MoonLIGHT: a new Lunar Laser Ranging Retroreflector and the lunar geodetic precession

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For the SCF_LAB Team

Vulcano Workshop 2012

Outline

Introduction:

- Science with Satellite/Lunar Laser Ranging
- Test of General Relativity

Experimental work:

- LLRRA21/MoonLIGHT experiment of INFN
  - SCF-Test @ INFN-LNF

Data analysis:

- Determination of K_{GP}
- Conclusions and future prospects

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Introduction

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Satellite Laser Ranging (SLR)
Lunar Laser Ranging (LLR)
Time of flight measurement

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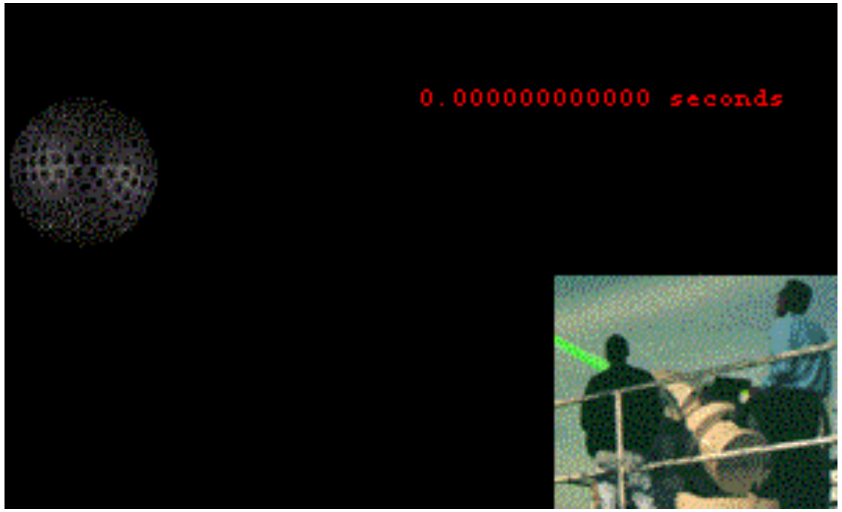
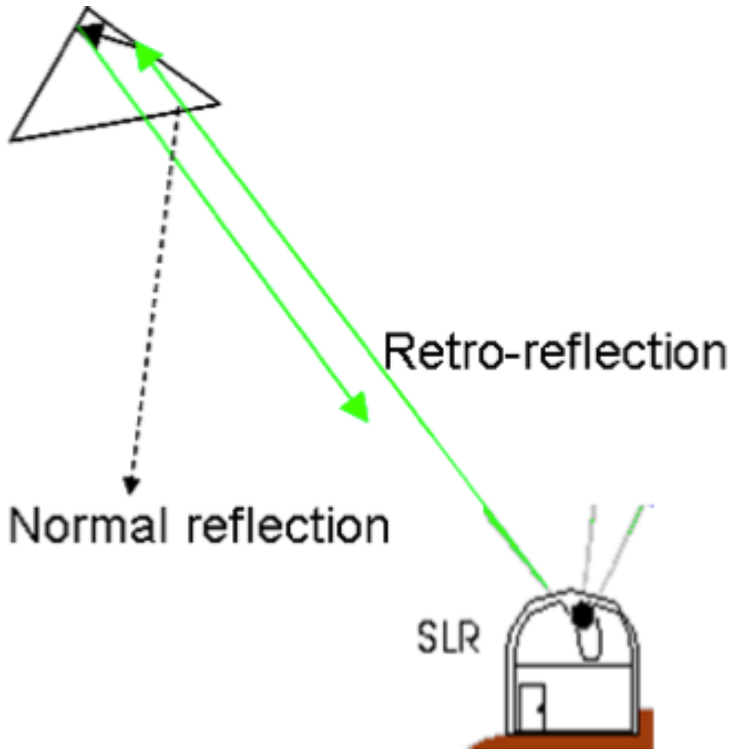
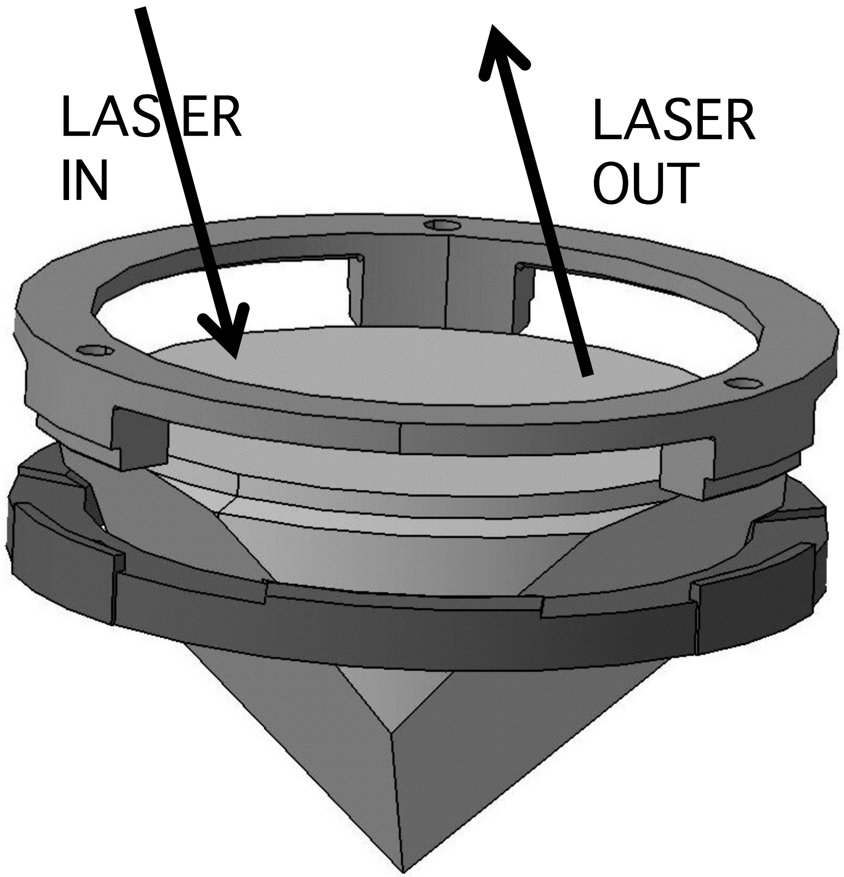
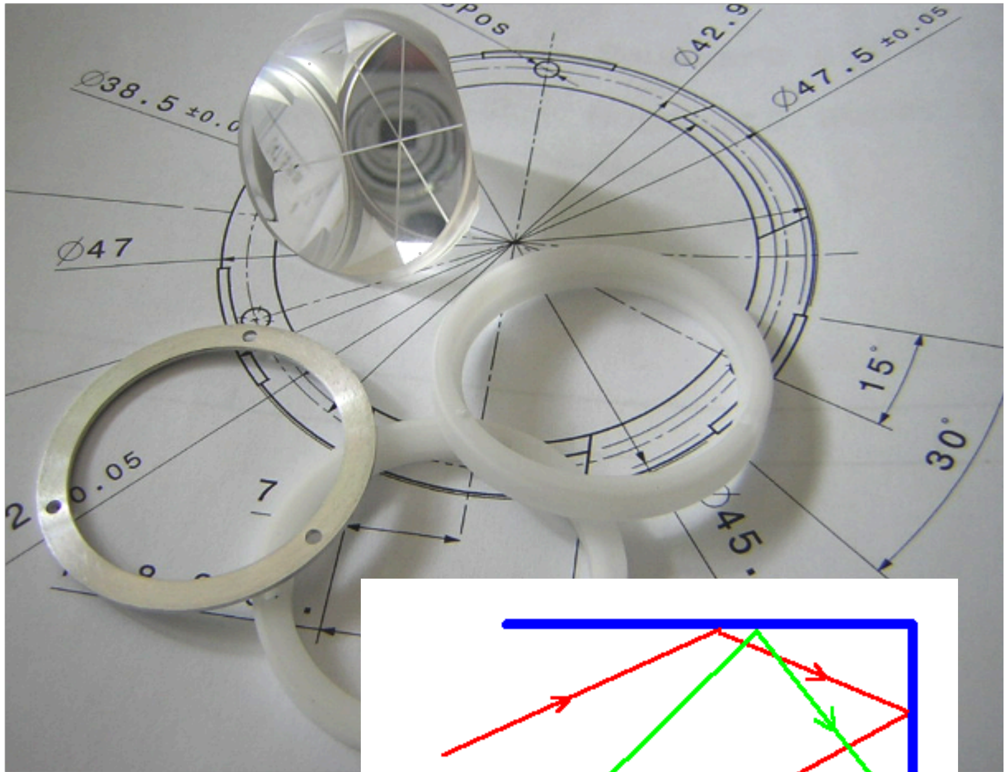


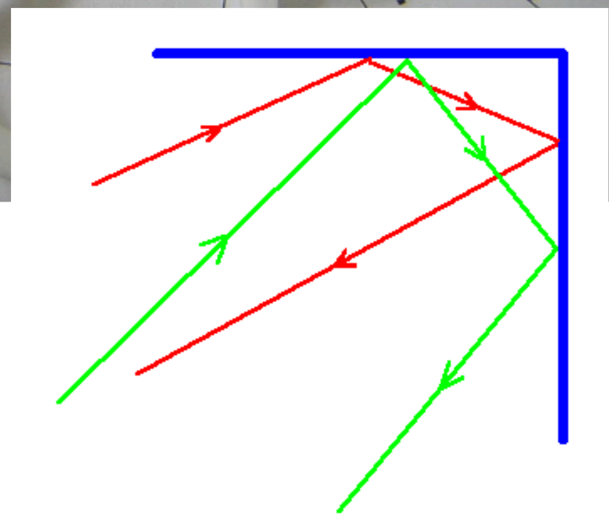


- The Moon as a test mass (1969+, Alley, Bender, **Currie**, Faller …)
- LAGEOS: "cannon-ball", point-like test-masses covered with laser retro-reflectors (raw orbit accuracy < 1 cm)

