Next-generation Laser Retroreflectors for Precision Tests of General Relativity

Emanuele Ciocci

M. Martini , S.Dell'Agnello, G.Delle Monache, S.Contessa, L.Porcelli, M.Tibuzzi, N.Intaglietta, L.Salvatori, M.Maiello, G.Patrizi, C.Mondaini,

Laboratori Nazionali di Frascati – Istituto Nazionale di Fisica Nucleare

D.Currie

University of Maryland, College Park

J.F.Chandler

Center for Astrophysics
Boston

G.Bianco

Agenzia Spaziale Italiana,
Centro di Geodesia Spaziale

emanuele.ciocci@lnf.infn.it

Outline

Introduction:

- CCRs and Lunar Laser Ranging
- 1st Generation Lunar CCRs and librations effect
- MoonLIGHT-2

MoonLIGHT-2 Experimental tests

- The SCF-TESTs
- Thermal and optical analysis
- Results of SCF-Tests

GR Simulations with Planetary Ephemeris Program - PEP:

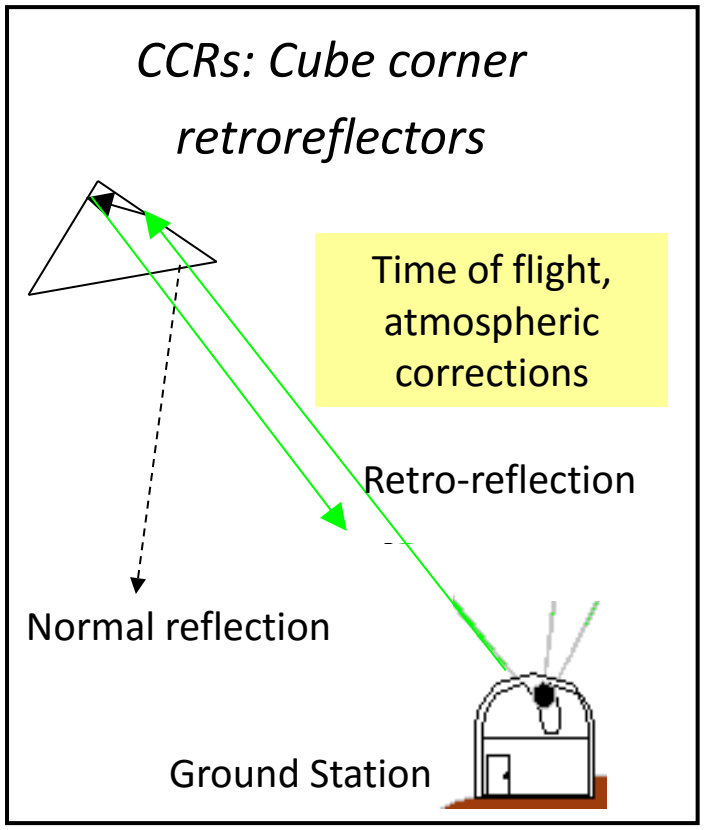
- PEP Software
- GR expected improvement simulation and result

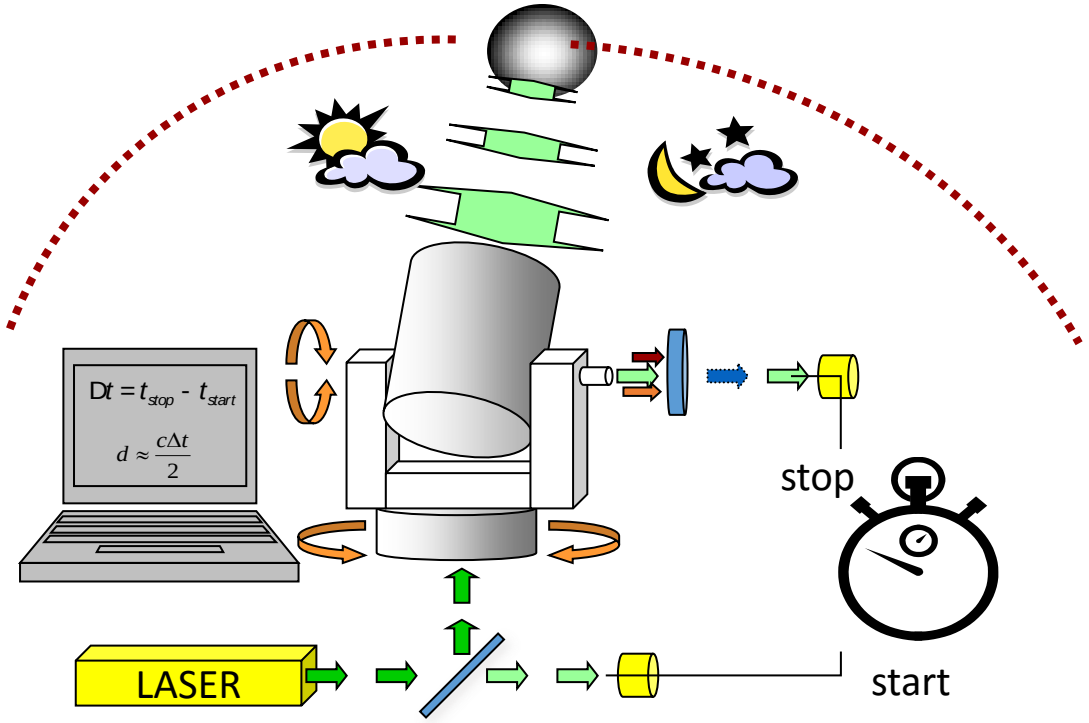
Conclusion and future works

emanuele.ciocci@lnf.infn.it

CCRs and Lunar Laser Ranging

- An observatory on Earth transmits a short pulse in towards a Cube Corner Retroreflector array on the Moon.
- The CCR reflect the pulse to the observatory.
- Distance from the time of flight measurement
- Track Moon orbit and obtain Moon orbit parameter





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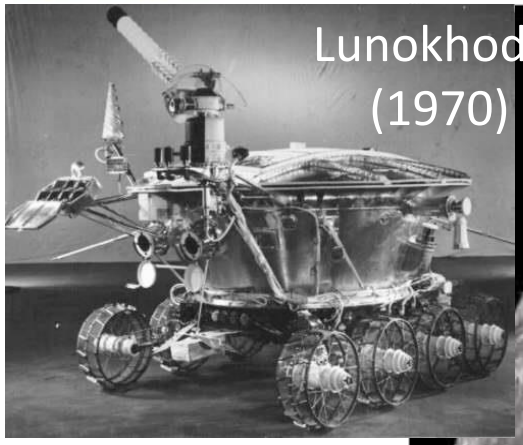
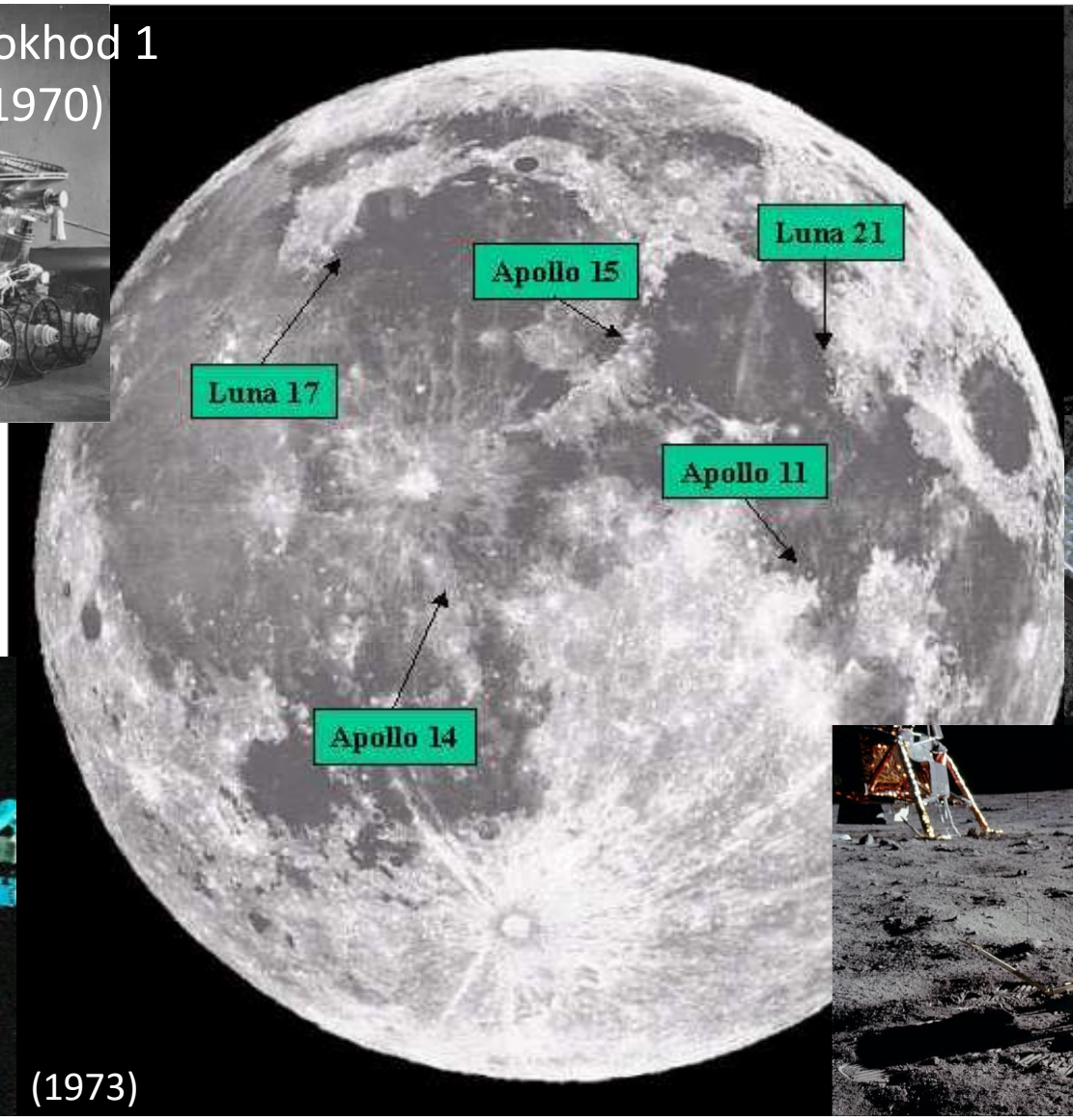
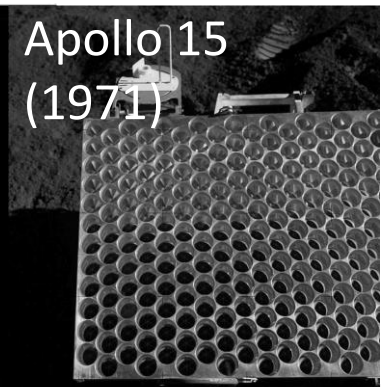
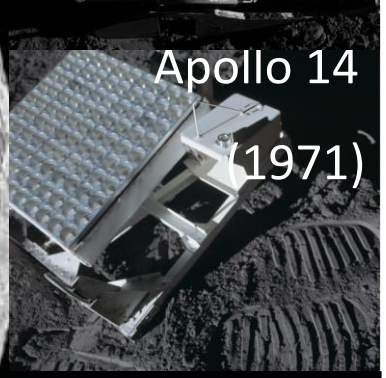
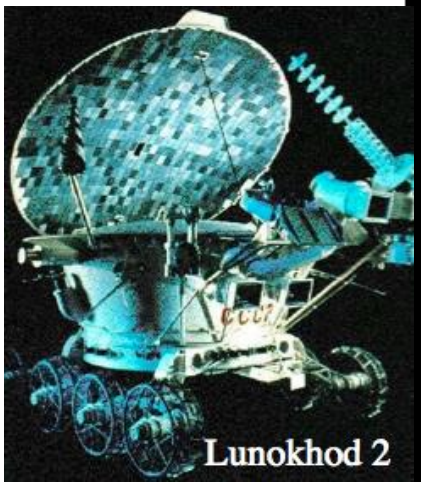
CCRs Array on Moon

