# MoonLIGHT-2

INFN-CSN2 Experiment - Test of Gravity and Planetary Sciences in the Solar System

CSN2 Workshop - 12-13 November 2020
https://agenda.infn.it/event/24144/

Luca Porcelli (INFN-LNF) for the MoonLIGHT-2 Collaboration

Partner Space Agencies:

# MoonLIGHT-2

Italian Participants:
INFN-LNF ~ 10 FTE + SCF_Lab (Dell'Agnello)
INFN/University - Padova ~ 2 FTE (Villoresi)
INFN/University - Napoli ~ 2 FTE (Capozziello)
ASI-Matera Laser Ranging Observatory ~ 5 FTE + Joint Lab (Bianco)

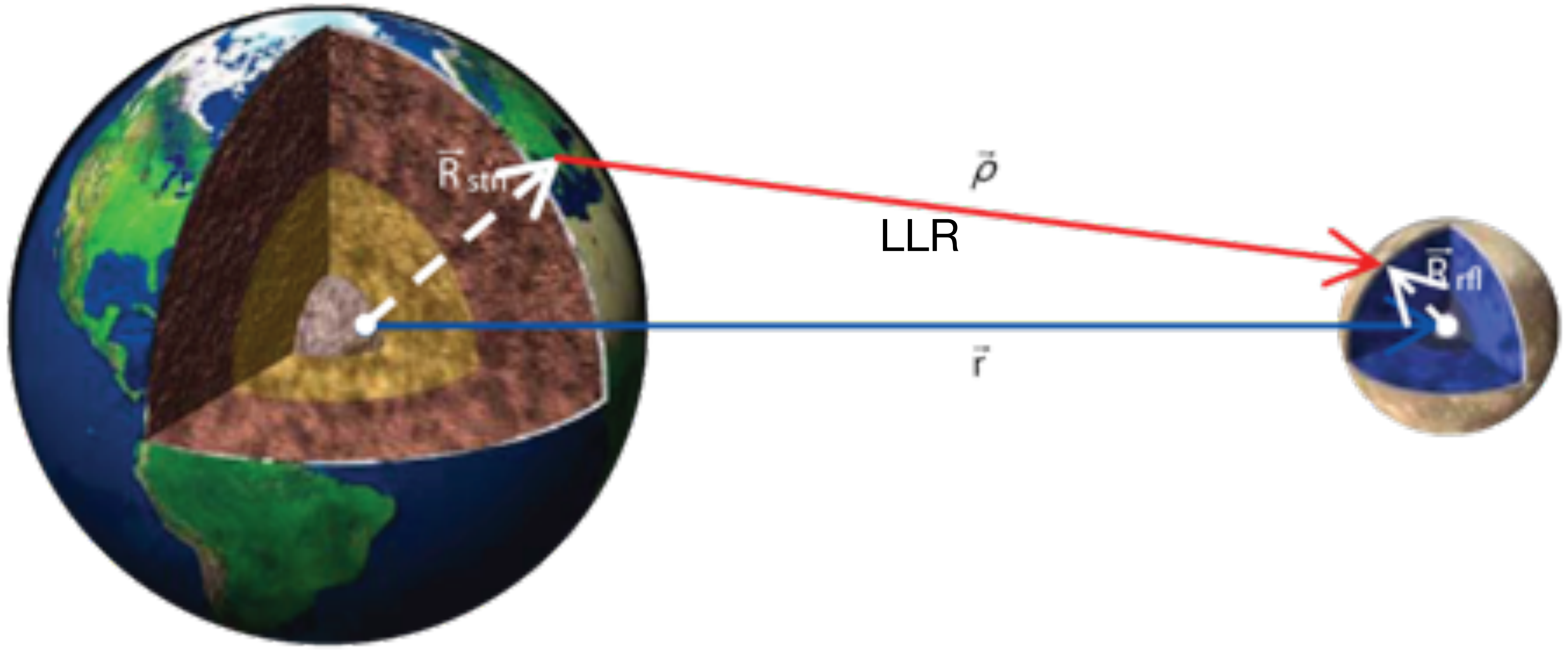
USA Participants:
University of Maryland (UMD) at College Park, MD
Harvard-Smithsonian Center for Astrophysics (CfA), Cambridge, MA
University of California at San Diego (UCSD)
NASA-SSERVI