Corner Cube Retroreflector







Lunar Laser Ranging

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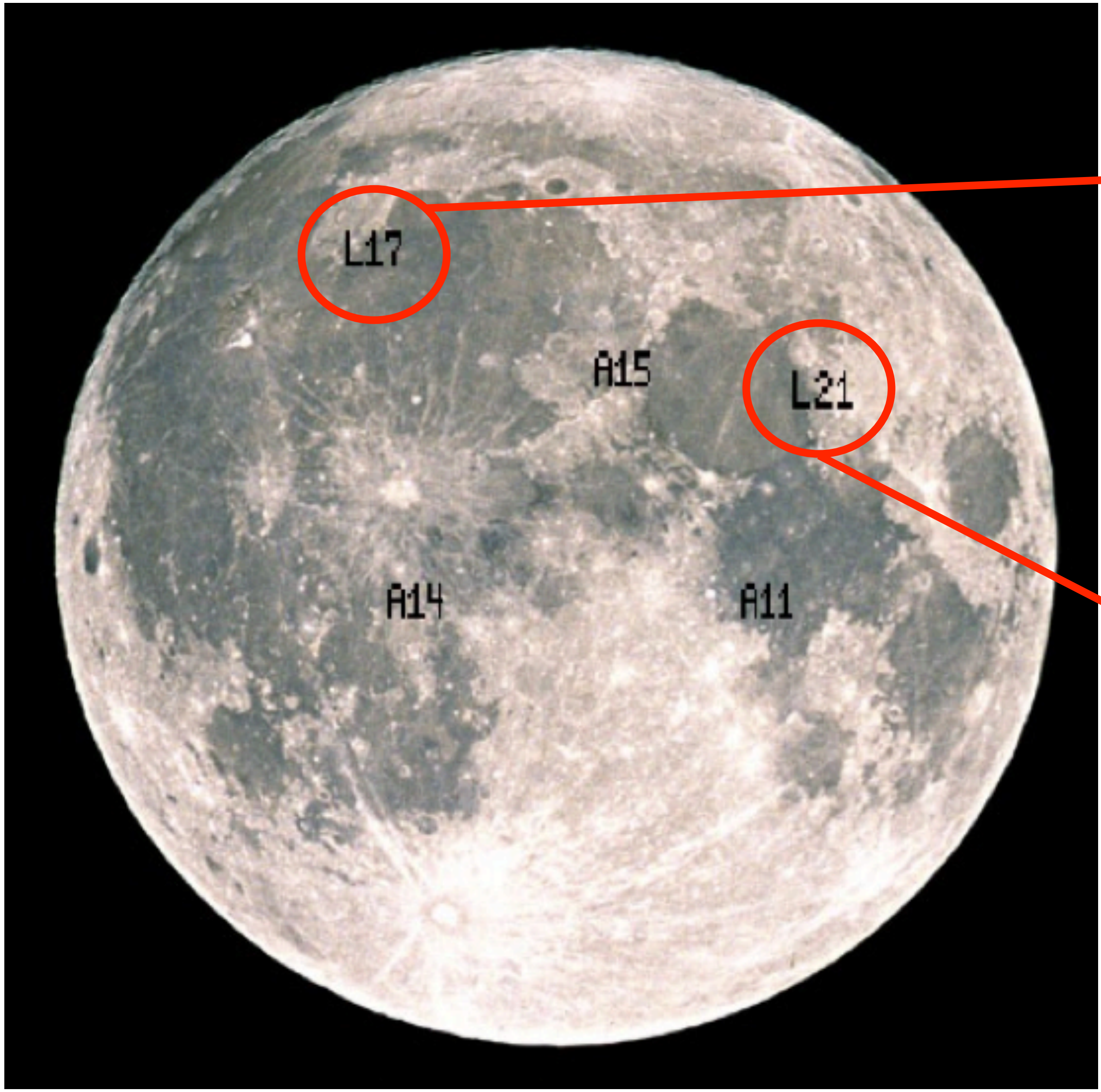
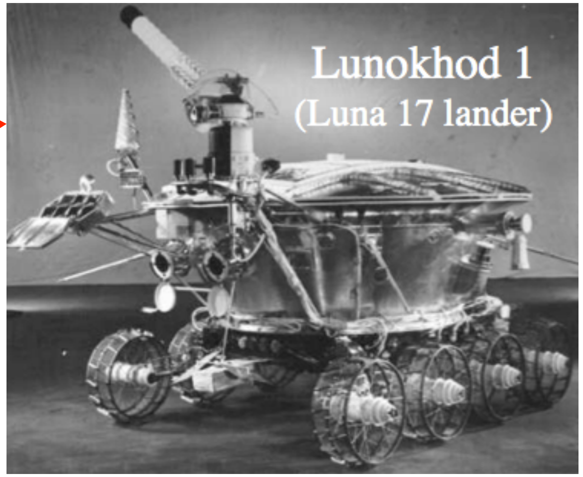
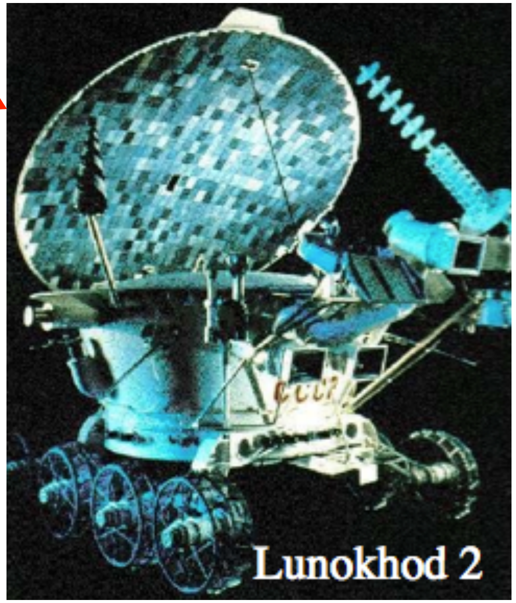
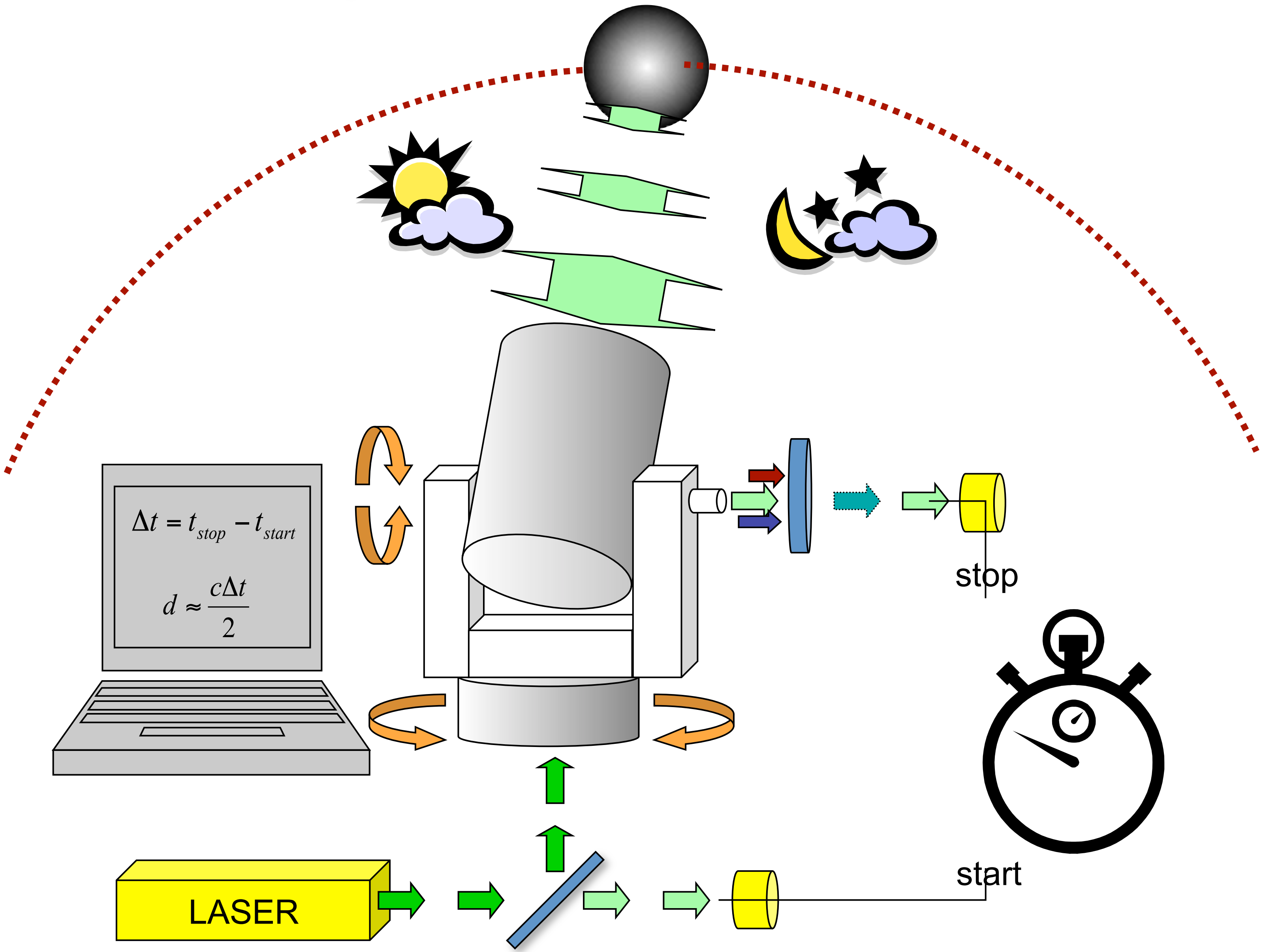