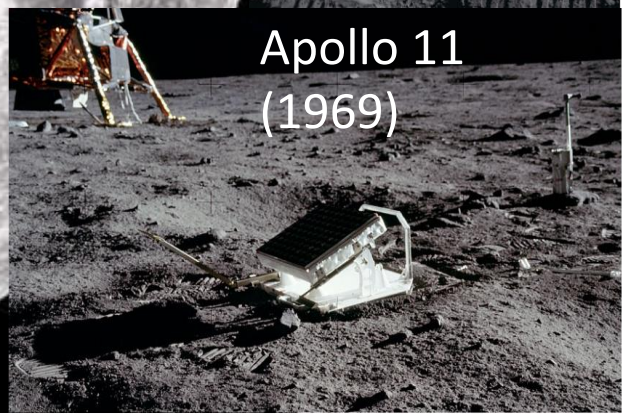












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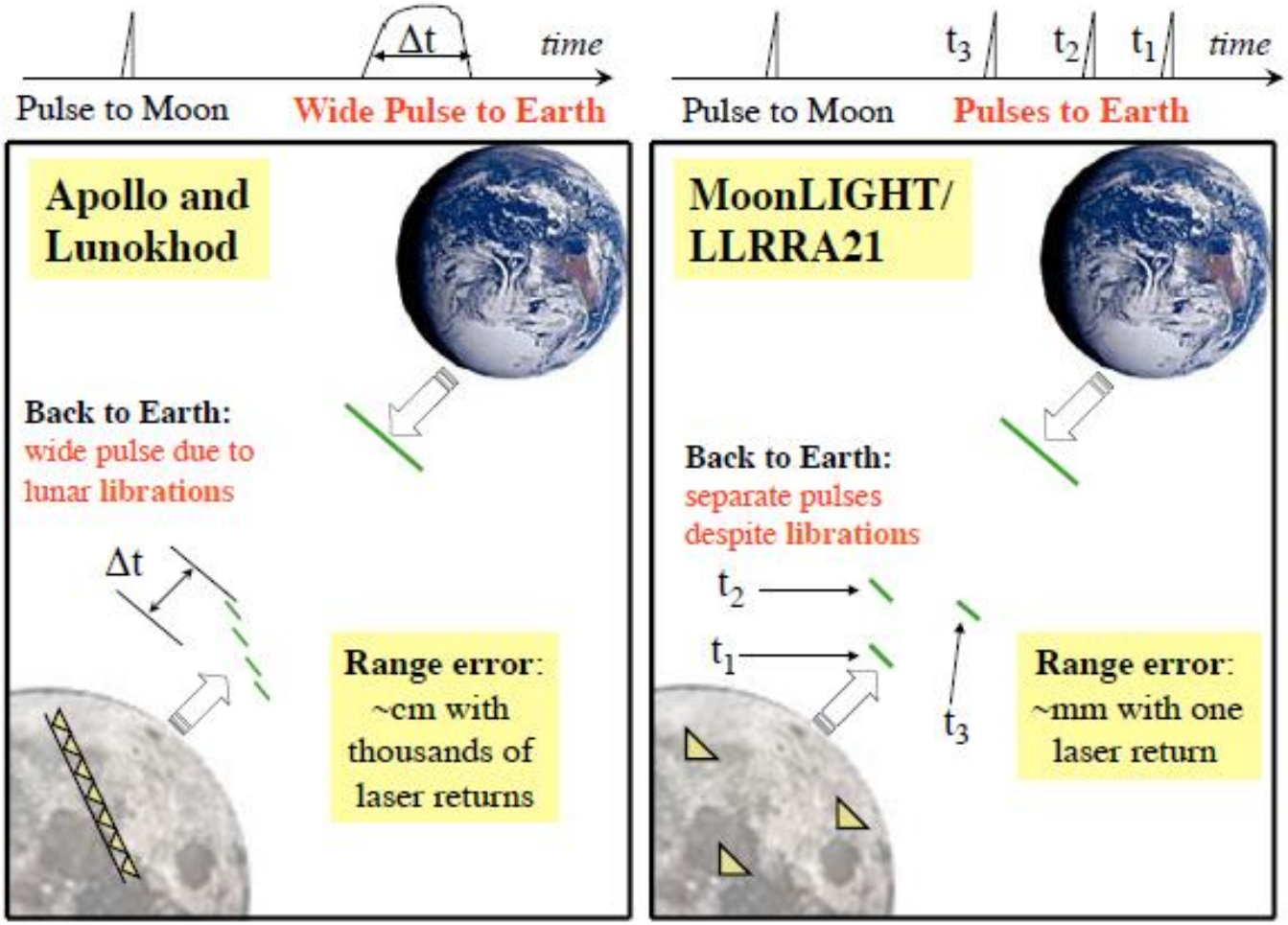
Lunar Librations Effect

- Due to this phenomenon the Apollo arrays are moved.
- 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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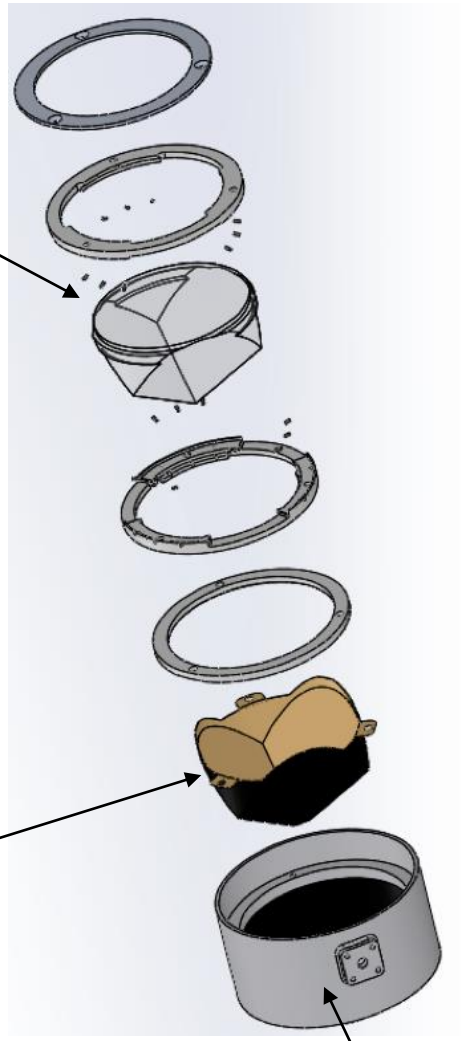
MoonLIGHT-2

Big CCR



Conformal CAN

Housing

MoonLIGHT:
Moon Laser Instrumentation for General relativity High-accuracy Tests

- Mass ≈1 kg.
- Dimensions: 100mm (r) x100mm (h).
- Housing structure designed to avoid any thermal gradient (will decrease optical performances).
- Unaffected by lunar libration.
- No dedicated active pointing system.

