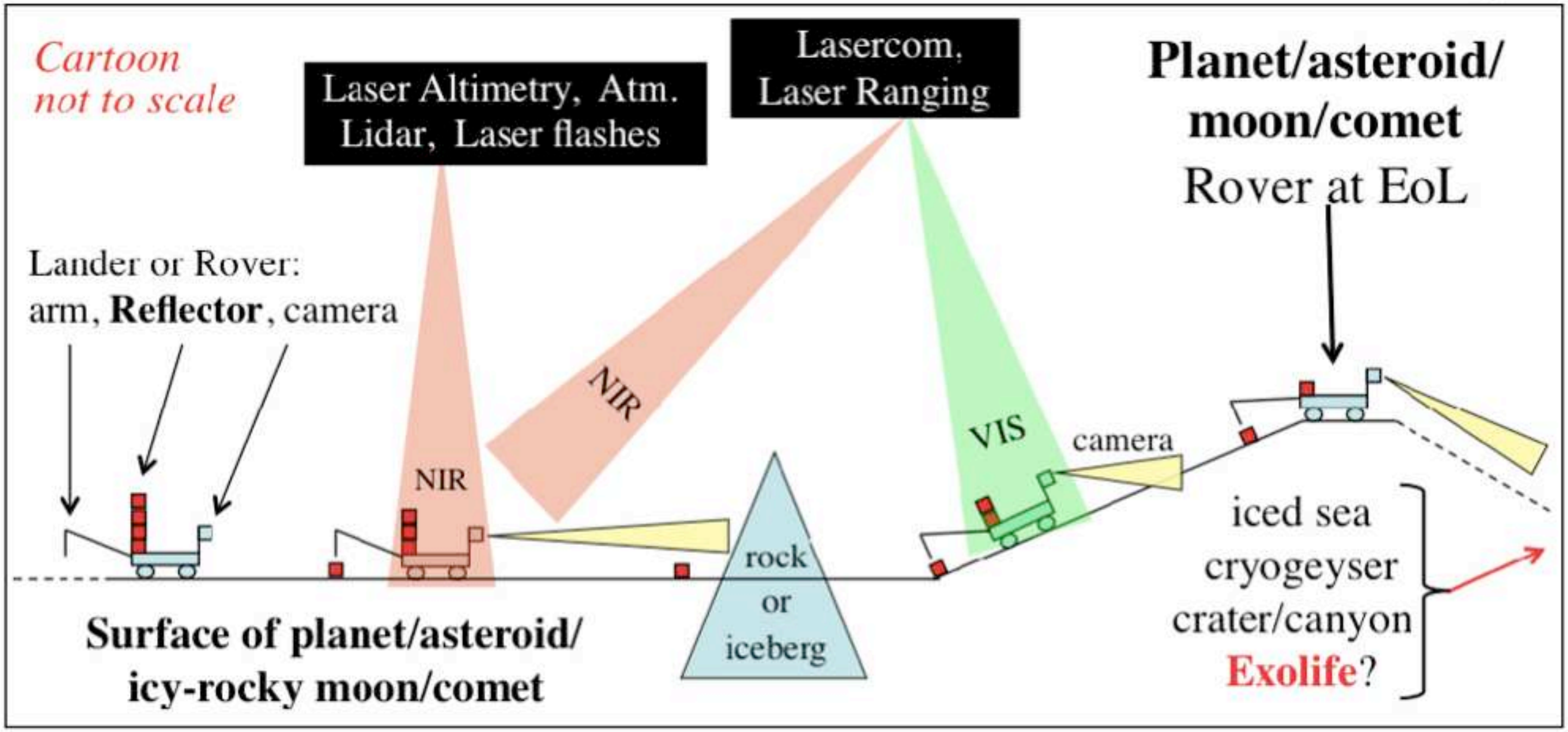
GR test improvement: Simulated observations



INRRI

INstrument for landing-**R**oving laser ranging/altimetry **R**etroreflector **I**nvestigations