LLR/SLR concept: Laser, receiving telescope; time of flight



Science with LLR

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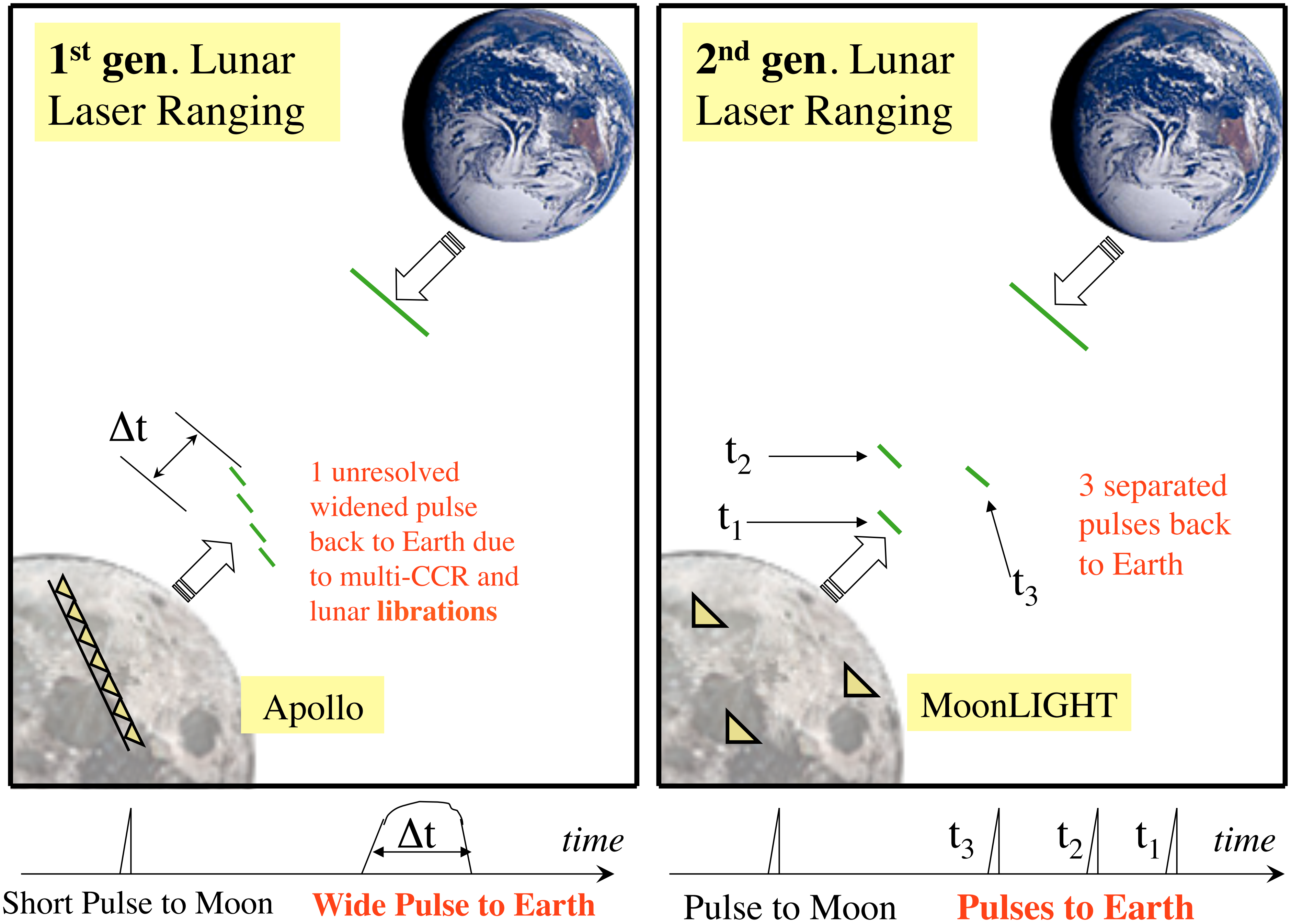
- Lunar geophysics
  - Librations, tides
- Towards an International Moon Reference Frame
  - Concept proposed of the LNF group
  - Apollo/Lunokhod + ANY lander, or rover, with radio-beacon and/or laser retroreflector
  - For lunar surface exploration and colonization
  - Analogous of the ITRF (International Terrestrial Reference Frame)
- Precision test of General Relativity
  - GR verified by many solar system experiments
  - But not the final theory, because it has unexplained singularities and cannot be unified with Quantum mechanics

Tests of General Relativity

- Measurement of relativistic geodetic precession of lunar orbit, a true three-body effect (3m ± 1.9 cm)/orbit
- Violation of Weak and Strong Equivalence Principle (WEP/SEP)
- Through SEP: Parametrized Post-Newtonian (PPN) parameter β, measures the non-linearity of gravity
- Time variation of universal gravitational constant G
- Tests of inverse square law ($1/r^2$)


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

LLR tests of General Relativity

Improvement in LLR efficiency and precision can only come from single large retroreflectors.

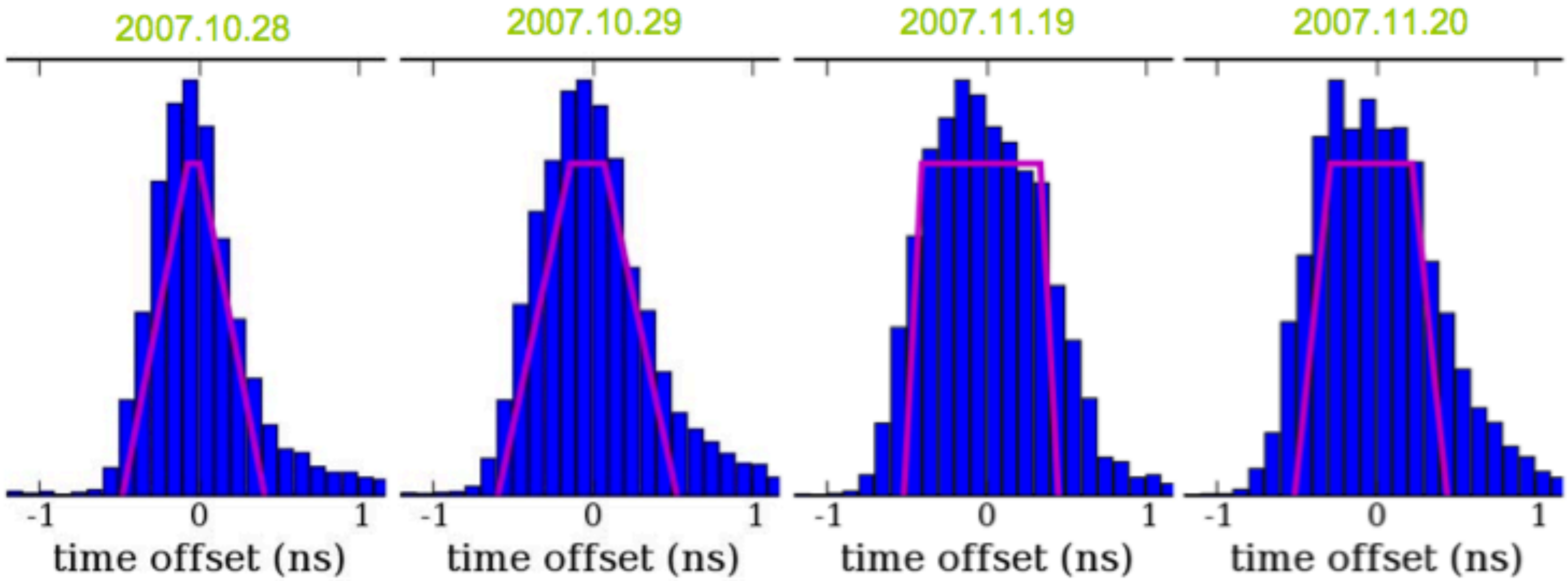
Efficiency (# returns to make a normal point) of single/large reflector is larger by factor of a few thousands with respect to the multi-CCR Apollo/Lunokhod arrays

Science measurement / Precision test of violation of General Relativity	Time scale	Apollo/Lunokhod few cm accuracy*	Single Reflectors 1 mm	Single Reflectors 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}

* J. G. Williams, S. G. Turyshev,and D. H. Boggs, PRL 93, 261101 (2004)

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 several centimeters. Because the libration tilt, the arrays increase the dimension of the LLR pulse coming back to the Earth.