Scientific goals:

- Precision tests of GR improved compared to old Apollo/Lunokhod.
- Precise positioning of landing site.
- Study properties of the lunar interior.

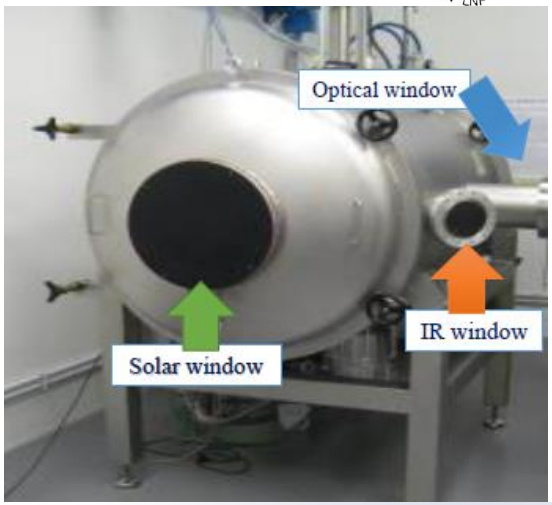
First (of four) launch with Moon Express mission in 2018.

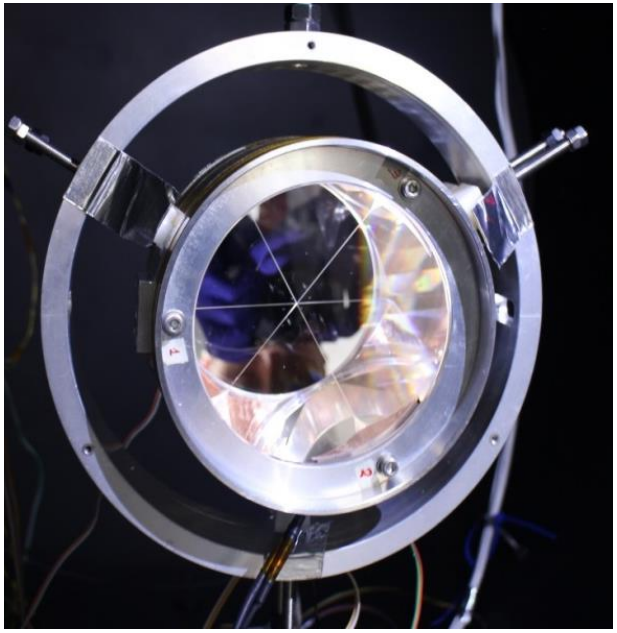
emanuele.ciocci@lnf.infn.it

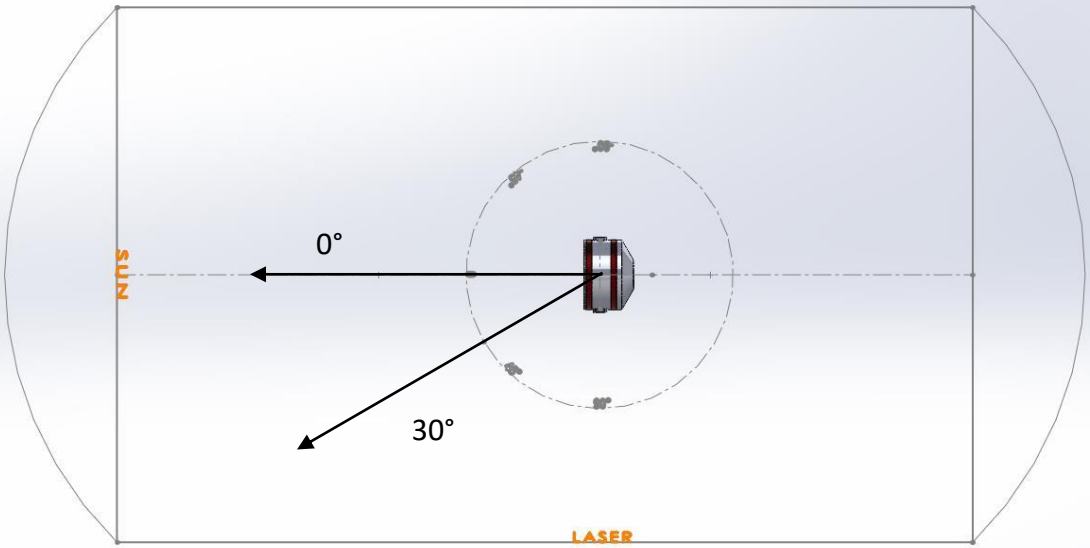
The SCF-TEST (1)

Standard **SCF-Test** in SCF_Lab:

- Simulated space conditions: $P \leq 10^{-6}\ mbar$, $T_{env} \sim 90K$.
- Housing kept at fixed temperature for whole test
- 14h SUN ON (facing Solar Simulator) + 14h SUN OFF (No Solar Simulator).
- Thermal and Optical Measurements







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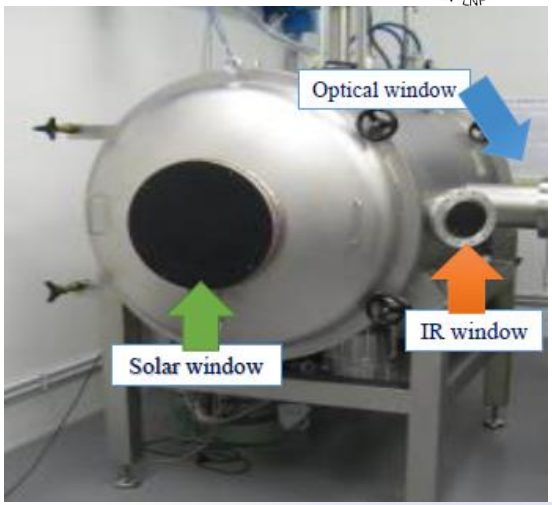
The SCF-TEST (2)

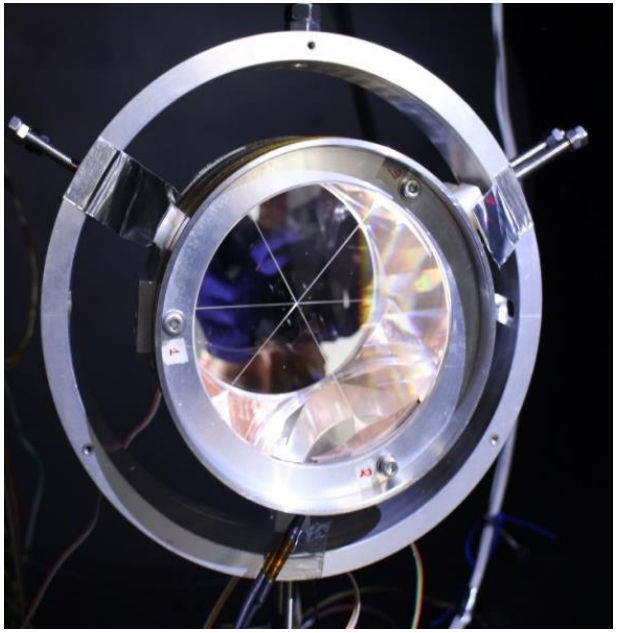
Thermal measurements

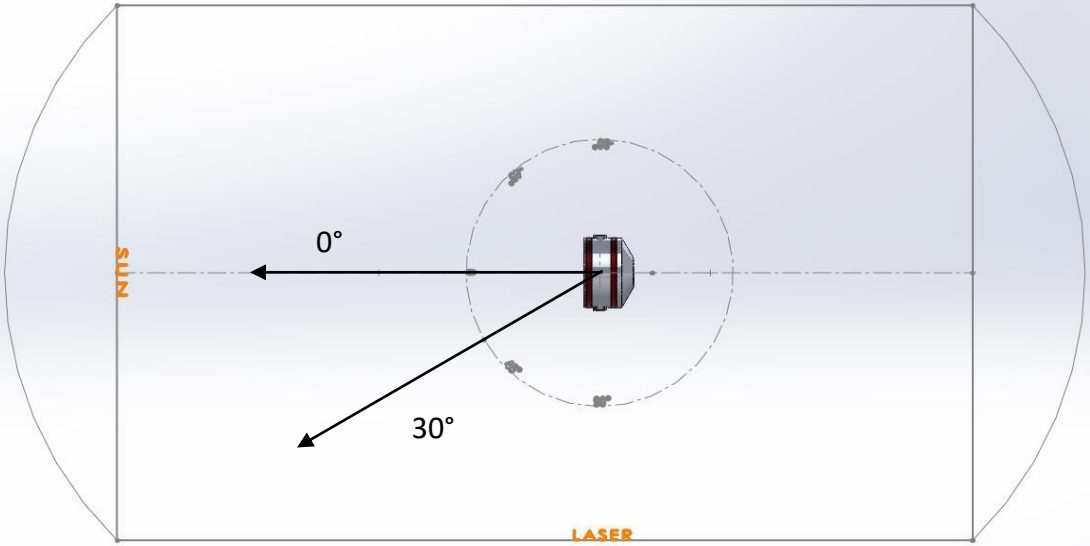
- IR pictures at SUN ON and SUN OFF phases
- Thermal constant analysis $[T(t) = T_0 \pm \Delta T\left(1 - e^{-t/\tau_{CCR}}\right)]$
- Thermal gradient on CCR front face analysis

