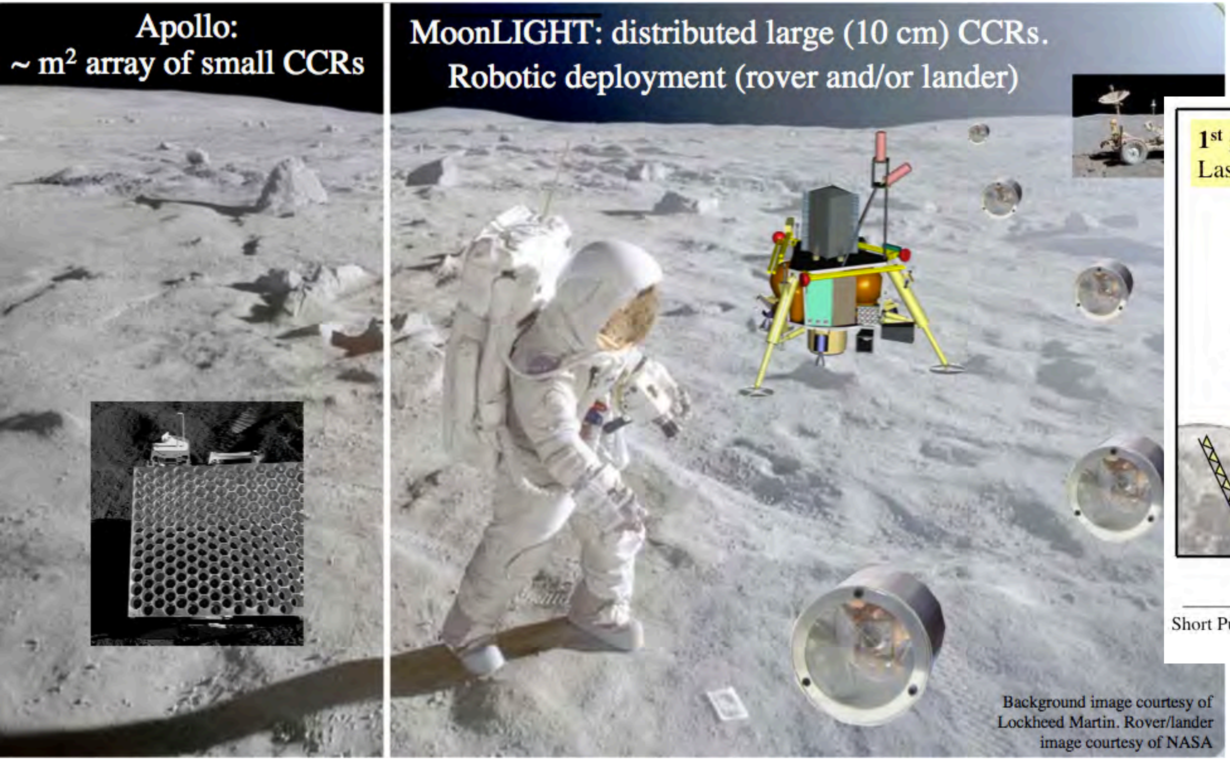
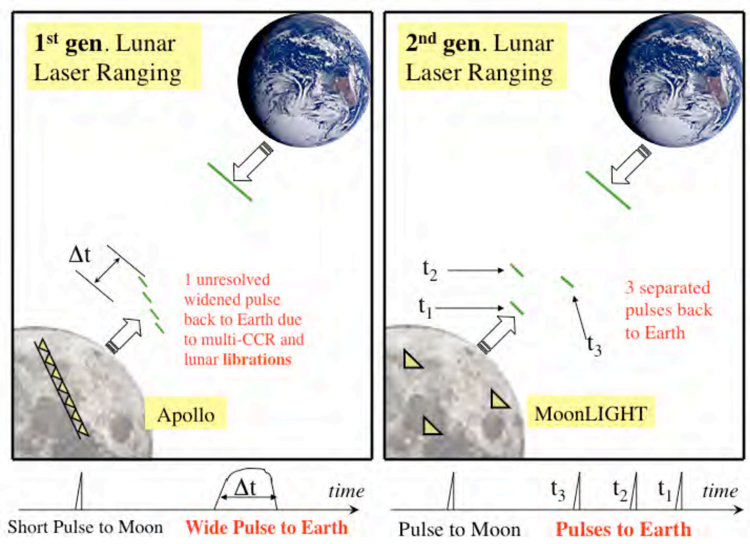
Testing and physics analysis of old (Lunokhod) and new (MoonLIGHT) lunar laser retroreflectors

L. Porcelli[1,2], C. Benedetto[5], G. Bianco[5,1], S. Casini[1], D. Currie[3], S. Dell'Agnello[1], G. Delle Monache[1], D. Dequal[5], M. Di Paolo Emilio[1], L. Ioppi[1], O. Luongo[1], C. Mondaini[1], M. Muccino[1], F. Pasquali[5], M. Petrassi[1], L. Salvatori[1], M. Tantalo[1], M. Tibuzzi[1], R. Vittori[4,1], J.-M. Torre[6], M. Maiello[1]

[1]Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati (INFN-LNF), Frascati, Italy.
[2]Dipartimento di Fisica, Università della Calabria, Cosenza, Italy.
[3]University of Maryland (UMD), MD, USA.
[4]Aeronautica Militare Italiana (AMI), Rome, Italy.
[5]Agenzia Spaziale Italiana - Centro di Geodesia Spaziale "Giuseppe Colombo" (ASI-CGS), Matera, Italy.
[6]Observatoire de la Côte d'Azur (OCA), Grasse, France.