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Experimental Work

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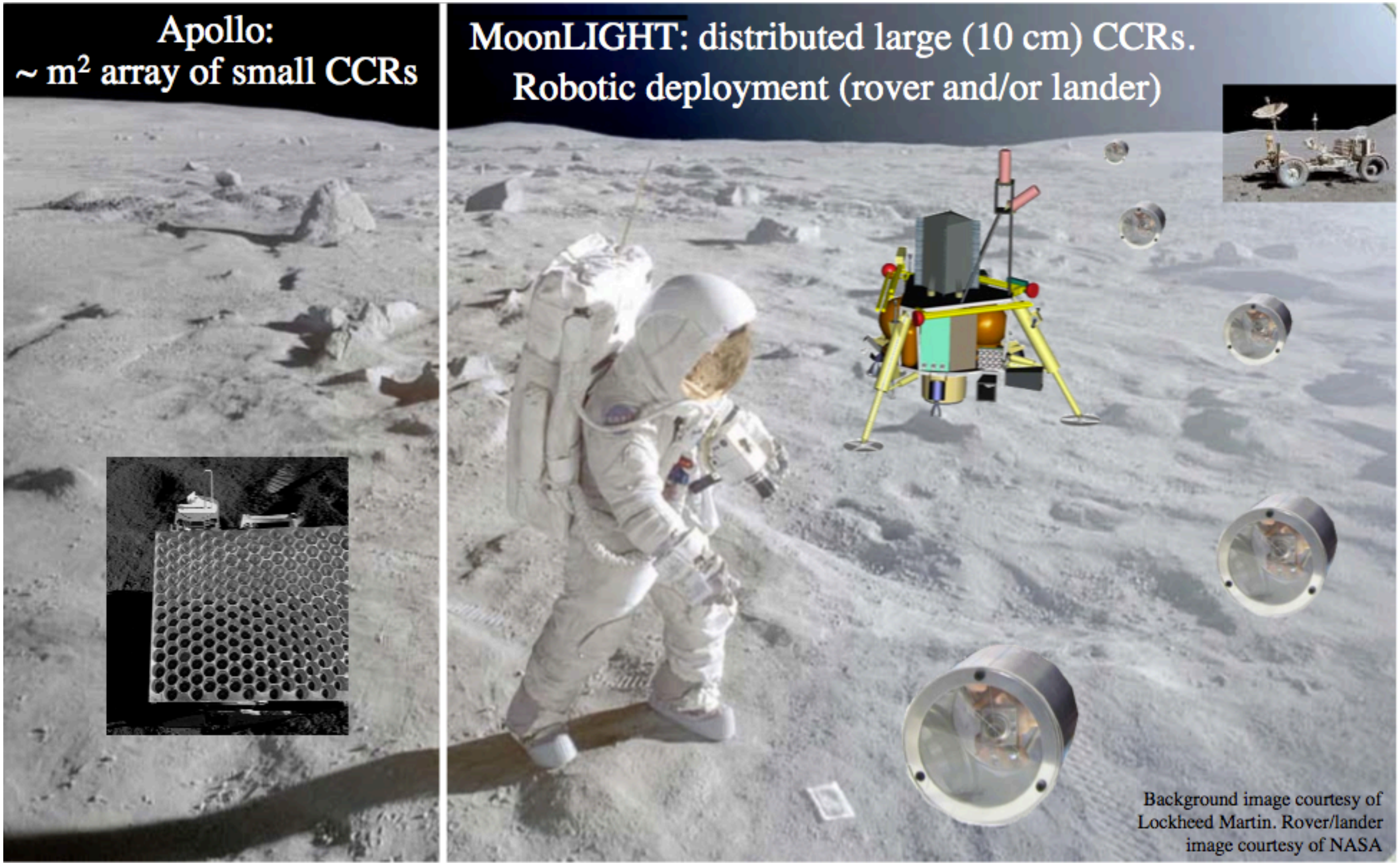
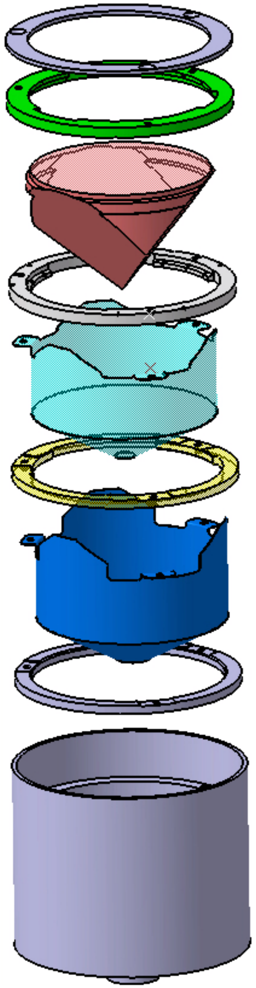
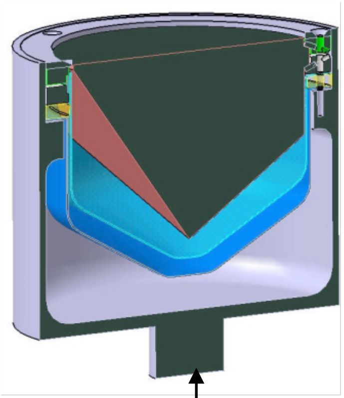
LLRRA21/MoonLIGHT

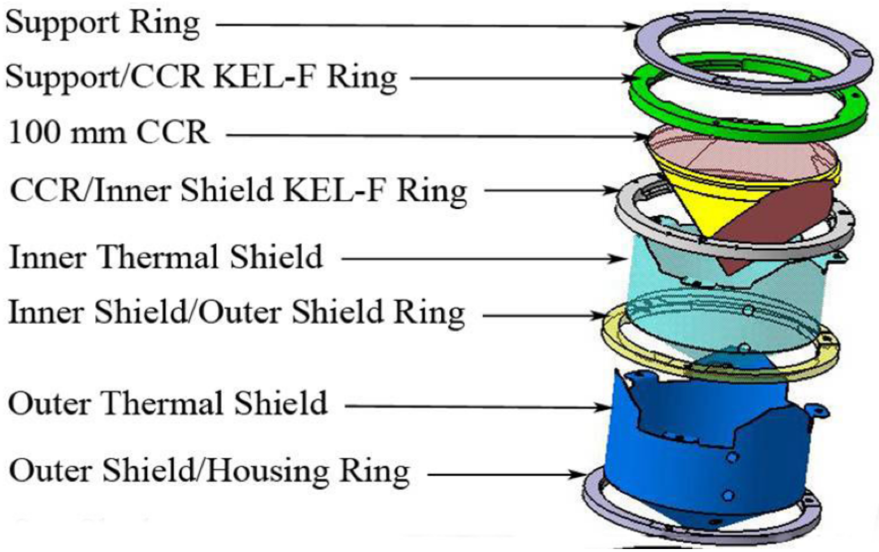


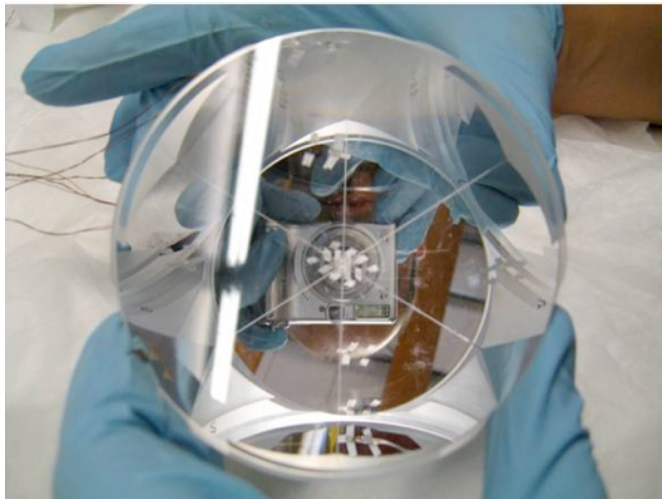
LLRRA21/MoonLIGHT





Threaded hole to deploy P/L on lander, rover, orbiter (or drill bore stem, like used by Apollo astronauts)





LLRRA21/MoonLIGHT

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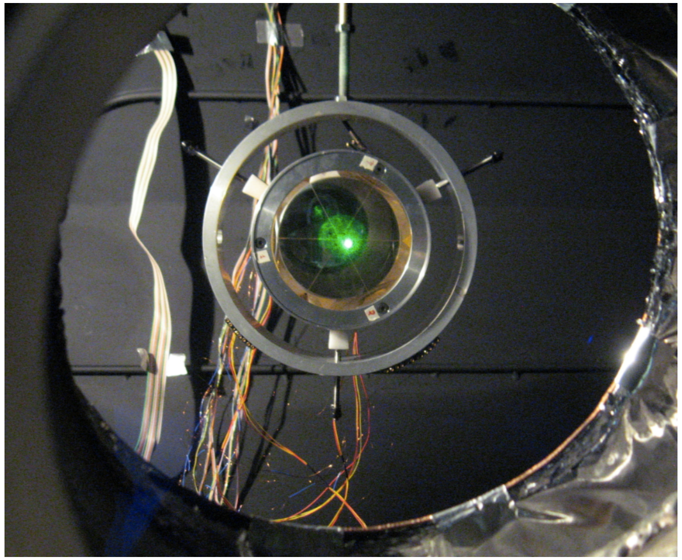
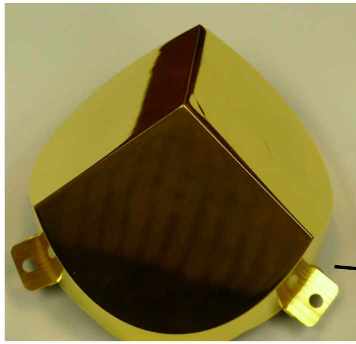
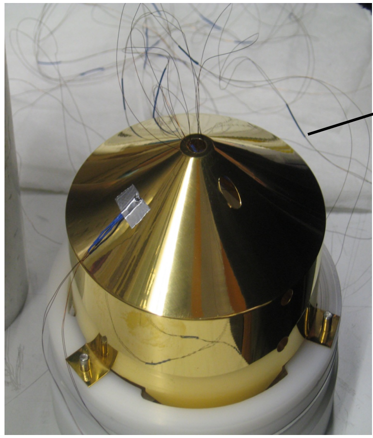
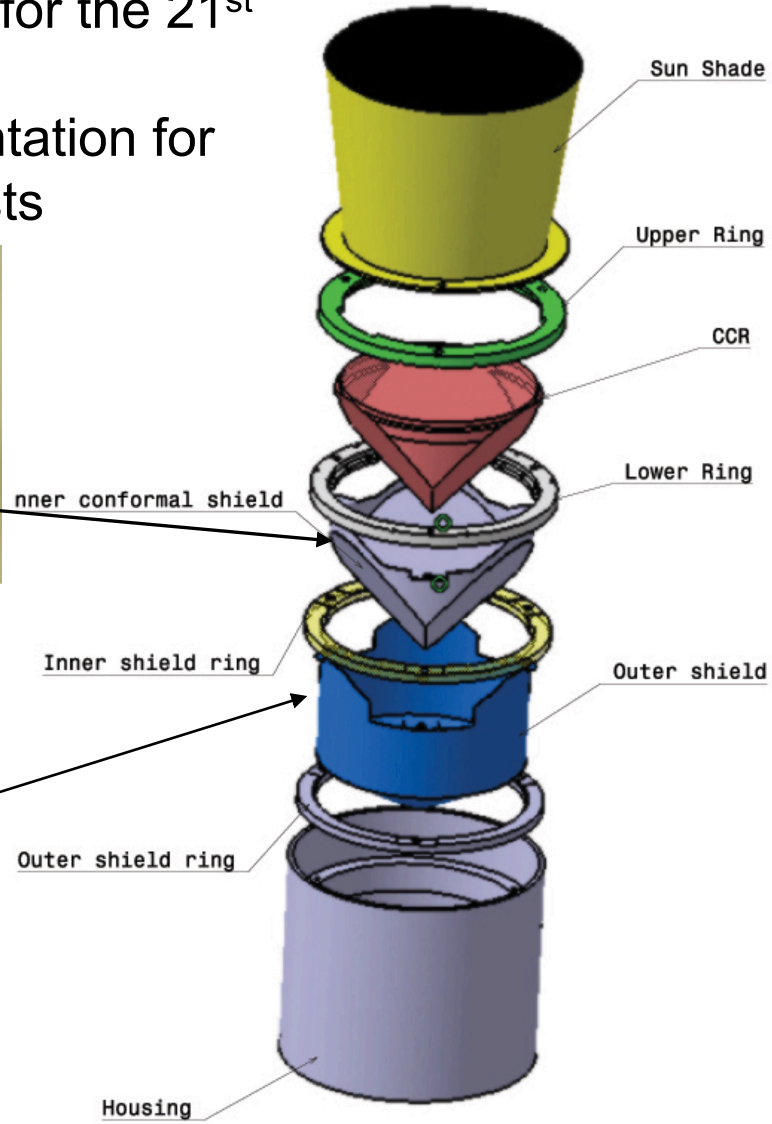
LLRRA21: Lunar Laser RetroReflector Array for the 21st century
MoonLIGHT (INFN): Moon Laser Instrumentation for General relativity High-accuracy Tests