Optical measurements

- FFDP at the beginning of SUN ON and for all SUN OFF
- Returning signal degradation at the Moon Velocity aberration
- Study of the optical performance at realistic space conditions







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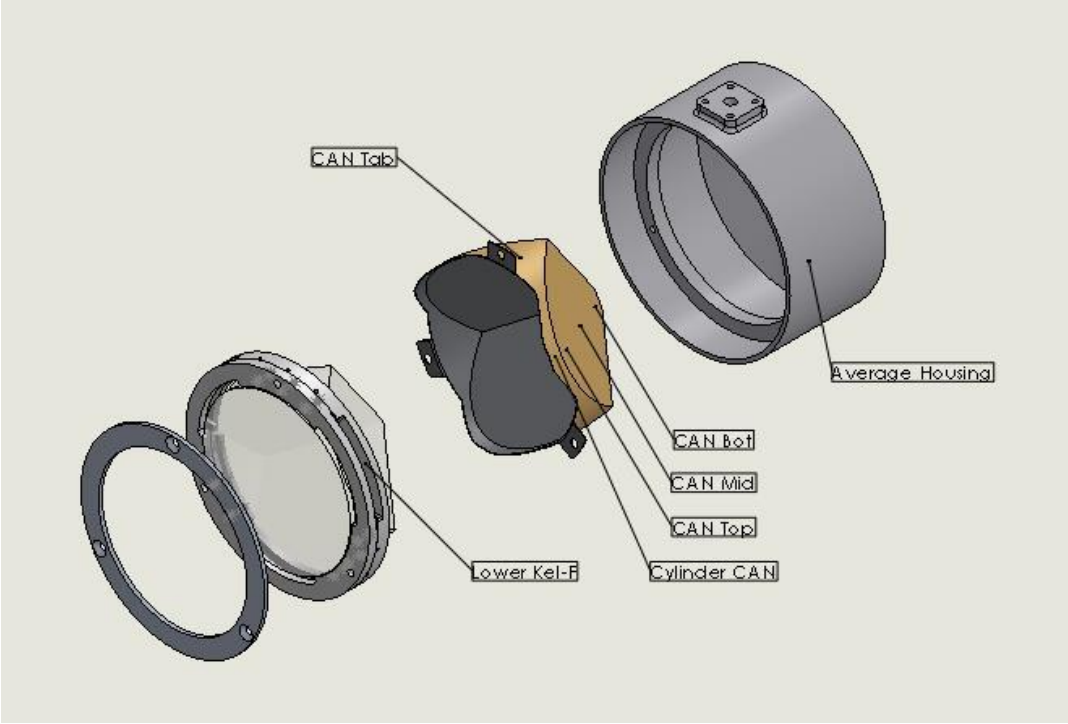
The SCF-TEST Campaigns

3 Different test configurations:

- With Conformal Can
  A. 300K with 0deg and 30deg SUN ON



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The SCF-TEST Campaigns

3 Different test configurations:

- With Conformal Can
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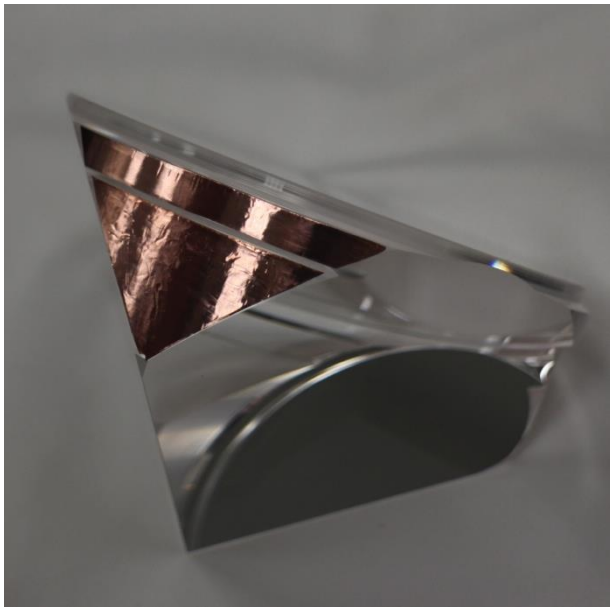
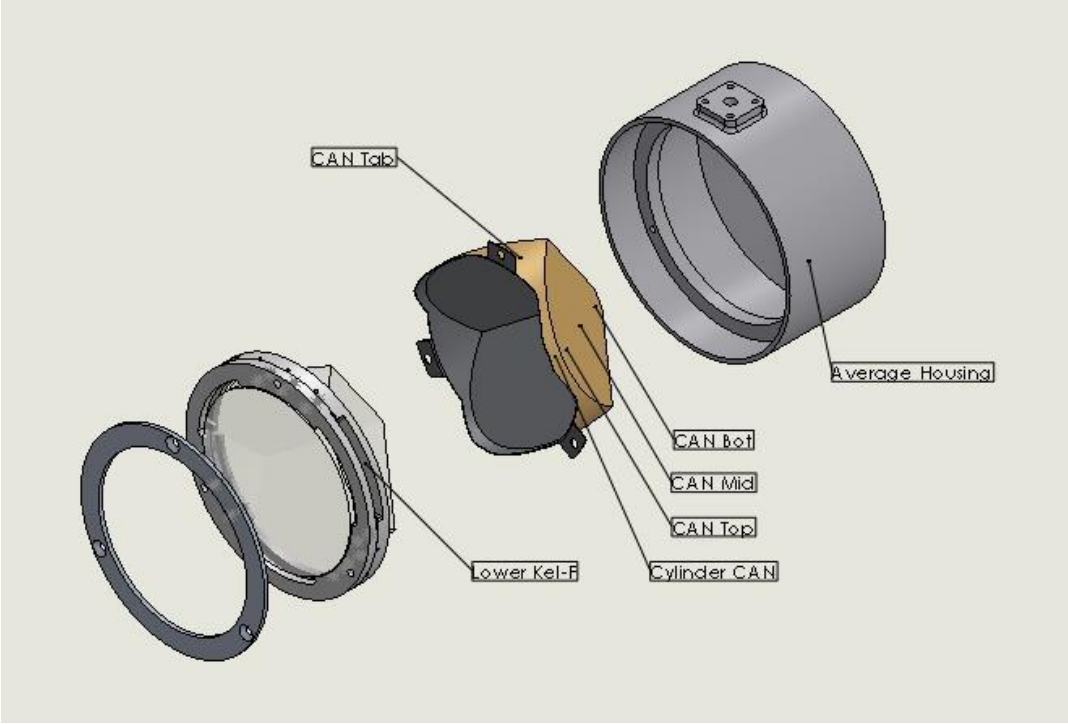
- With Conformal Can and copper tape on tab
  B. 250K-300K-330K with 0deg SUN ON





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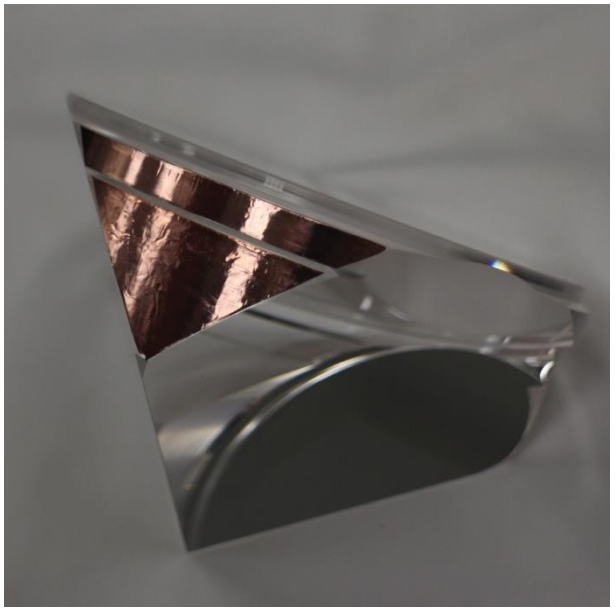
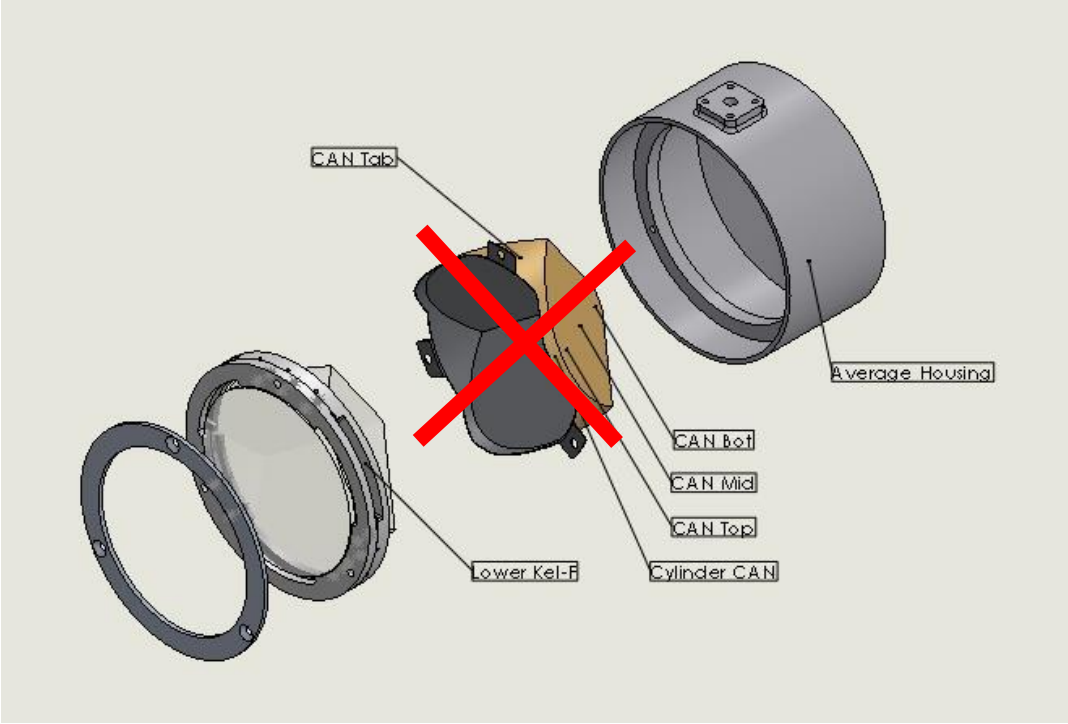
  C. 300K with 0deg and 30deg SUN ON