MoonLIGHT / NGLR





LLR test of General Relativity

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

* Williams et al., PRL 93, 261101 (2004).

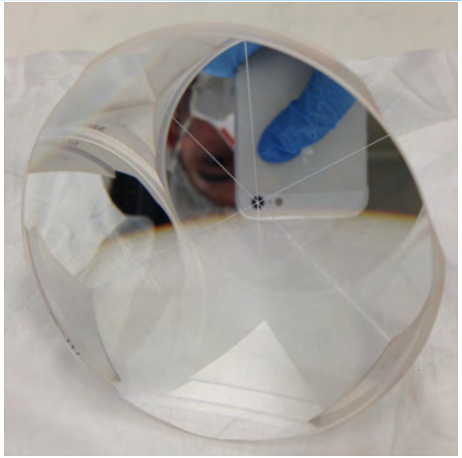
** Chandler et al., submitted to PRD, 2018.

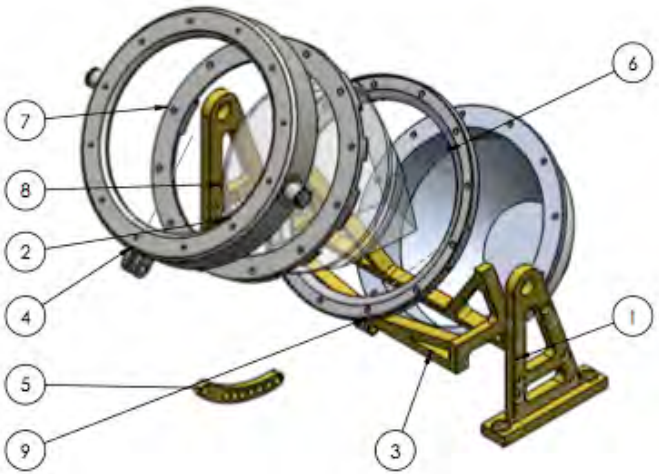
** Martini M., Dell'Agnello S. (2016), In: Peron et al. (eds.), Springer.

MoonLIGHT / NGLR

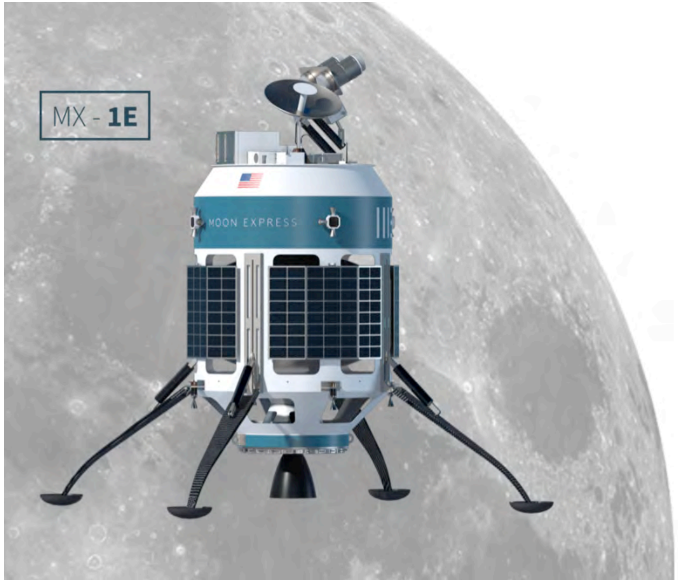
Lunar landing opportunities for MoonLIGHT / NGLR (and INRRI) include:

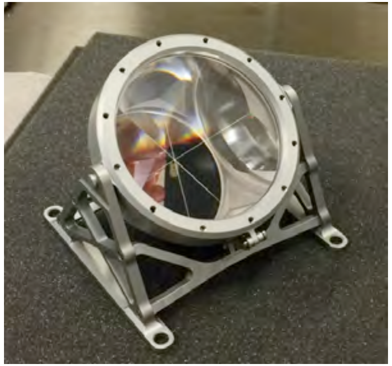
- Moon Express (US, commercial, ≥ 2020), via NASA CLPS / ROSES 2018 Calls.
- Astrobotic (US, commercial, ≥ 2020), via NASA CLPS / ROSES 2018 Calls.
- Chinese Chang'E missions.
- Team Indus (India, commercial, ≥ 2020).