Reflector under test in the "SCF" facility in INFN-LNF, Frascati, Italy









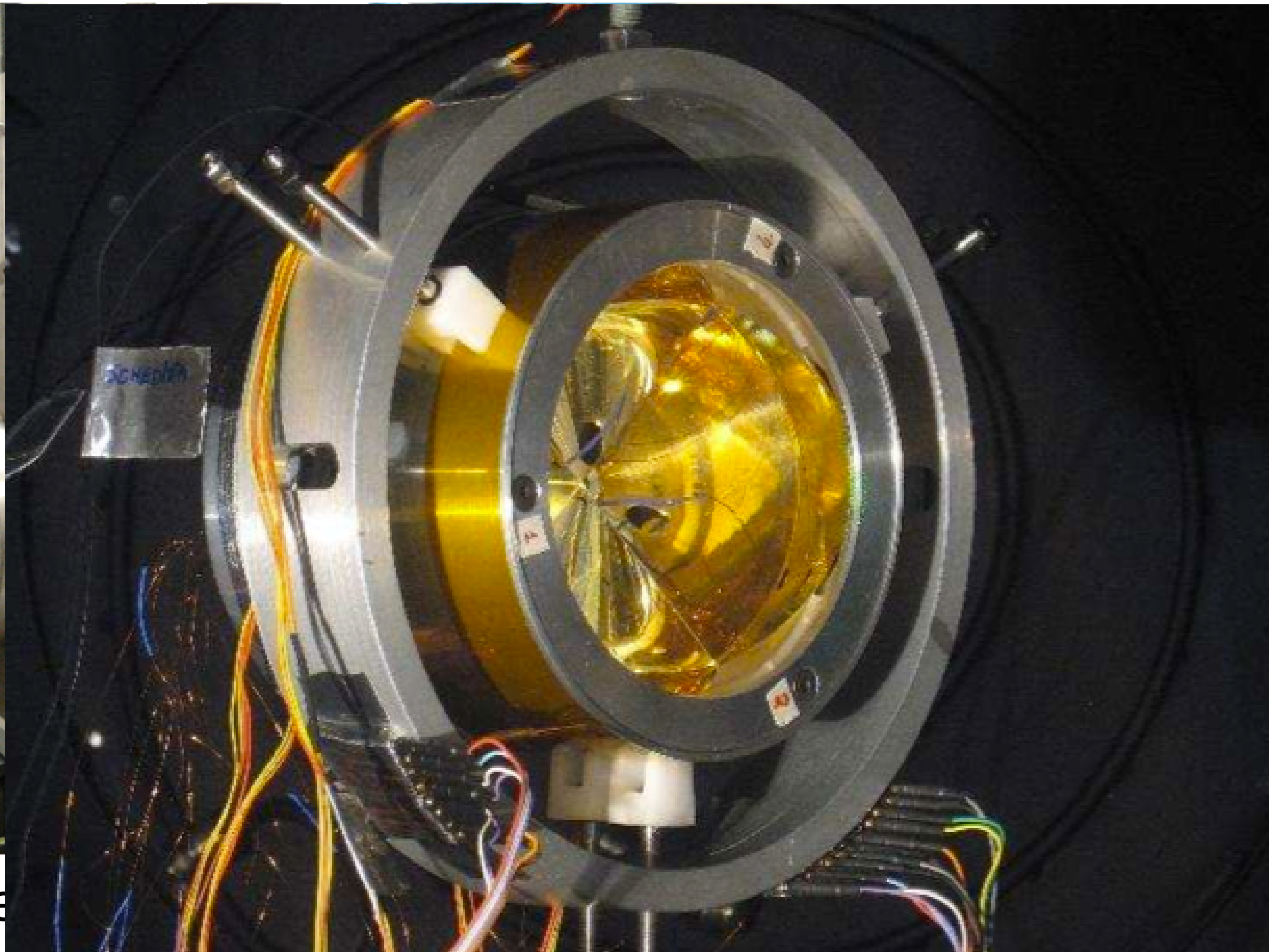
SCF-Test @ INFN-LNF

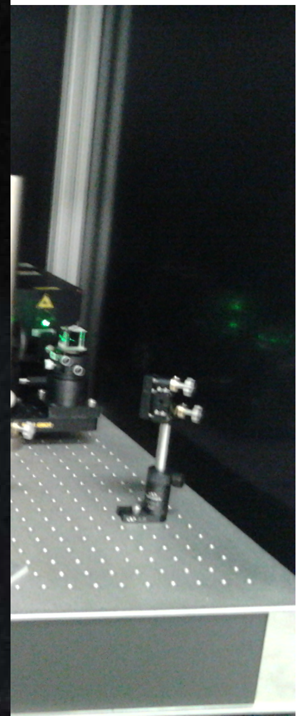
The "SCF-Test" is a new and unprecedented test procedure to characterize and model the detailed thermal behavior and optical performance of LRA in simulated space conditions

For the SCF-test, the CCR with its housing was installed inside the SCF, attached to the rotation positioning system

We heated the CCR with the SS, with the beam orthogonal to the CCR face.
We simulated also an illumination of the Sun at lower elevations, so the CCR was rotated of 30° clockwise and 30° counterclockwise with respect to the SS.