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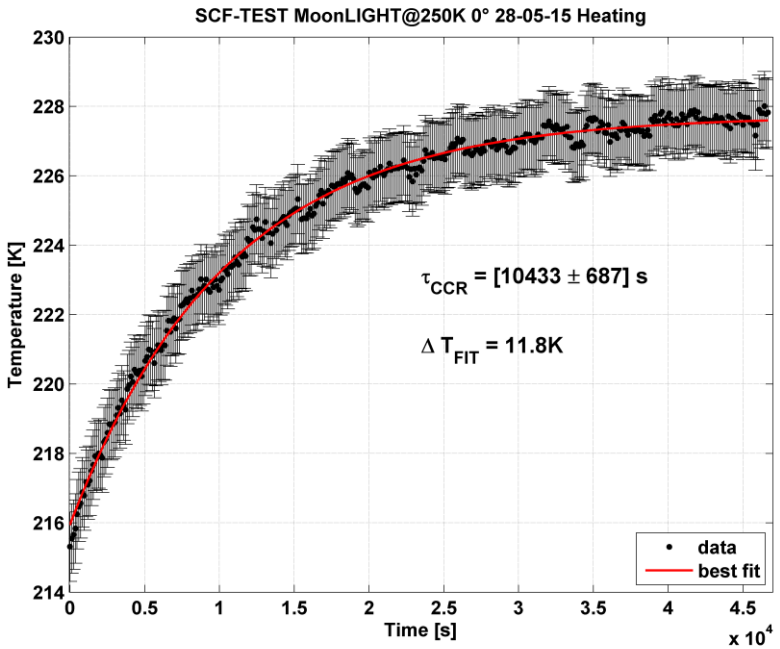
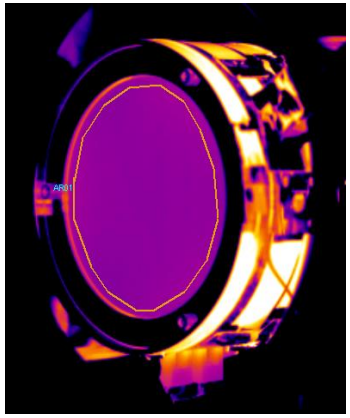
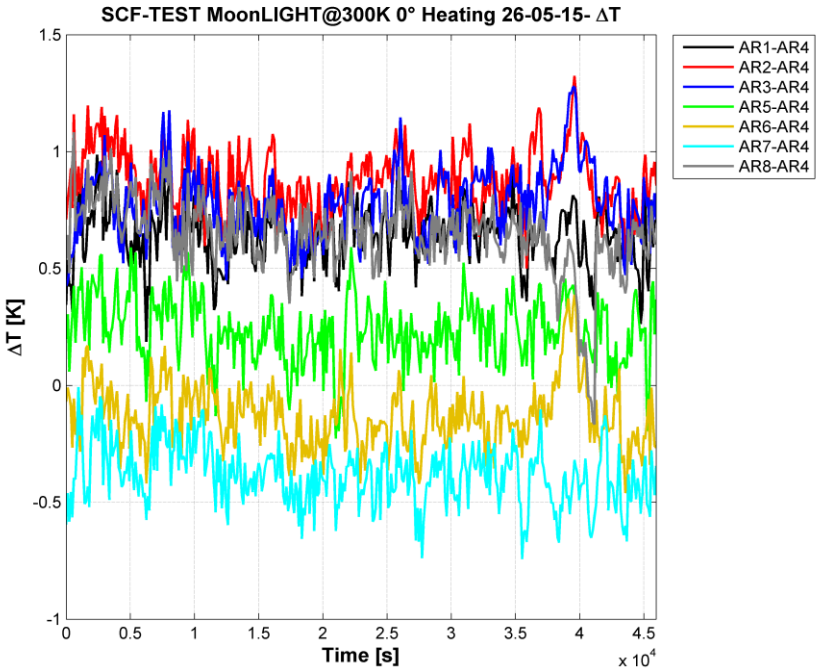
Results Thermal Analysis

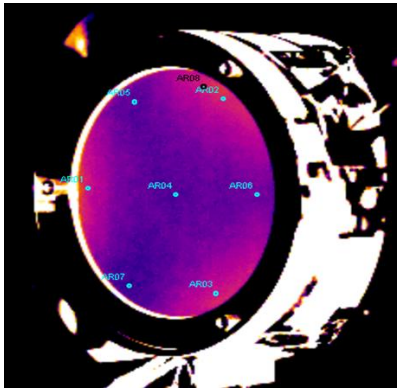
τ_{CCR}





ΔT Front Face





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Results Thermal Analysis

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

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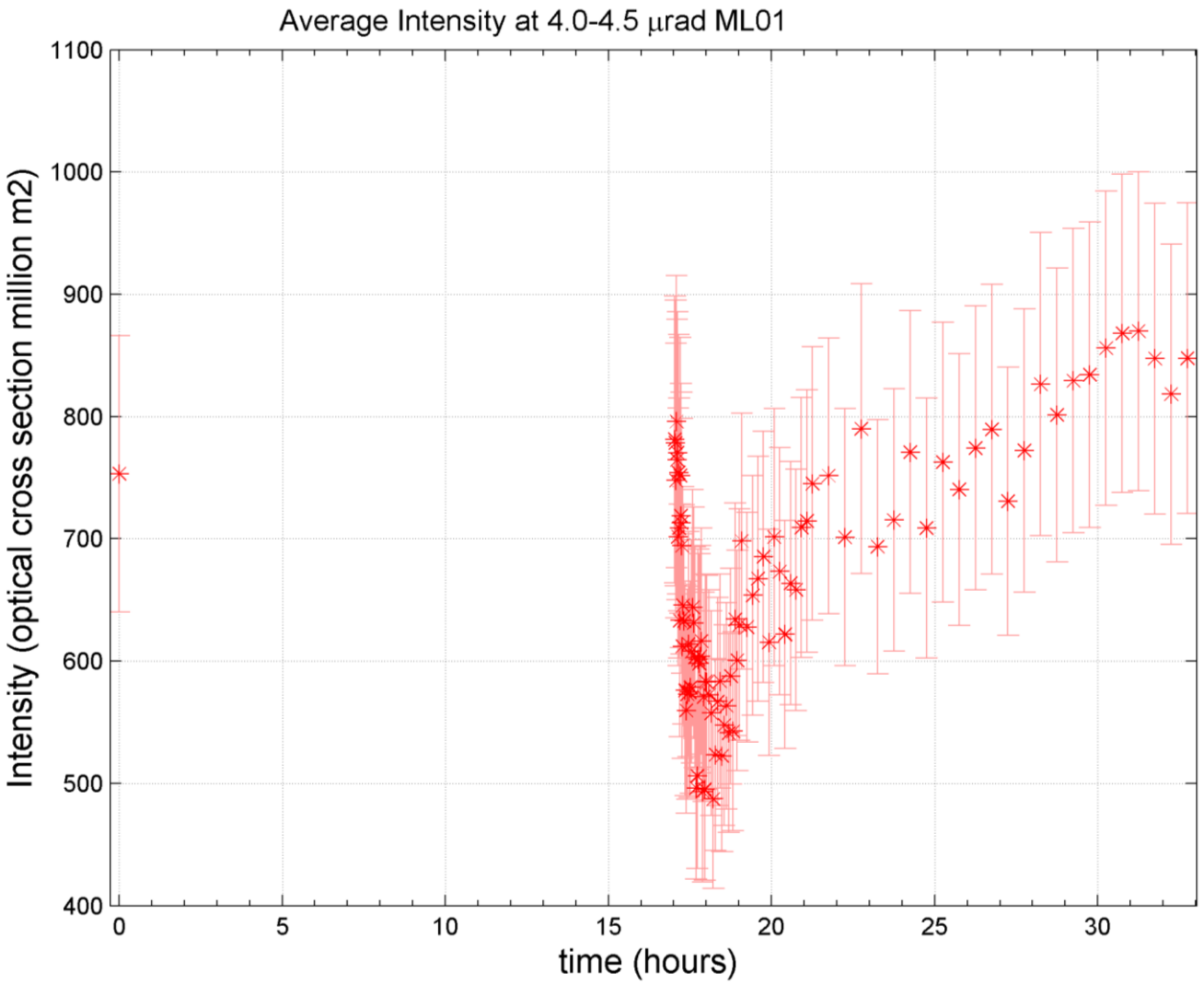
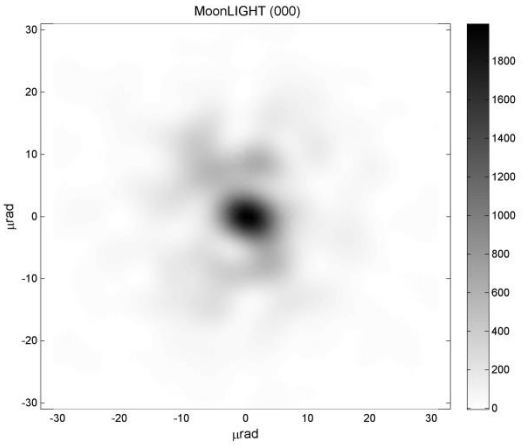
Results Optical Analysis