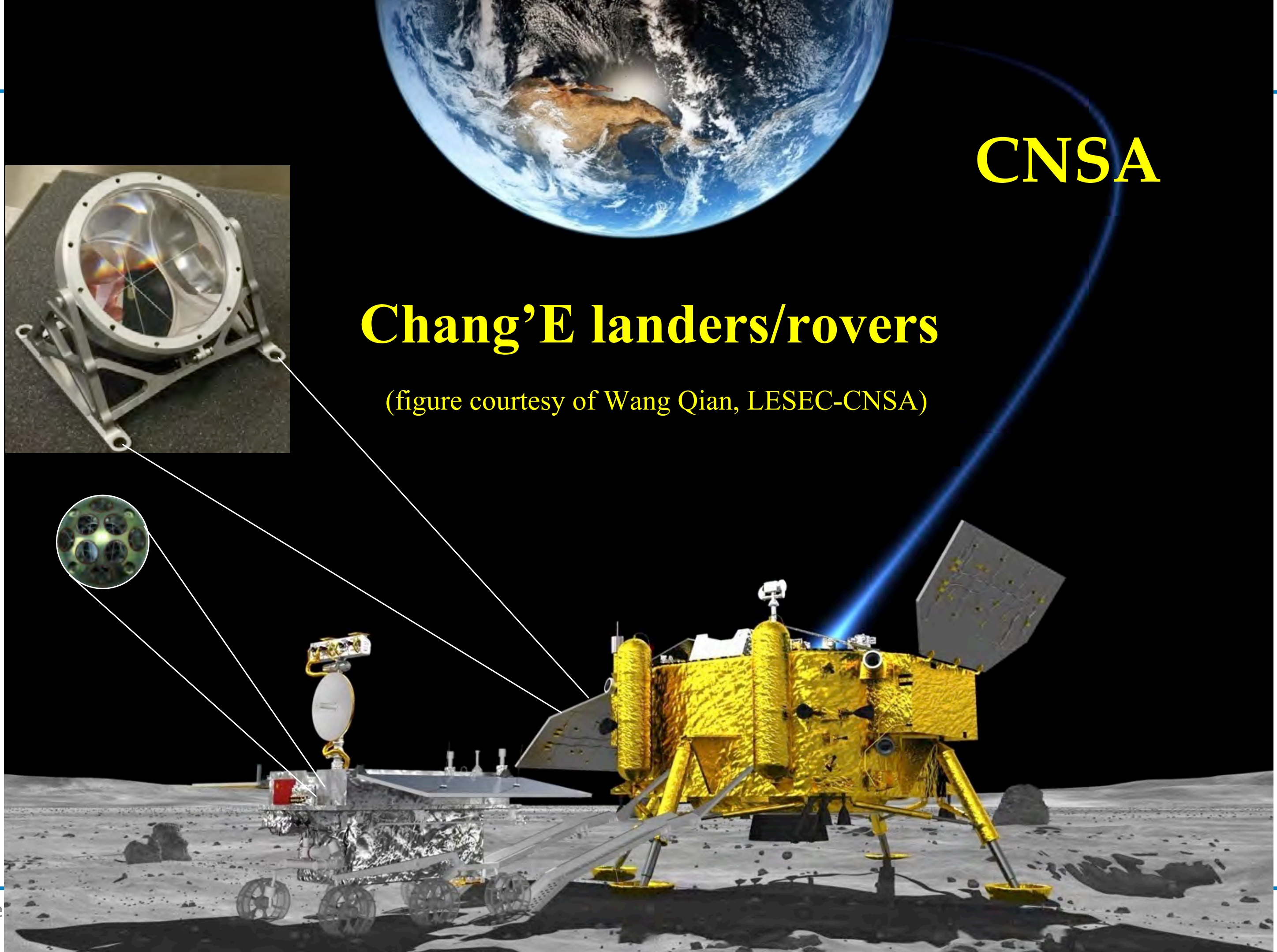




Moon Express (www.moonexpress.com)



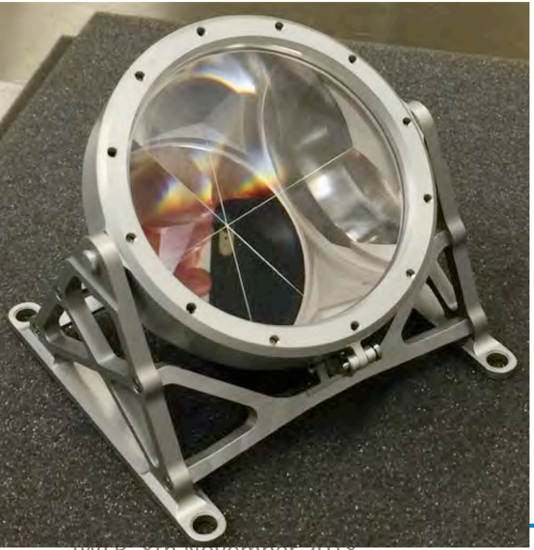


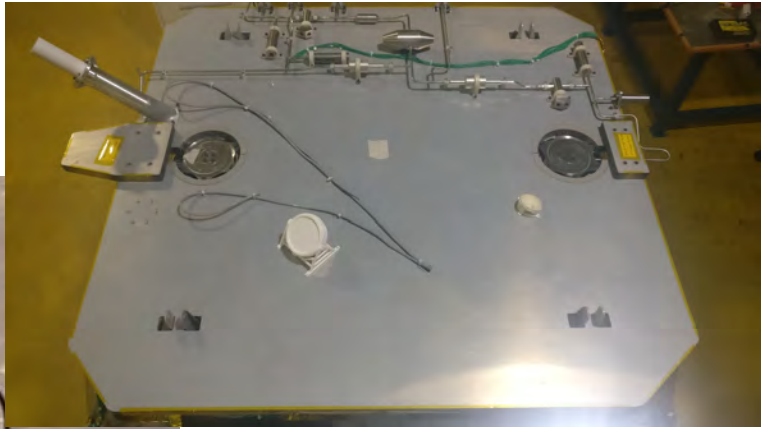

CNSA
Chang’E landers/rovers
(figure courtesy of Wang Qian, LESEC-CNSA)

MoonLIGHT / NGLR

Team Indus:

- Delivery of ML+INRRI mockups (Bangalore, August 2017).
- Delivery of FMs during 2019 after extensive testing.
- Launch ≥ 2020.





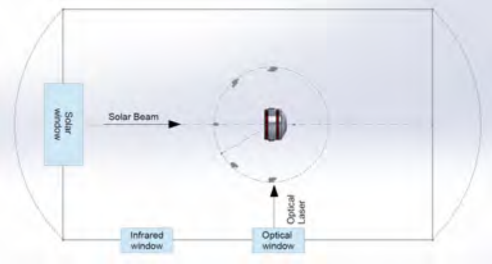
MoonLIGHT 75

MoonLIGHT 75 is a 0.5 kg, 75 mm payload designed to fit within weight constraint required by Team Indus.