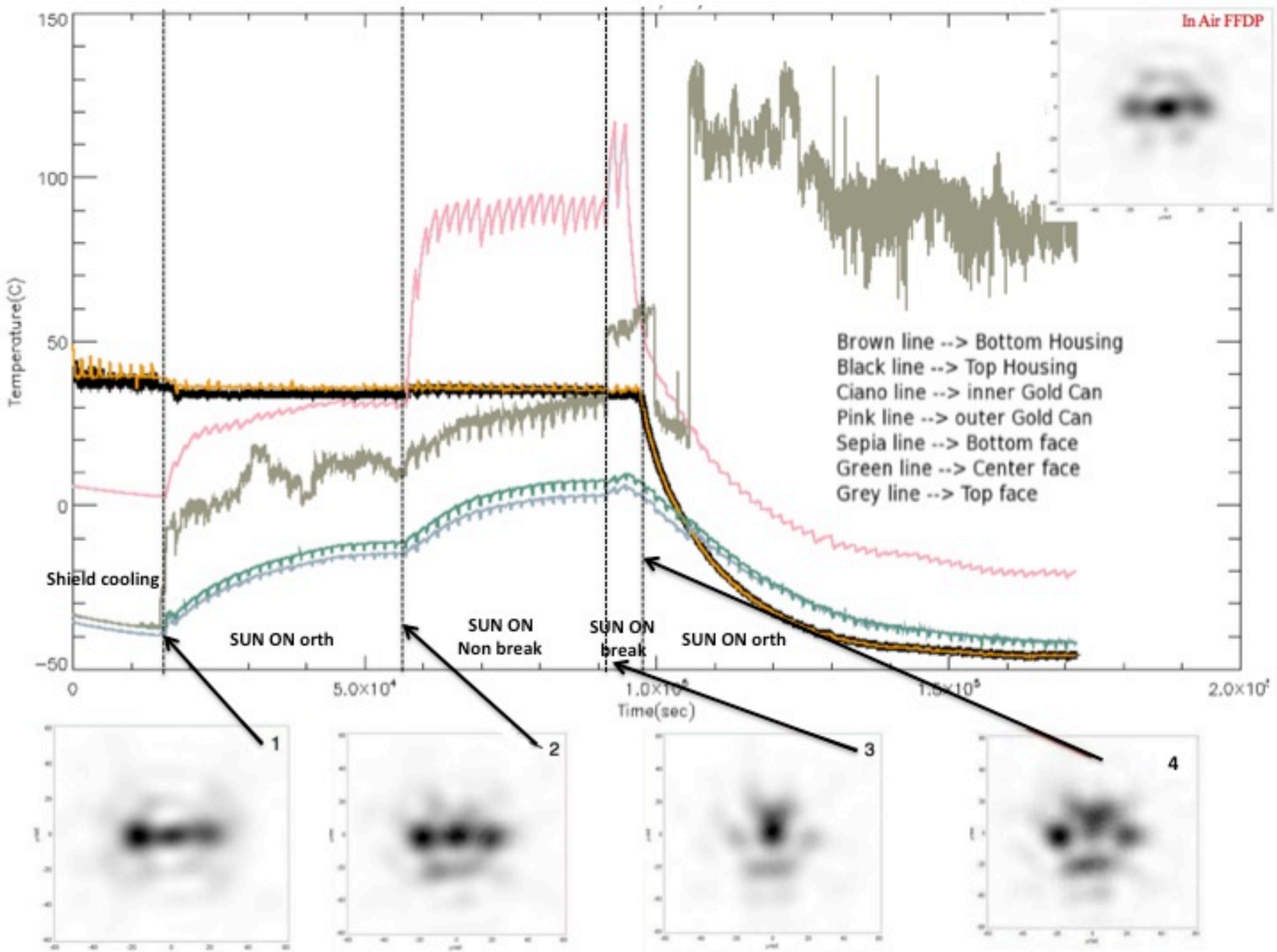
SCF-Test @ INFN-LNF





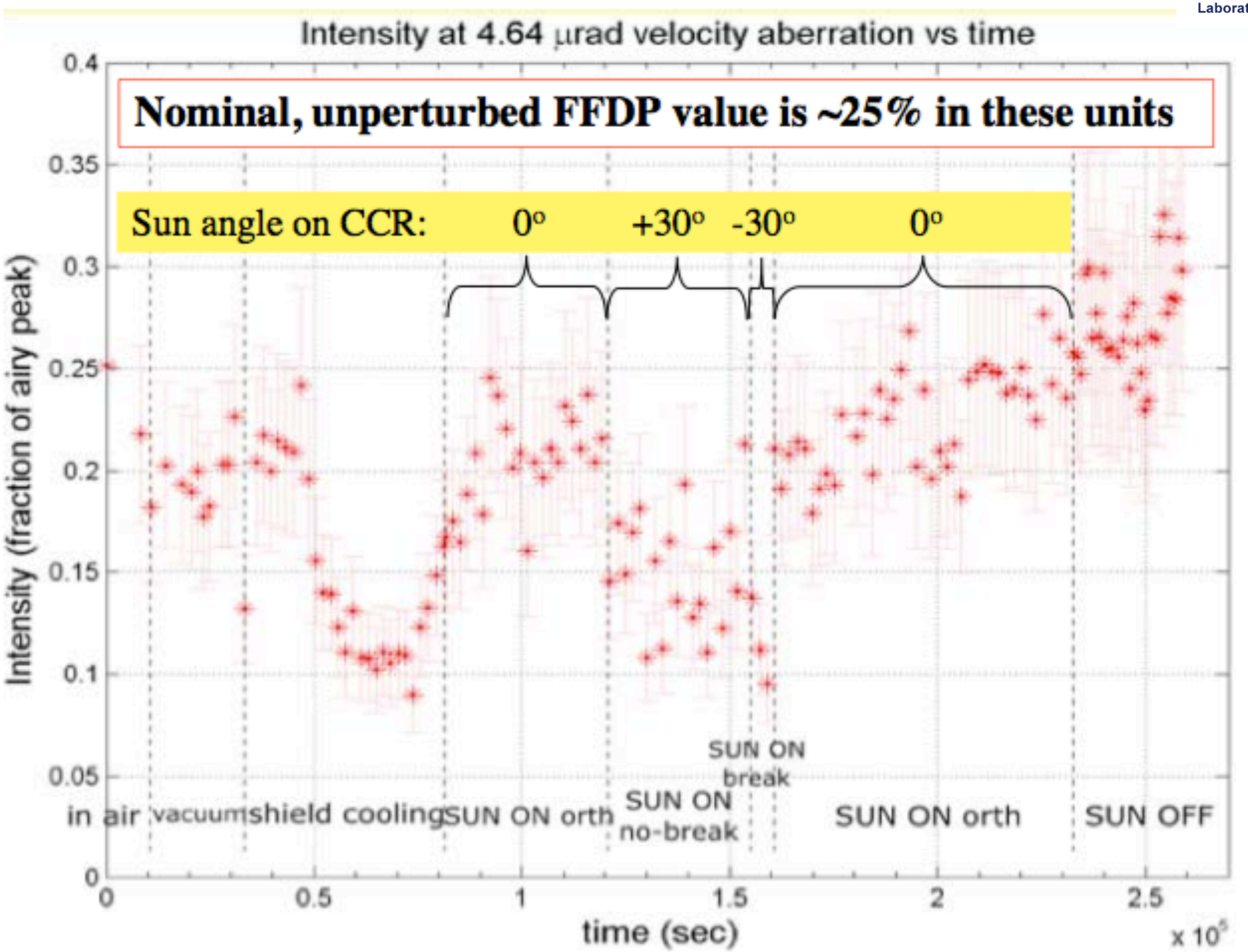
Inte ments
in laboratory-simulated space environment

Temperature of MoonLIGHT under the sun



SCF-Test of MoonLIGHT/LLRRA21

Optical Far Field Diffraction Pattern (FFDP)



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Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS

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Data Analysis

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Geodetic Precession

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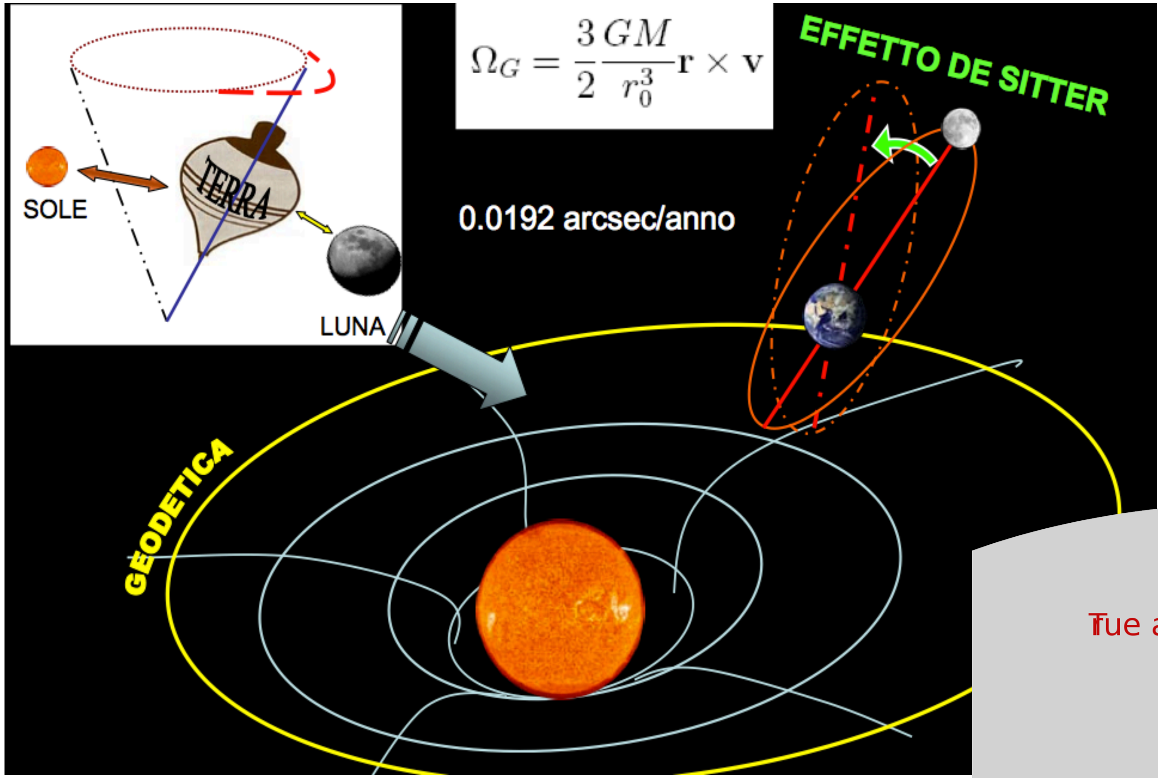
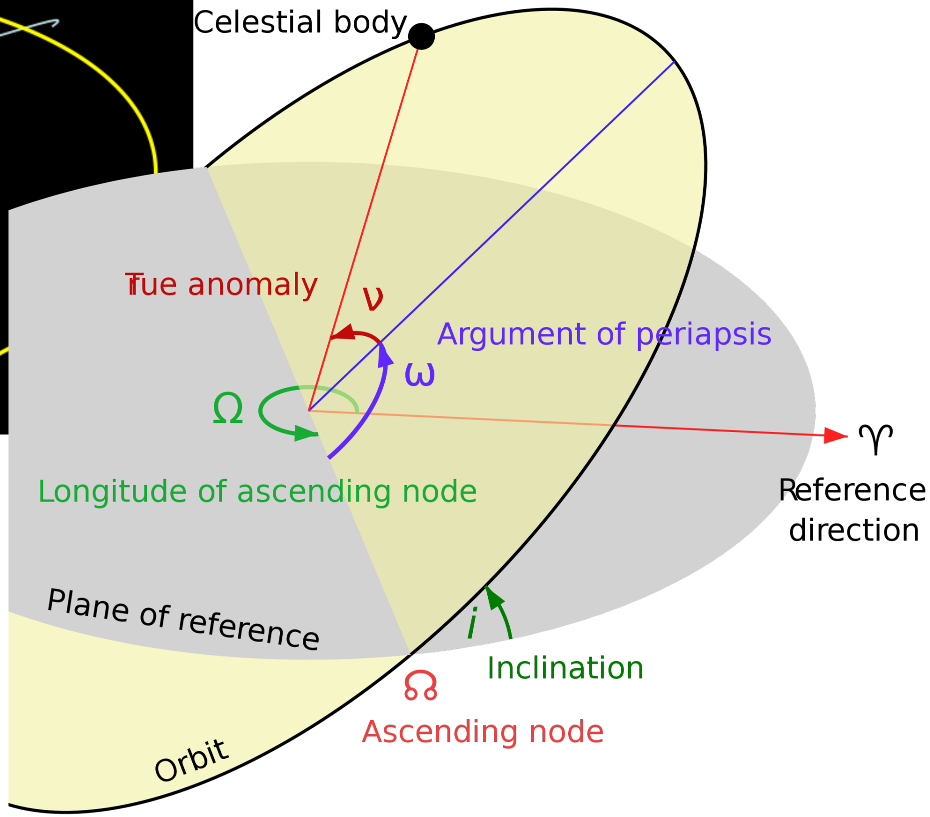
The term geodetic effect has two slightly different meanings as the moving body may be spinning or non-spinning. Non-spinning bodies move in geodesics, whereas spinning bodies move in slightly different orbits.

The difference between de Sitter precession and Lense-Thirring precession is that the de Sitter effect is due simply to the presence of a central mass, whereas Lense-Thirring precession is due to the rotation of the central mass.