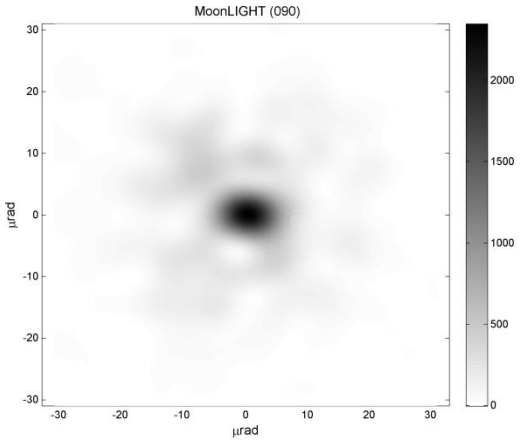
NO CAN, WITH TAPE. 300K, 0deg



BEGINNING



END TEST



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PEP software

PEP: Planetary Ephemeris Program.

- Fortran SW package developed by the CfA, by I. Shapiro starting from 1969.
- Detailed mathematical model of the Solar System.
- Process both real and dummy LLR data
- Simulate real ground station.
- The model parameter are estimated minimizing the residual differences between observations (O) and model predictions (C)
- High accuracy GR simulation of:

***PPN:* β-1** ***PPN:* γ-1** $\dot{G}/G$ k_{GP}

- One of best GR tests with CCR actually installed on the Moon:

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	$\|\dot{G}/G\|<9\times10^{-13}\mathrm{yr}^{-1}$
Inverse Square Law (ISL)	$\|\alpha\|<3\times10^{-11}$
Geodetic Precession	$\|K_{gp}\|<6.4\times10^{-3}$

G. Williams, et al PRL 93, 261101, 2004

emanuele.ciocci@lnf.infn.it

GR Tests with PEP for MoonLIGHT

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, 90°E 0°N, 90°W	APOLLO	0,1 cm
				CERGA	0,2 cm
				MLRS	
				MLRO	

➢ **GR tests expected improvement:**

- 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.

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GR Tests with PEP for MoonLIGHT

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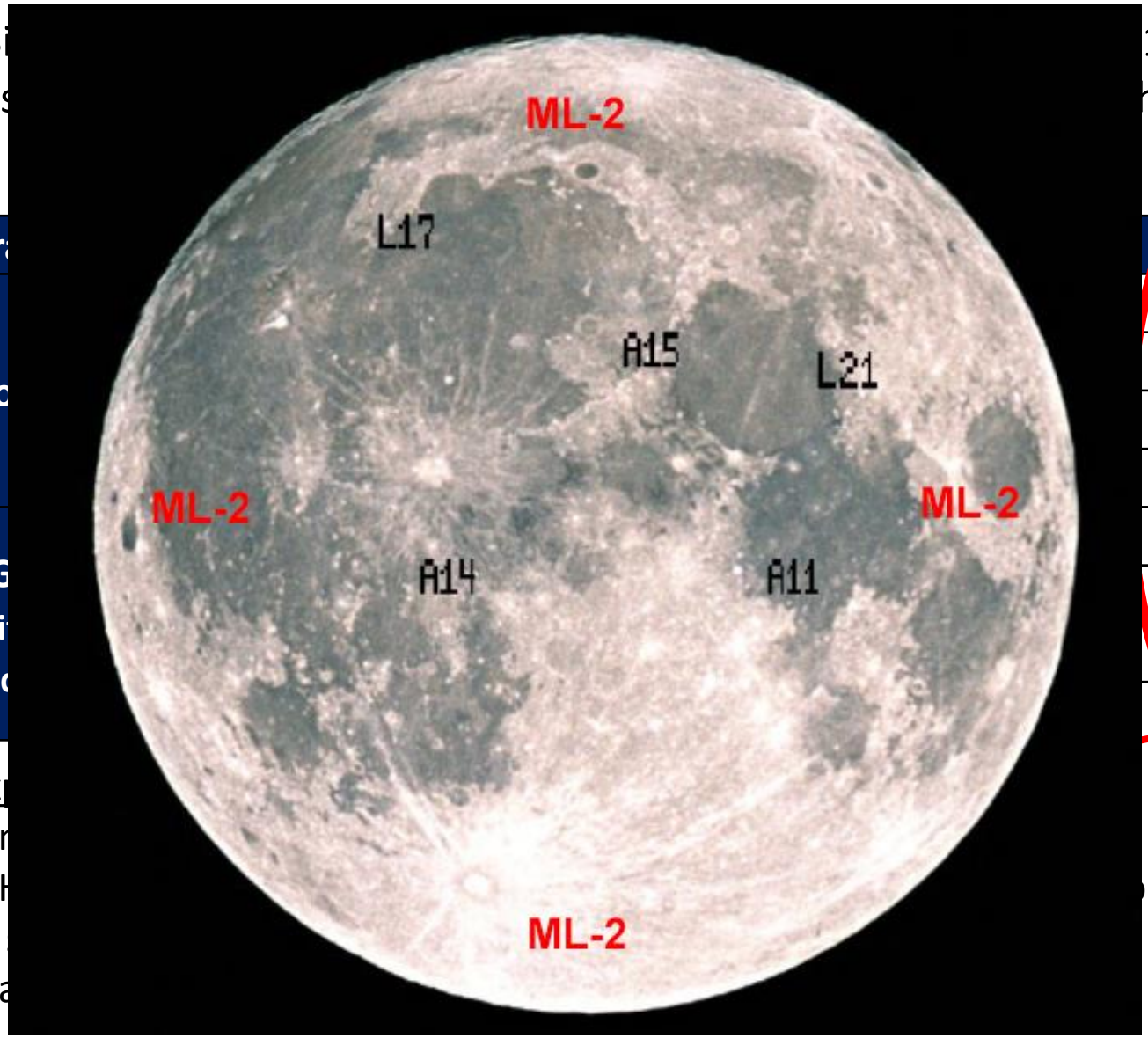

CCR Arr	Accuracy
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	0,2 cm

- **GR tests ex**
- Accuracy sir
- 4 MoonLIGH
- 15 years of
- 3 different a

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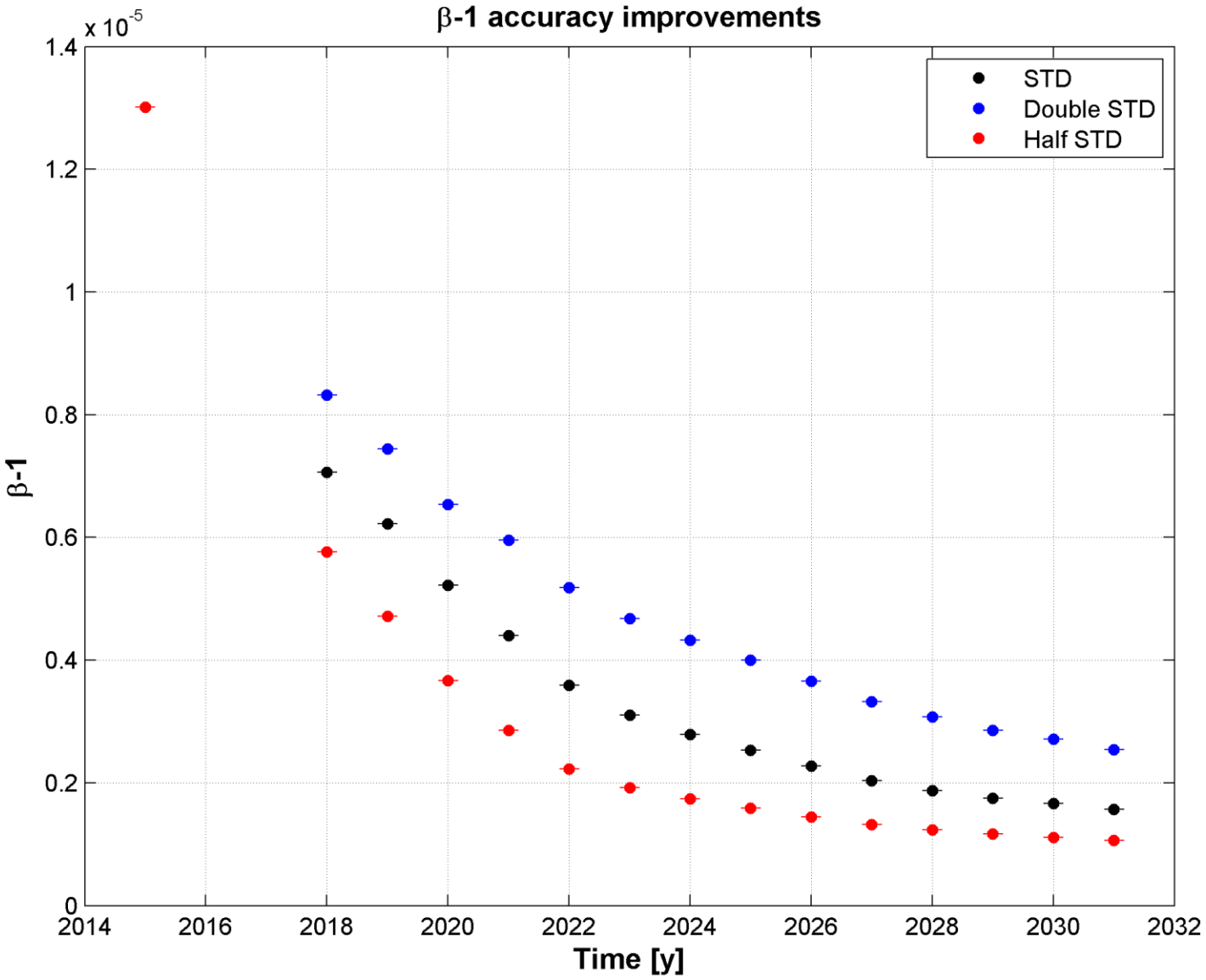
Results: GR expected improvement