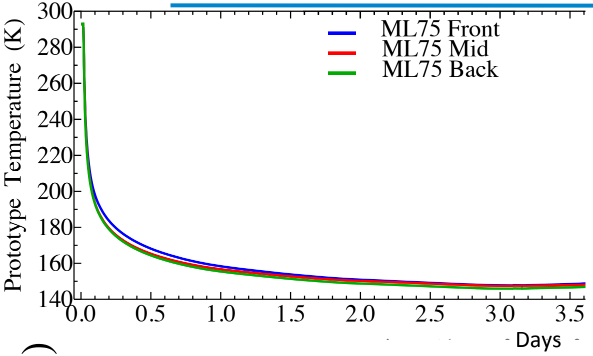
The performances of MoonLIGHT 75 were tested in the SCF_Lab through the measurements of the far field diffraction pattern, and the temperature distribution of the CCR under conditions simulating space environment during the lunar night.

Indeed, the payload always returned to the reference steady-state optical conditions, and met the required performances to guarantee an acceptable laser return for LLR purposes to the ground stations.

All the following optical tests (performed on MoonLIGHT 75 and other CCRs) were carried out with a green laser (λ = 532 nm, linear H-polarization).



MoonLIGHT 75



The test shown here lasted about 3.5 d.

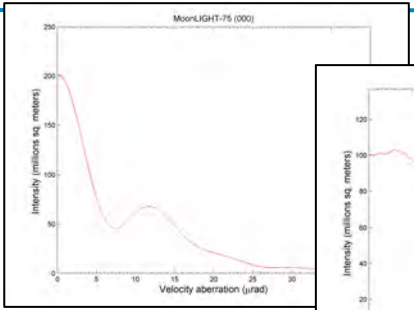
The payload was constantly facing the optical window to allow a continuous optical monitoring whilst LN2 fluxed through the cryostat.

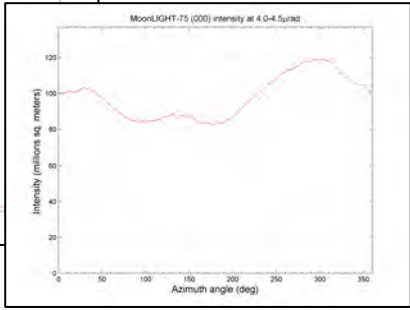
$T_{initial} \approx 290$ K, $T_{final} \approx 150$ K

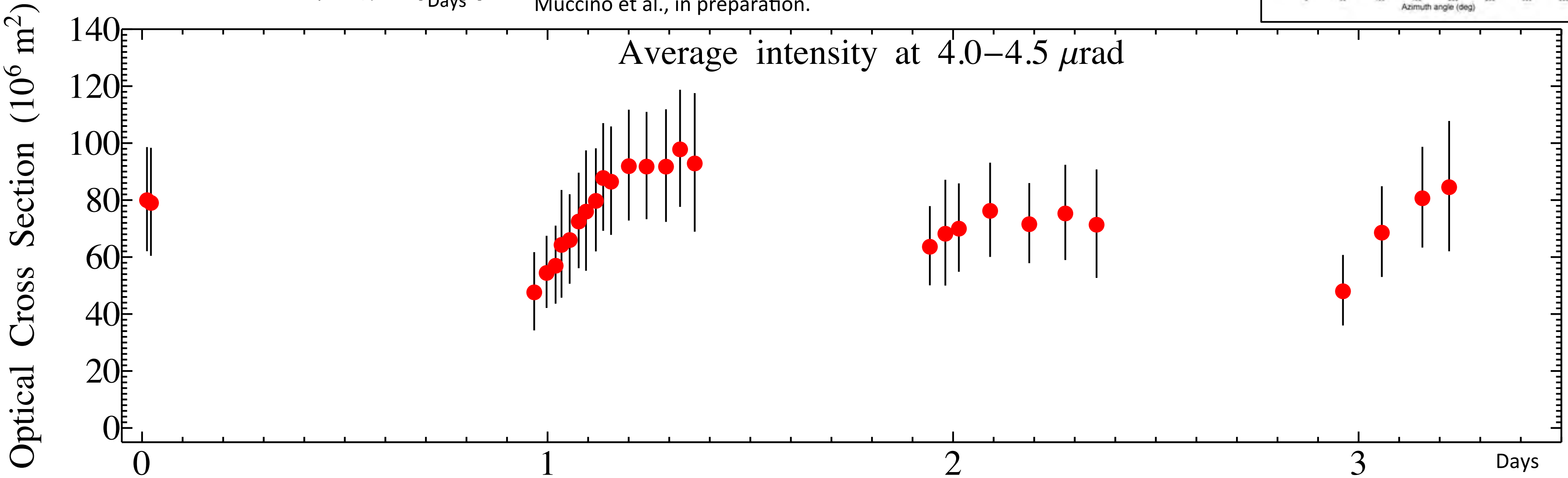
$OCS_{VA} \approx (80 \pm 16) \times 10^6$ m² (w.r.t. 100 ± 20)

$\tau_{CCR} \approx 4 \times 10^3$ s ≈ 1 h (in vacuum)

Muccino et al., in preparation.







MoonLIGHT 100

MoonLIGHT 100 is a 1.5 kg, 100 mm payload.

The test shown here lasted about 33 h.