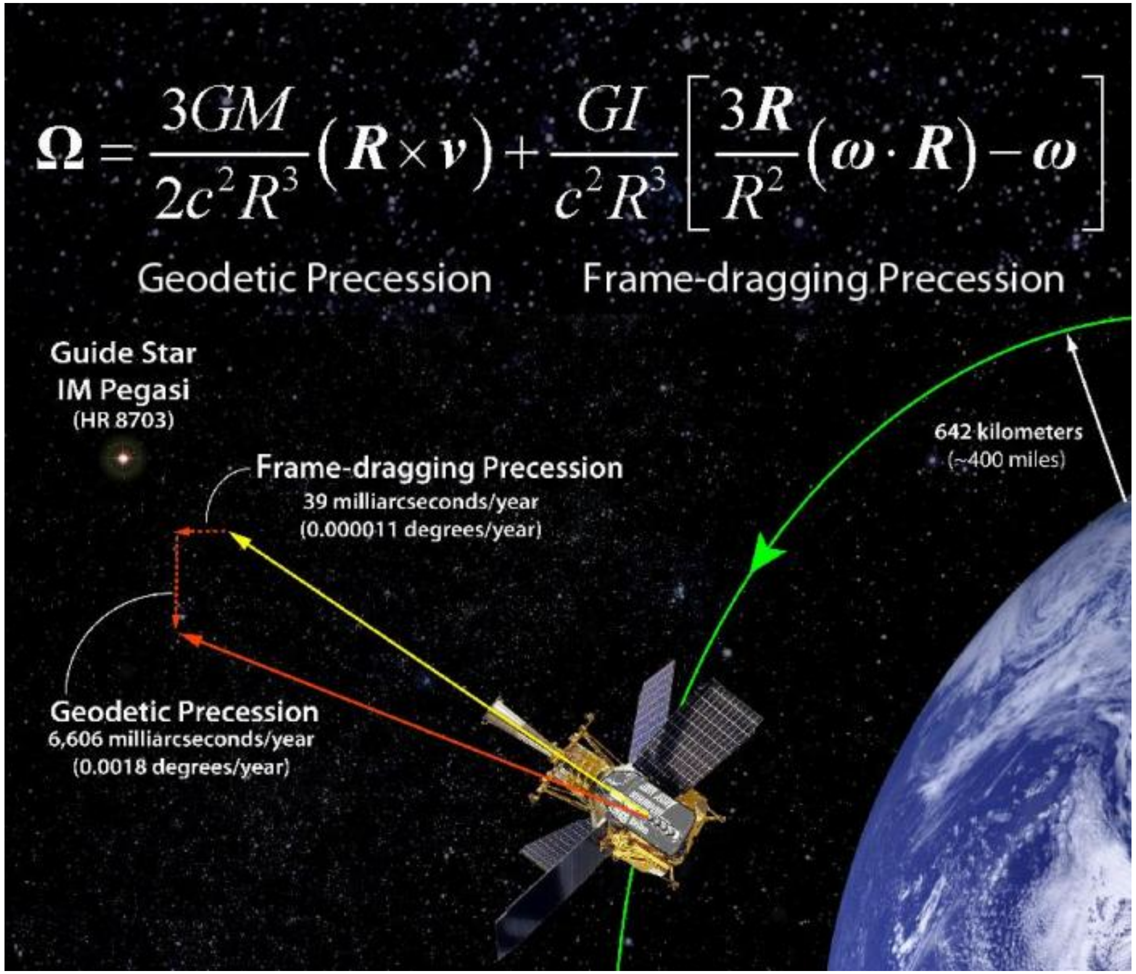
The total precession is calculated by combining the de Sitter precession with the Lense-Thirring precession.

Geodetic Precession





Geodetic Precession



The GR test of the geodetic precession, evaluated with LLR data and expressed as a relative deviation from the value expected in GR, is:

$K_{GP} = -0.0019 \pm 0.0064$

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.

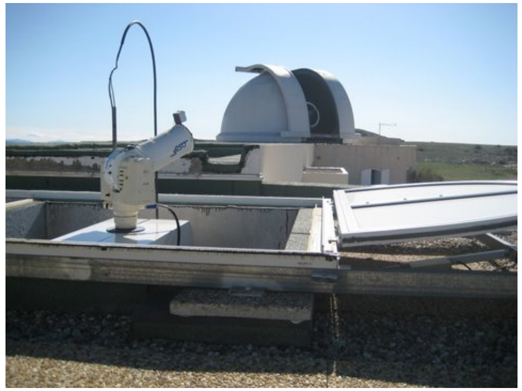
The model parameter estimates are refined by minimizing the residual differences, in a weighted least-squares sense, between observations (O) and model predictions (C, stands for ”Computation”), O-C.

”Observed” is round-trip time of flight. ”Computed” is modeled by the PEP software.

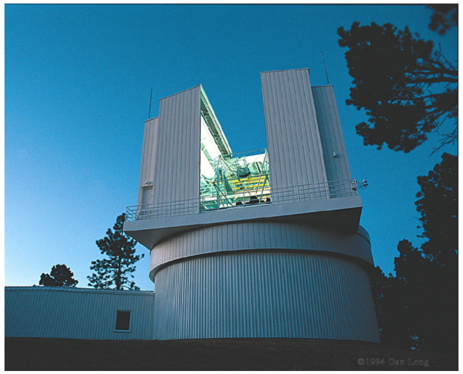
Planetary Ephemeris Program

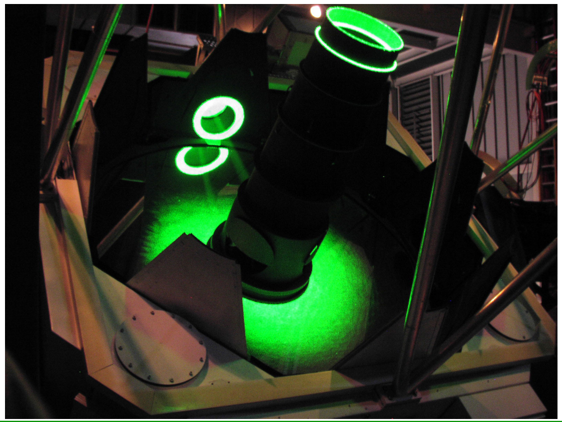
Two different way to proceed:

- "old stations" (McDonald, Grasse, MLR2)