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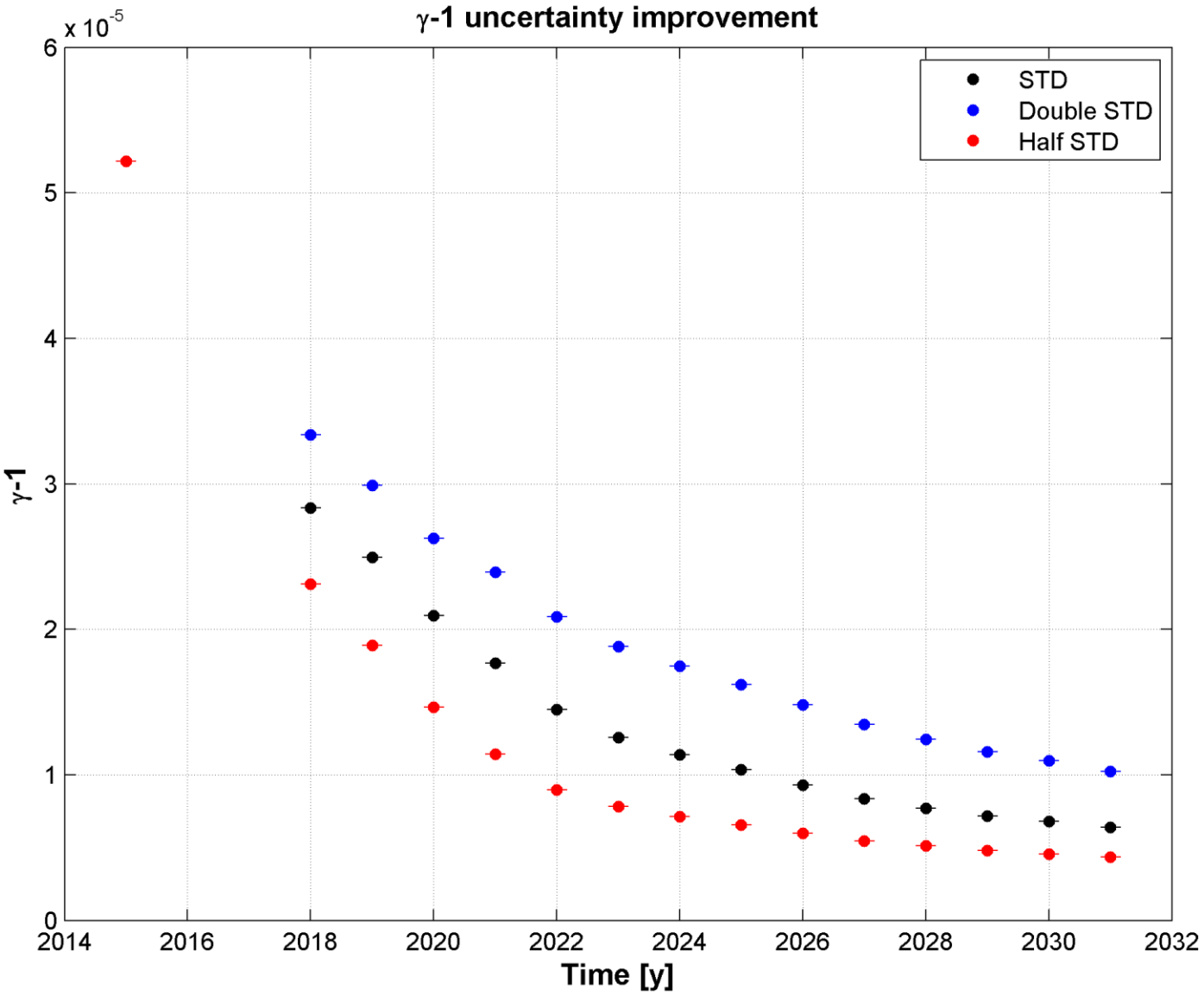

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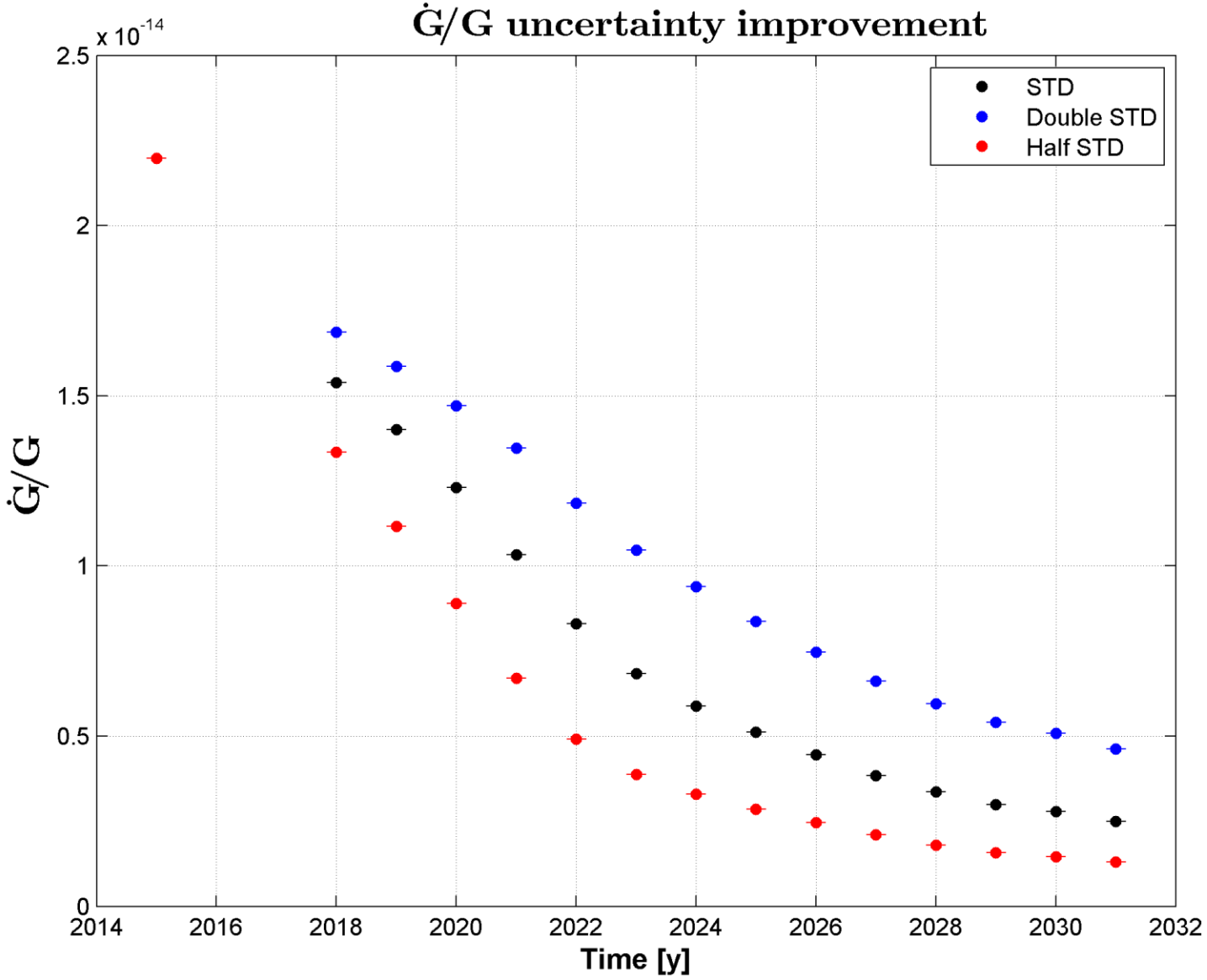
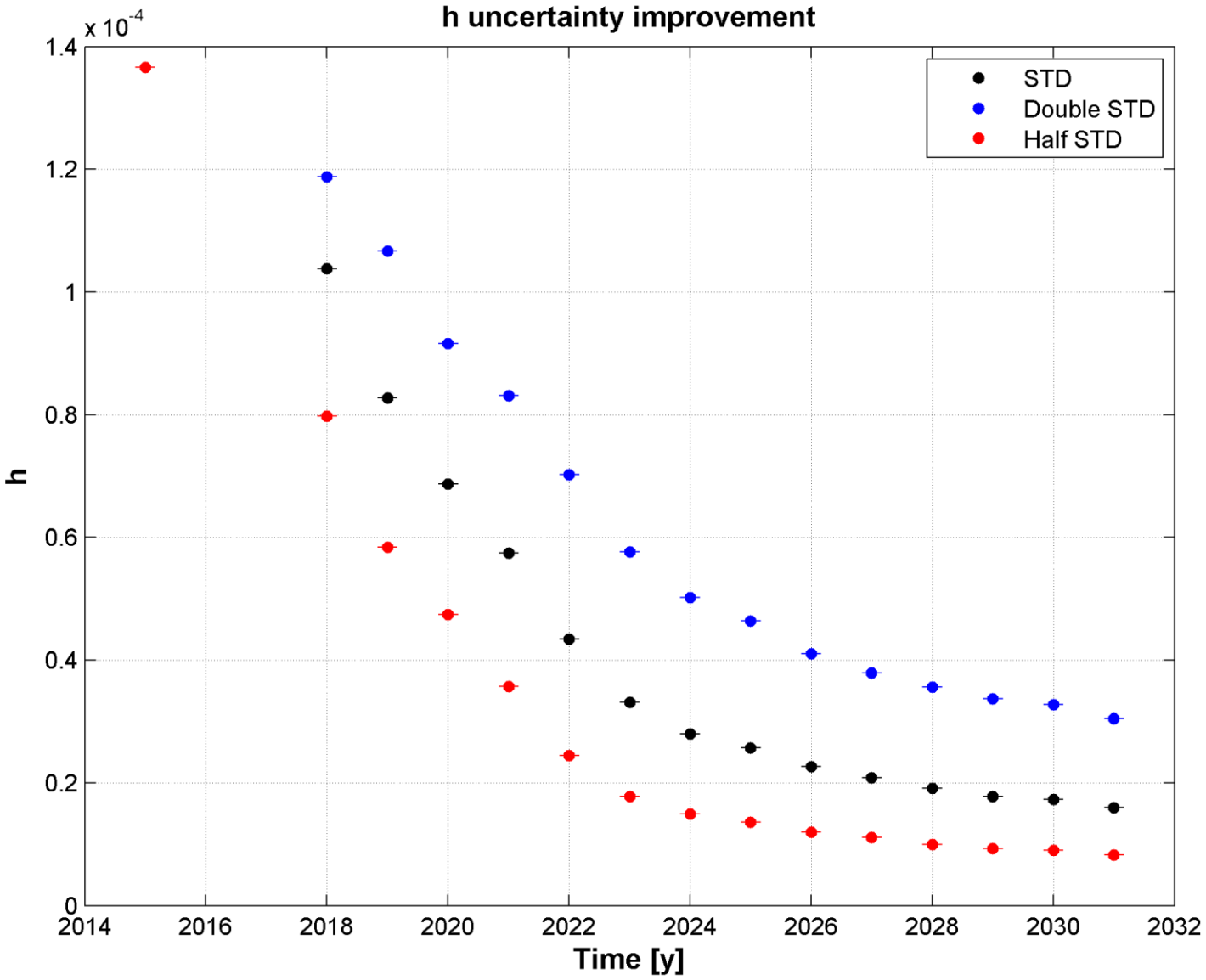