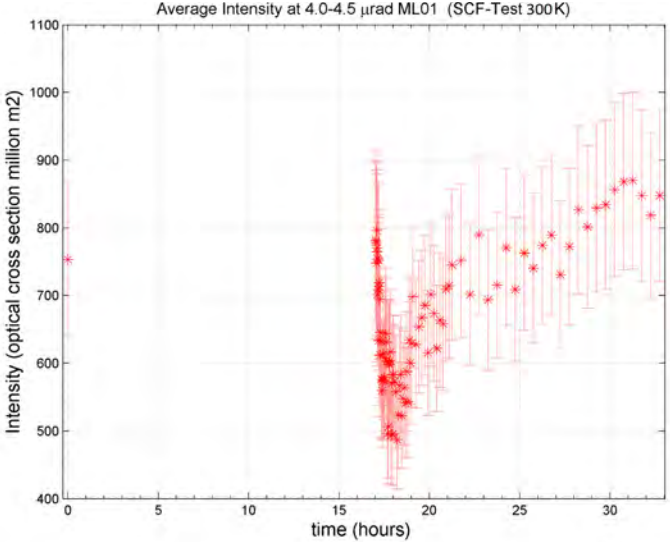
Steady state conditions; heating phase with the solar simulator for 17 h; cooling phase towards the optical window for 16 h.

$T_{ctrl} \approx 300$ K

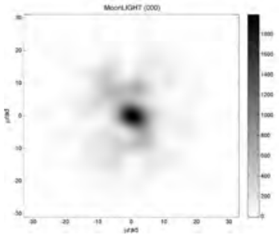
OCS_{VA} ‘unaltered’

$\tau_{CCR} \approx 10^4$ s ≈ 2.5 h (in vacuum)

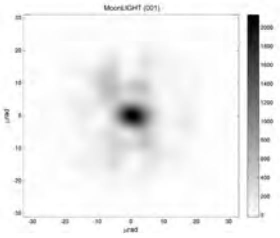
Ciocci et al., **Performance analysis of next-generation lunar laser retroreflectors**, Advances in Space Research 60 (2017), 1300-1306.



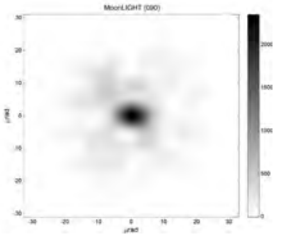
(a) Average intensity vs time at range 4.0 to 4.5μrad during the SCF-Test.



(b) 1^{st} *FFDP*

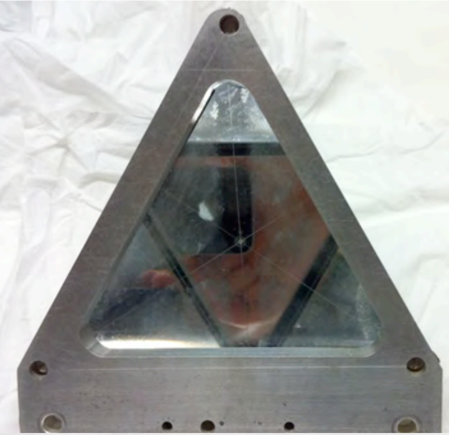


(c) 2^{nd} *FFDP*



(d) *Last FFDP*.

Lunokhod

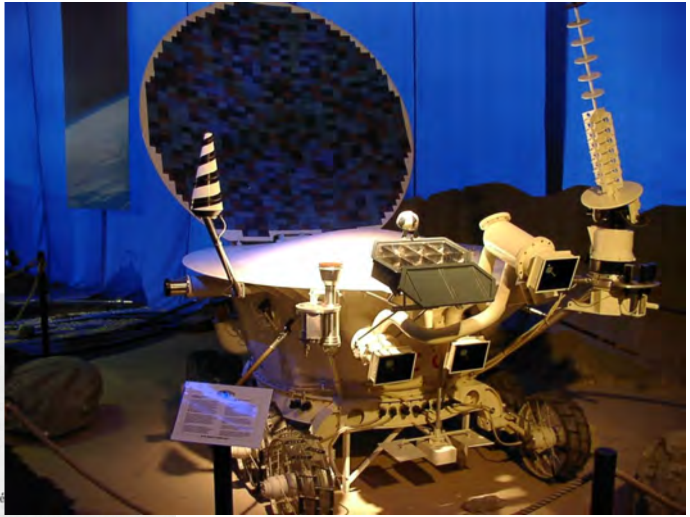


As a figure of merit, MoonLIGHT / NGLR thermal and optical behaviours were compared to those of the one of the very few remaining Lunokhod CCRs, cut and polished in France about 50 years ago.

Extended comparisons will be shown in a following paper.

INFN is truly thankful to OCA for providing the retroreflector.

Fournet, **Le reflecteur laser de Lunokhod**, Space Research XII - Akademie-Verlag, Berlin 1972.



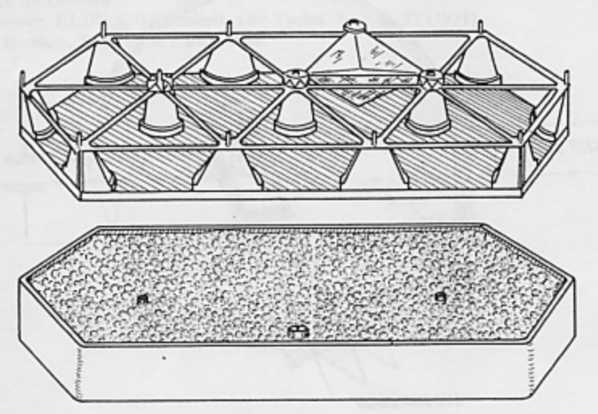


Fig. 8. Structure et conditionnement thermique.