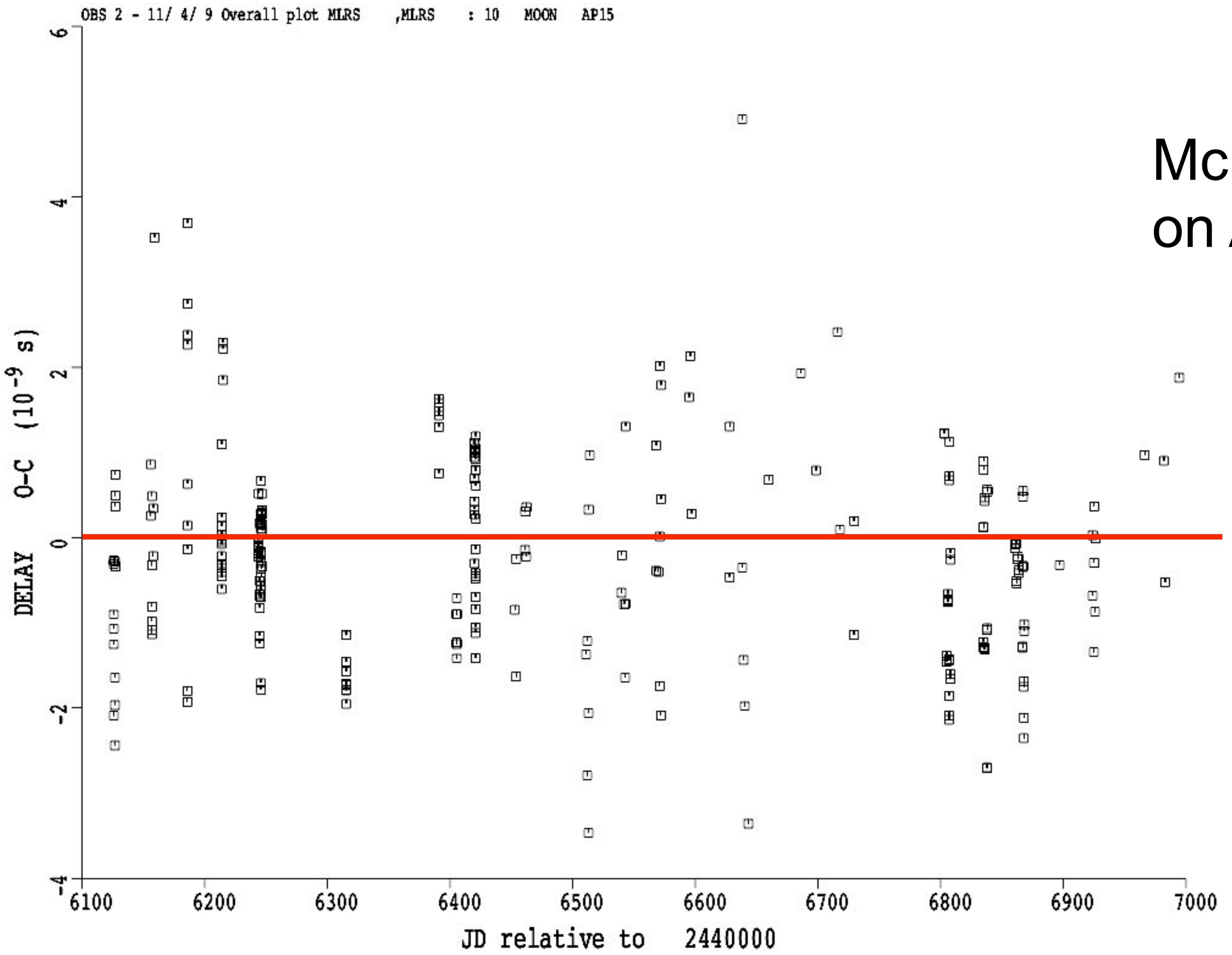


- Apache Point station





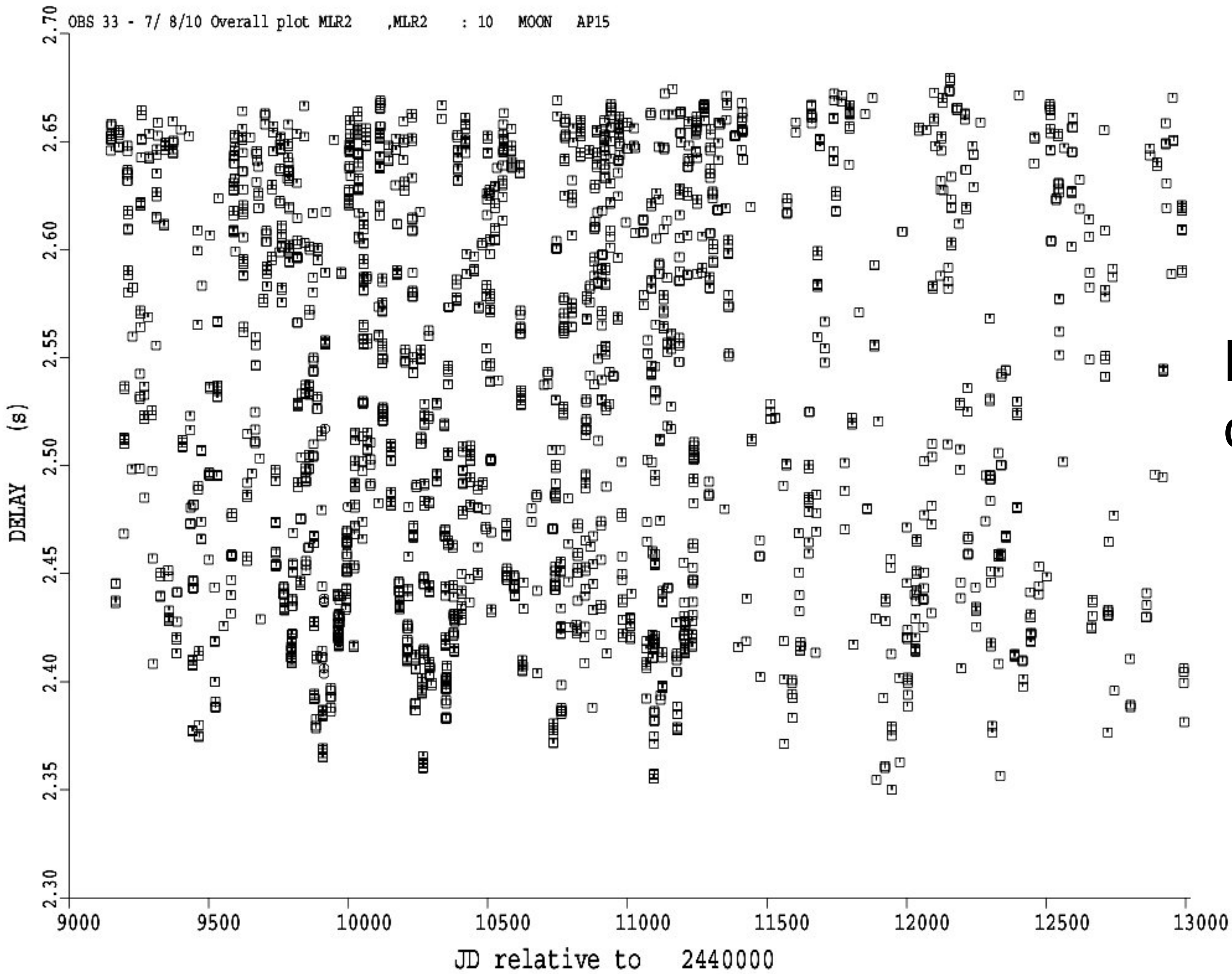
O-C residual analysis with PEP



McDonald station on Apollo 15 array

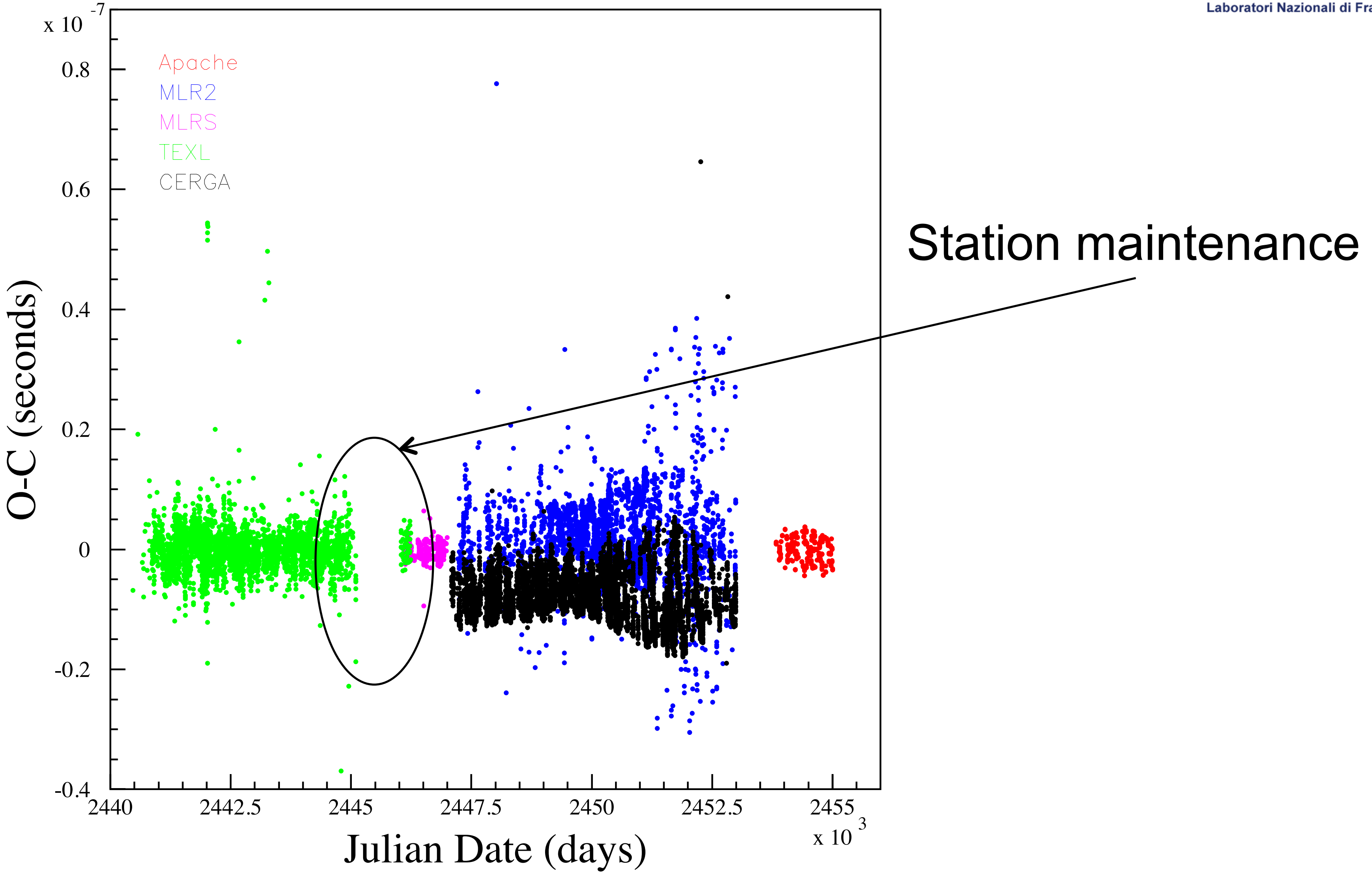
JD is the interval of time in days and fractions of a day since January 1, 4713 BC Greenwich noon.

O-C residual analysis with PEP



McDonald station on Apollo 15 array

O-C residual analysis with PEP



Determination of K_{GP}

K_{GP} is the relative deviation from the value of geodetic precession expected in GR

All together old stations:

$$K_{GP} = (9 \pm 9) \times 10^{-3}$$

Apache Point station:

$$K_{GP} = (-9.6 \pm 9.6) \times 10^{-3}$$

In this analysis $\beta=\gamma=1$, $dG/dt=0$. Nominal errors returned by the fit are significantly smaller than the above estimated values of K_{GP}.

Determination of K_{GP}

Parameter	GR initial value	Final value
K_{GP} CERGA	0	-0.0162

Parameter	GR initial value	Final value
K_{GP} MAUI	0	0.0060

Parameter	GR initial value	Final value
K_{GP} MLR2	0	0.0095

Parameter	GR initial value	Final value
K_{GP} TEXL	0	-0.0441

Determination of K_{GP}

This preliminary measurements are to be compared with the best result published by JPL obtained using a completely different software package

$$K_{GP} = (-1.9 \pm 6.4) \times 10^{-3}$$

On the contrary, after the original 2% K_{GP} measurement by CfA in 1988, the use of PEP for LLR has been resumed only since a few years, and it is still undergoing the necessary modernization and optimization.

Conclusions

We have created a unique facility and a new industry-standard laboratory test to validate the thermal and optical behavior of laser retroreflectors

We have obtained a preliminary measurement of geodetic precession that is consistent with the prediction of GR. This is an interesting and promising preliminary study.

Future prospects

- Deepen our knowledge about data and software in order to better estimate the K_{GP} uncertainty and other GR parameters.

- Improve the precision of these kind of measurements ranging not only to the Moon, but also to satellites around the Earth and primarily to LAGEOS, thus improving station intercalibration.

- We have the option to implement the equations of motion of space-time torsion gravity inside PEP and study <u>not only the secular variation</u> of geodetic precession , but also <u>periodic signatures</u> of torsion on the geodesic precession and on other PPN parameters

- Before the end of the decade, robotic mission on the lunar surface will deploy new scientific payloads, which include MoonLIGHT-type laser retroreflectors

THANK YOU FOR YOUR ATTENTION

ANY COMMENTS/QUESTIONS?