emanuele.ciocci@lnf.infn.it

Results: GR expected improvement



emanuele.ciocci@lnf.infn.it

Conclusions

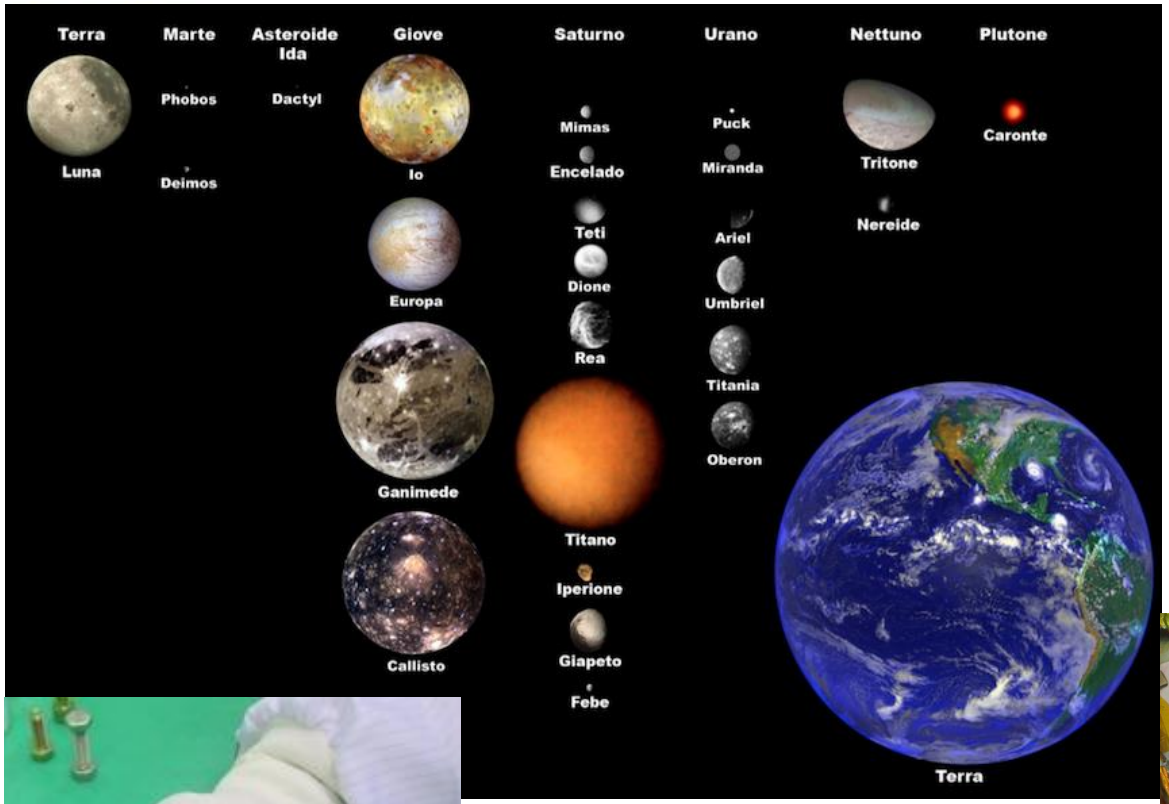
- Preliminary results of MoonLIGHT-2 experimental tests shown a very long thermal cycle as expected and good thermal isolation.
- FFDP analysis according to simulations: good returning signal.
- GR expected improvement with 4 MoonLIGHT-2 (around 10y):

Science measurement / Precision test of violation of General Relativity	Apollo/Lunokhod state of art	MoonLIGHT-2 simulations
Parameterized Post-Newtonian (PPN) β	$\lvert\beta-1\rvert<2.2\times10^{-4}$	1.6×10^{-5}
Time Variation of the Gravitational Constant	$\lvert\dot{G}/G\rvert<9.8\times10^{-14}\,yr^{-1}$	$2.5\times10^{-15}\,yr^{-1}$
Relative deviation from the value of geodetic precession expected in GR	$\lvert k_{gp}\rvert<1.7\times10^{-4}$	1.6×10^{-5}

- The GR tests with MoonLIGHT-2 will be not dependent from the MoonLIGHT-2 deployment site with the exceptions of the poles (because of the lunar libration, the array is not always visible from Earth).
- The improvements in the simulations represent the most pessimistic case where we do not considerate the LLR station upgrade or any software update.

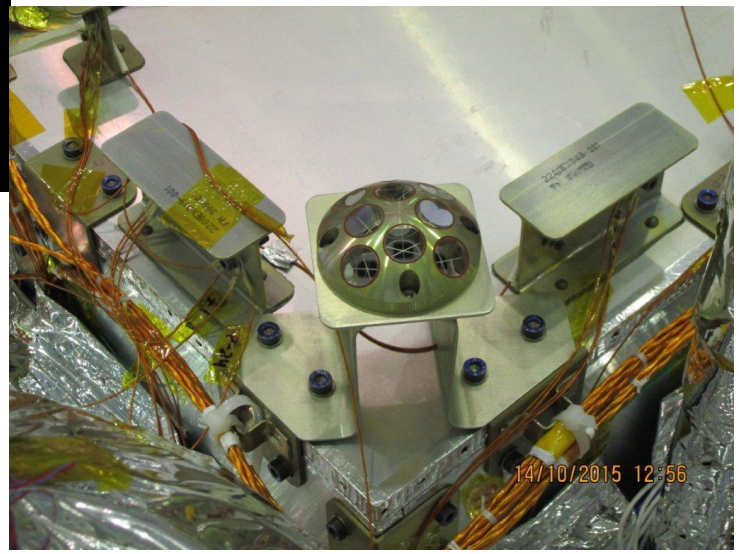
emanuele.ciocci@lnf.infn.it

Future works



- Complete the tests for the MoonLIGHT-2 deployment in 2018 with Moon Express mission (first of four mission).
- Install INRRI also on other rocky solar system bodies
- Improvements in the PEP software in collaboration with CfA

INRRI on EXOMARS EDM,
the first retroreflector array on Mars



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Thank you for your attention

ANY COMMENTS/QUESTIONS?

emanuele.ciocci@lnf.infn.it