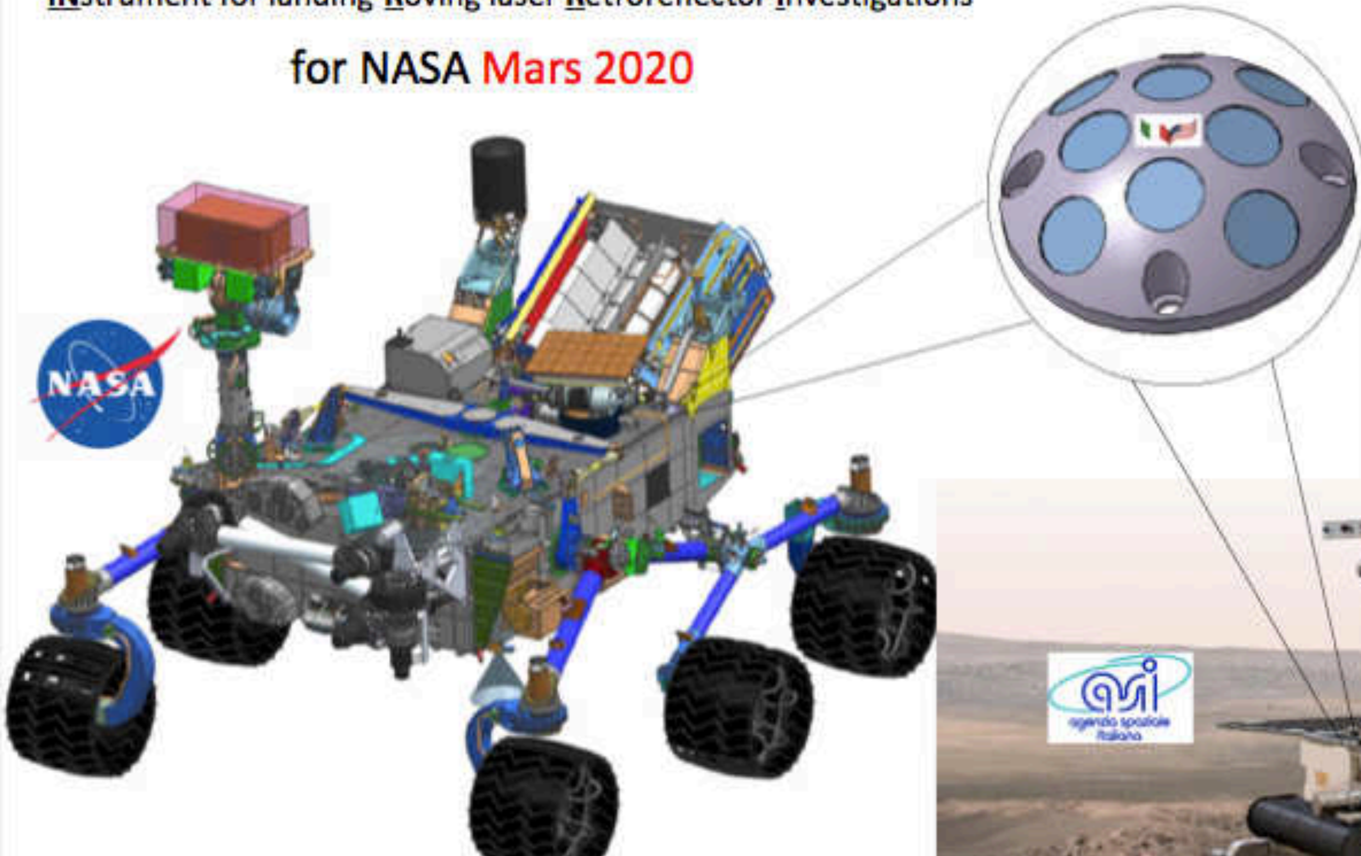
Microreflector: Passive: 25 gr; Compact: 54 mm × 20

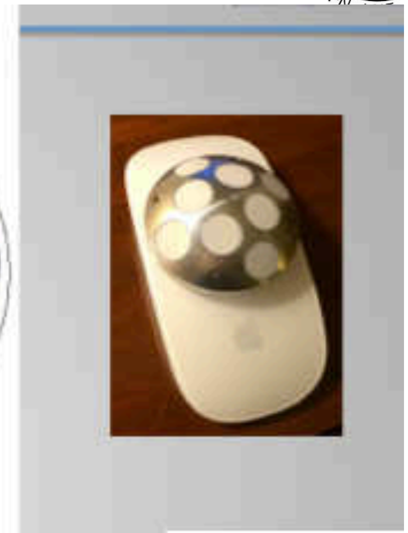


Next steps

INRRI-2020:
INstrument for landing-Roving laser Retroreflector Investigations

for NASA Mars 2020





25 grams
Smaller than a computer mouse