Space Research XII — Akademie-Verlag, Berlin 1972

LE REFLECTEUR LASER DE LUNOKHOD

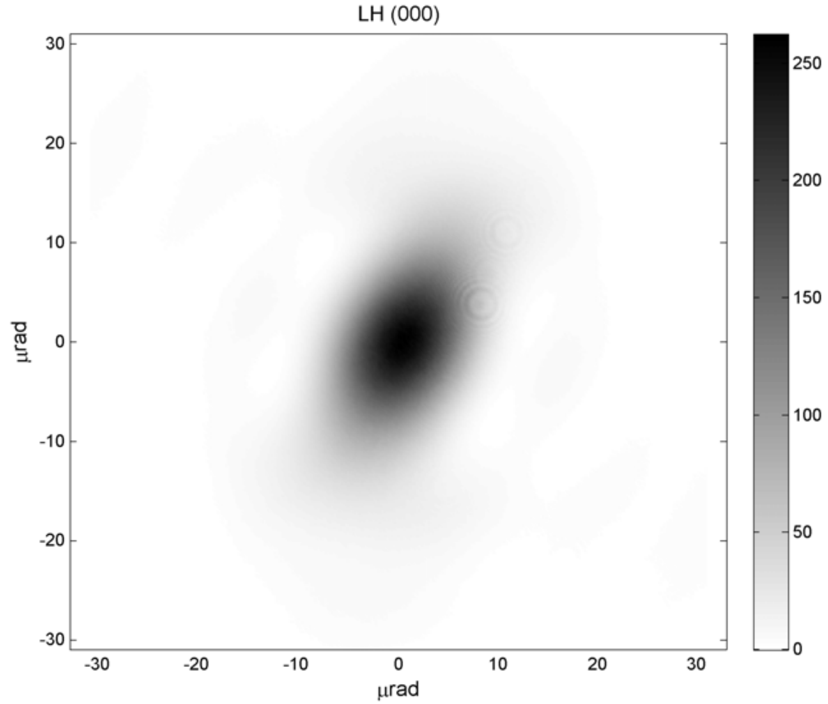
M. FOURNET

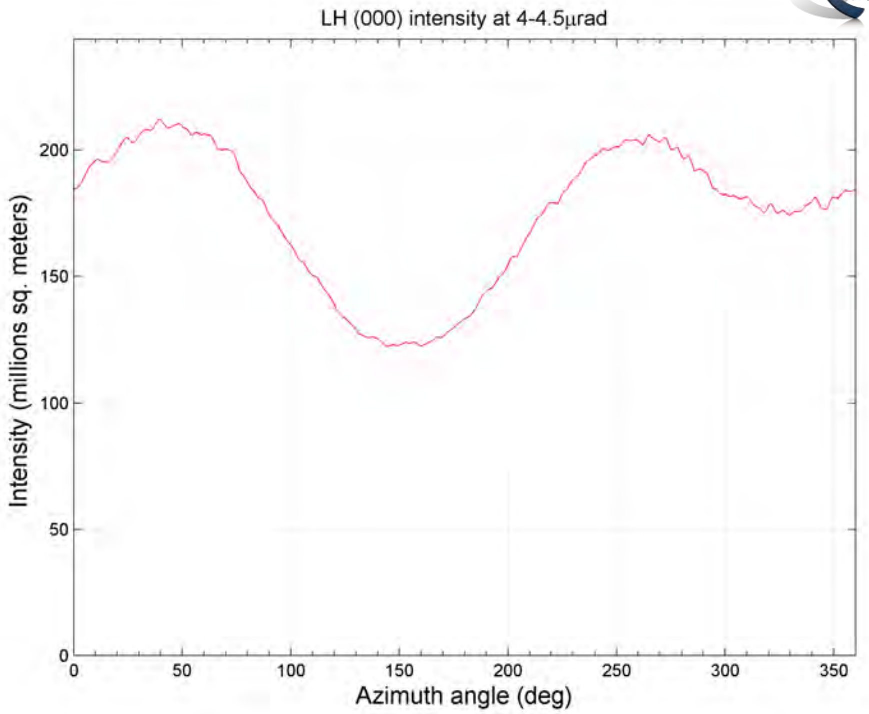
Direction des Programmes et du Plan, Centre National d'Etudes Spatiales, Bré

The Lunokhod panel was deposited on the moon by Luna 17 on 17 November 1970 in order to allow the earth–moon ranging experiment to be undertaken. Due to thermal problems, it was accepted that the first objective would be night-time operation. Therefore the adopted design is founded on a good thermal equilibrium hypothesis. The retroreflectors are quite large (triangular aperture of 10.6 cm side) and the rear surfaces are coated with silver. Experimental results on the optical bench are in agreement with theoretical predictions. Constructing the reflector needs much manual adjustment. A special photoelectric interferometer, giving an accuracy to 0″.1 was designed for successive tests.

Thermal decoupling from moon environment was made very carefully. An optical evaluation in simulated moon environment conditions was made; this confirmed the capability of the instrument for night-time use and showed a great deterioration 12 hours after sunrise.

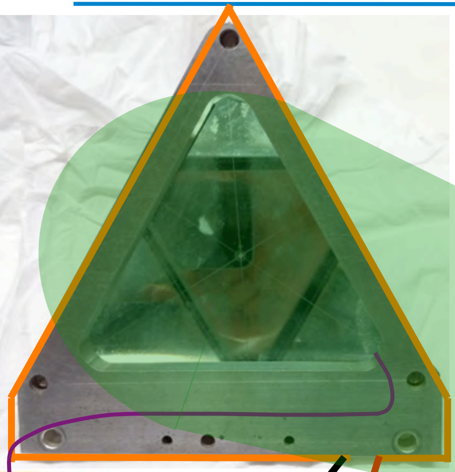
Lunokhod





FFDP in air at T = 21.8 ˚C

Lunokhod



CCR in air on the optical bench. Steady state FFDP acquired at $T_{initial}$ = 21.8 ˚C (previous slide).

DC power supply heated up the CCR pumping 10 W for 20 min through heater tape resistor.

After 20 min, T_{MAX} = 80.0 ˚C; power supply was switched off, and first cooling FFDP was acquired (next slide).

Thereafter, 4 more FFDPs were acquired. At the end of the test, temperature of the CCR was back at $T_{initial}$ = 21.8 ˚C (next slide).

OCS_{VA} spanning over 2 order of magnitudes

$\tau_{CCR} \approx 4 \times 10^3$ s ≈ 1 h (in air)

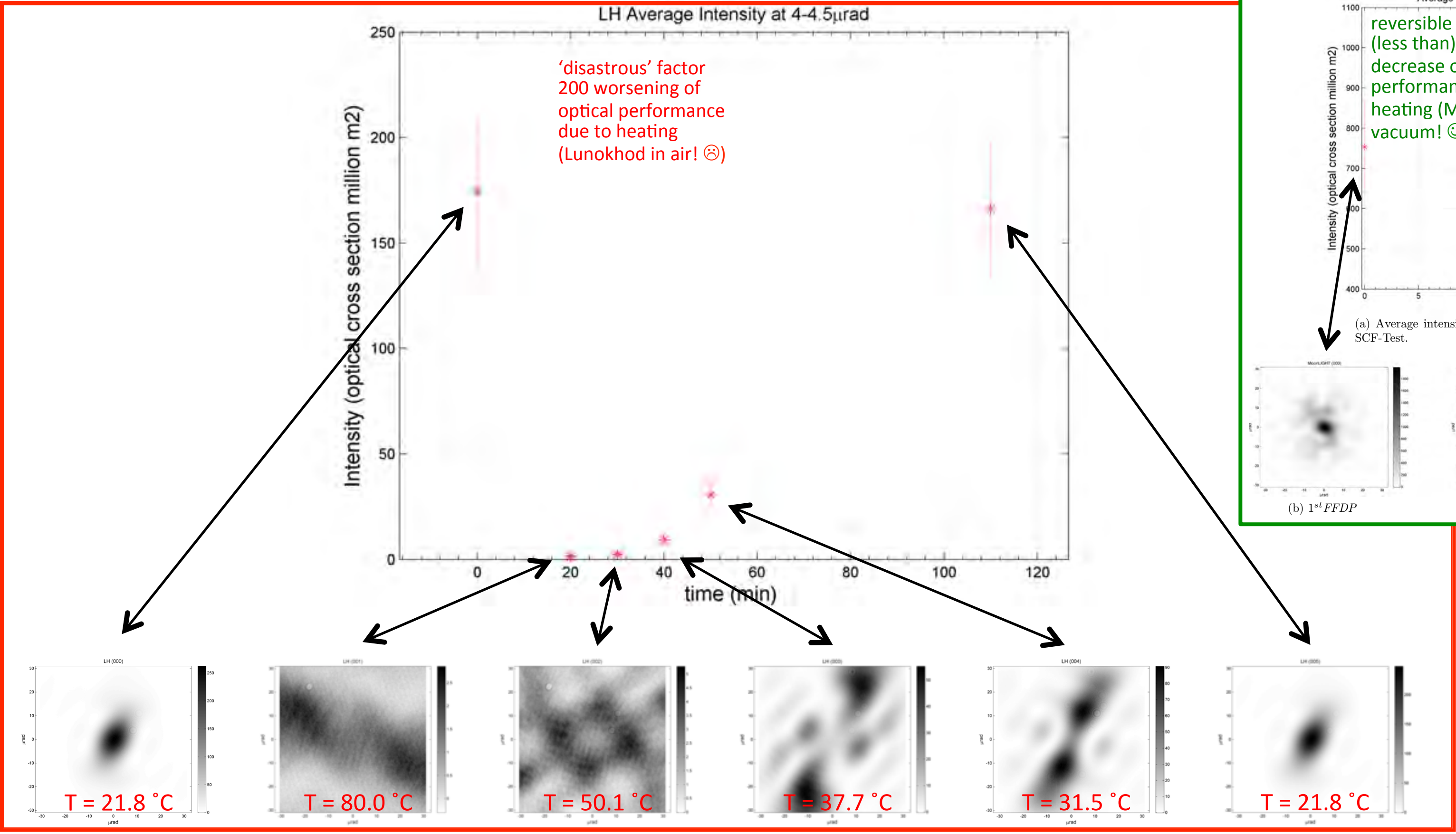
Extended comparisons will be shown in a following paper.

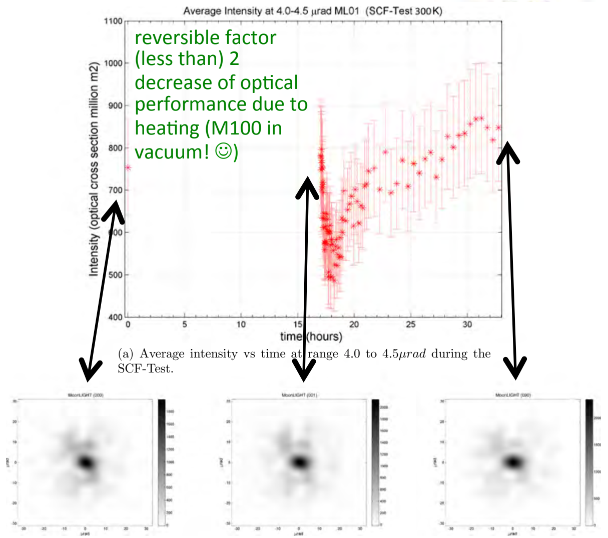
thermocouple thermometer

DC power supply

optical bench simulating LLR far-field operations

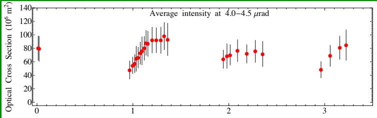
Lunokhod vs. MoonLIGHT





(a) Average intensity vs time at range 4.0 to 4.5μrad during the SCF-Test.

(b) 1st *FFDP* (c) 2nd *FFDP* (d) *Last FFDP.*



contained factor
(less than) 2
decrease of optical
performance due to
cooling (M75 in
vacuum! ☺)

MoonLIGHT / NGLR summary

- 'Big' (75 mm and 100 mm) single-CCR space-qualified retroreflector payload ready for hot and cold lunar environments, awaiting for installation on board next lunar landers.

- It will improve fundamental physics measurements as per our past and future works:

  - Martini M., Dell'Agnello S. (2016), ***Probing Gravity with Next Generation Lunar Laser Ranging***, In: Peron et al. (eds.), ***Gravity: Where Do We Stand?***, Springer.

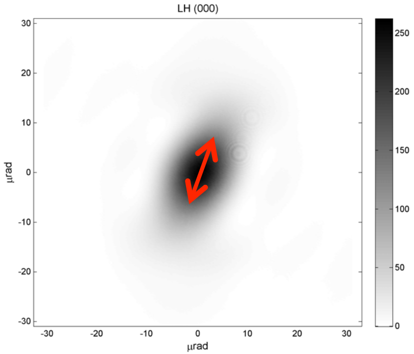
  - Ciocci et al., ***Performance analysis of next-generation lunar laser retroreflectors***, Advances in Space Research 60 (2017), 1300-1306.

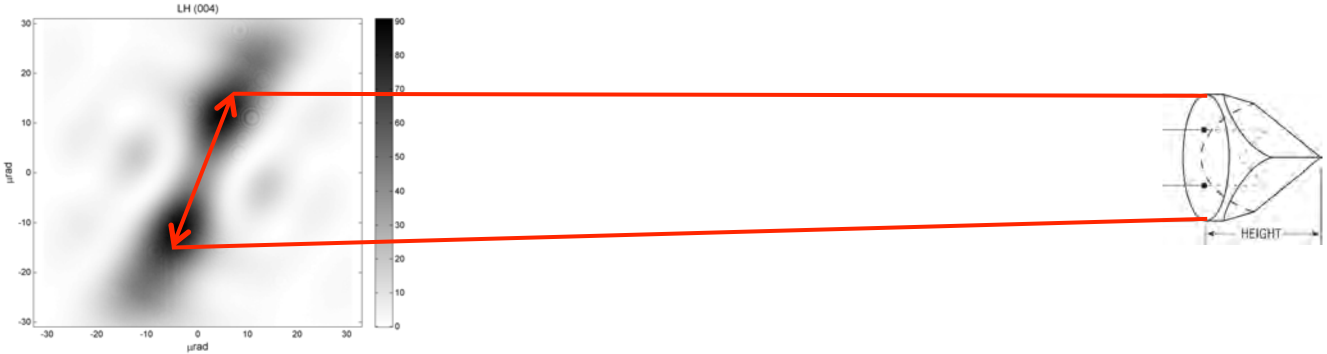
  - Chandler, J. F., Luongo, O., Muccino, M., Porcelli, L., Tantalo, M., Dell'Agnello, S., ***Simulating Solar System constraints in f(R) gravity via Lunar Laser Ranging***, submitted to PRD, 2018.

- Comparison with Lunokhod coated cube further showed the goodness of selecting MoonLIGHT / NGLR uncoated cubes for next-generation lunar laser ranging.

- MoonLIGHT / NGLR will be coupled with an INRRI-like device (routinely on board Mars landers, as described by M. Muccino in his talk and Porcelli et al., accepted by Space Science Reviews, 2018).

Lunokhod thermochromism? - ROM approach





- T = 21.8 ˚C.
- Steady state.
- Roughly less than 10 μrad on FFDP plane.

- T = 31.5 ˚C.
- Energy moves out.
- Roughly more than 10 μrad on FFDP plane.
- 532 nm 'blindness'.

Let's 'translate' the thermal widening of the FFDP into a physically optical deformation of the CCR generated by the heating.

Caveat: this is a very ROM approach!

$$10\ \mu\text{rad} \times 5\ \text{cm} \approx 10^{-5}\ \text{rad} \times 5 \times 10^{-2}\ \text{m} \approx 500\ \text{nm} \approx \lambda\ @\ 532\ \text{nm}$$

$$10\ \mu\text{rad} \times 5\ \text{cm} \approx 10^{-5}\ \text{rad} \times 5 \times 10^{-2}\ \text{m} \approx 500\ \text{nm} \approx \lambda/2\ @\ 1064\ \text{nm}$$

$$10\ \mu\text{rad} \times 5\ \text{cm} \approx 10^{-5}\ \text{rad} \times 5 \times 10^{-2}\ \text{m} \approx 500\ \text{nm} \approx \lambda/3\ @\ 1555\ \text{nm}$$

…and $D_{FFDP} \approx \text{const} \times \lambda$,

but $\sigma_{CCR} \approx \text{const} \times \lambda^{-2}$