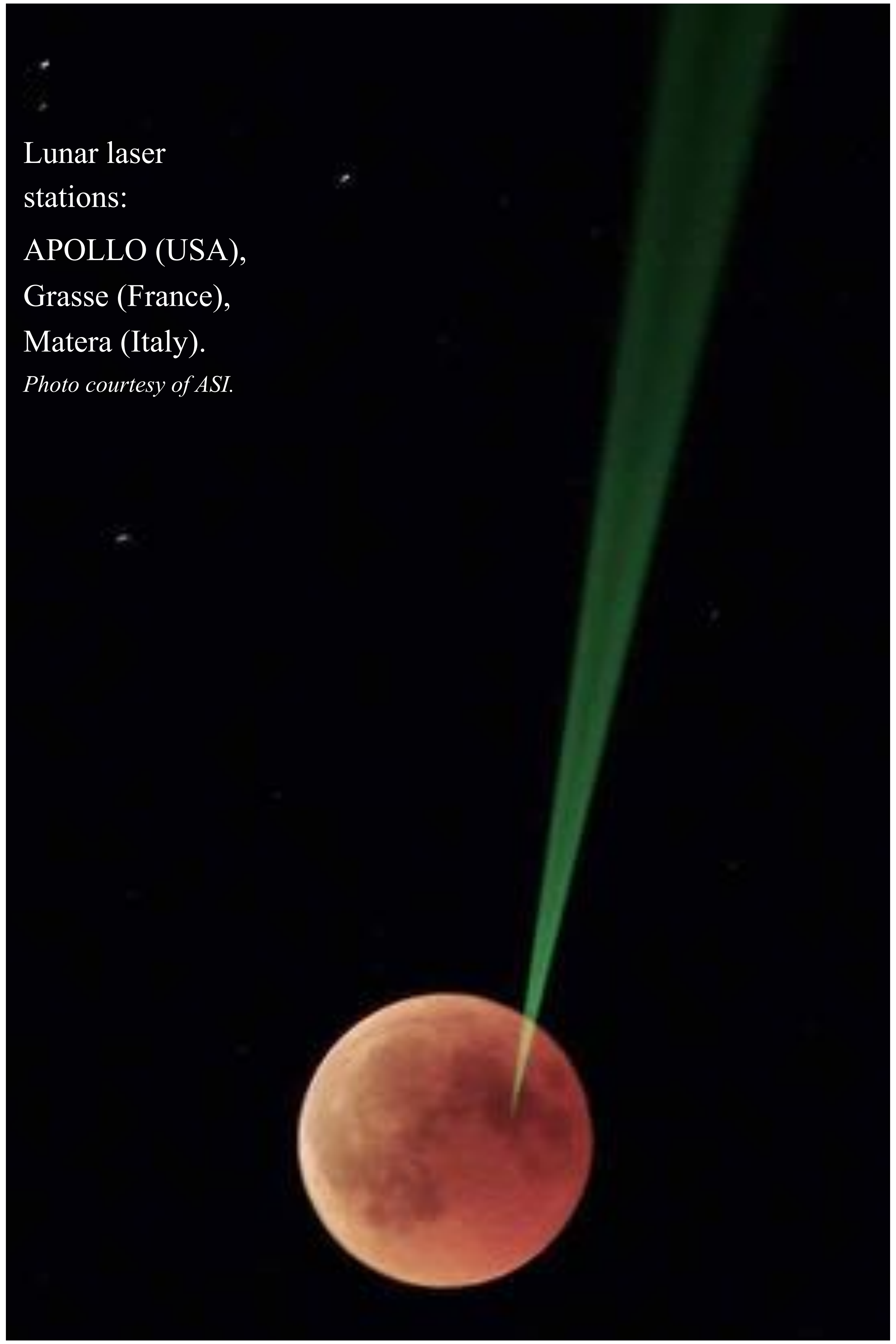
Approved flights:
NASA (Prime = Intuitive Machines): by 2021
NASA (Prime = TBD): by 2022
ESA (Prime = TBD): by 2022

# Satellite/Lunar Laser Ranging (SLR/LLR)

Accurate Time of Flight (ToF) of short laser pulses, timed by accurate ground atomic clocks.

Right: LLR during lunar eclipse of July 28, 2018 from ASI-Matera.



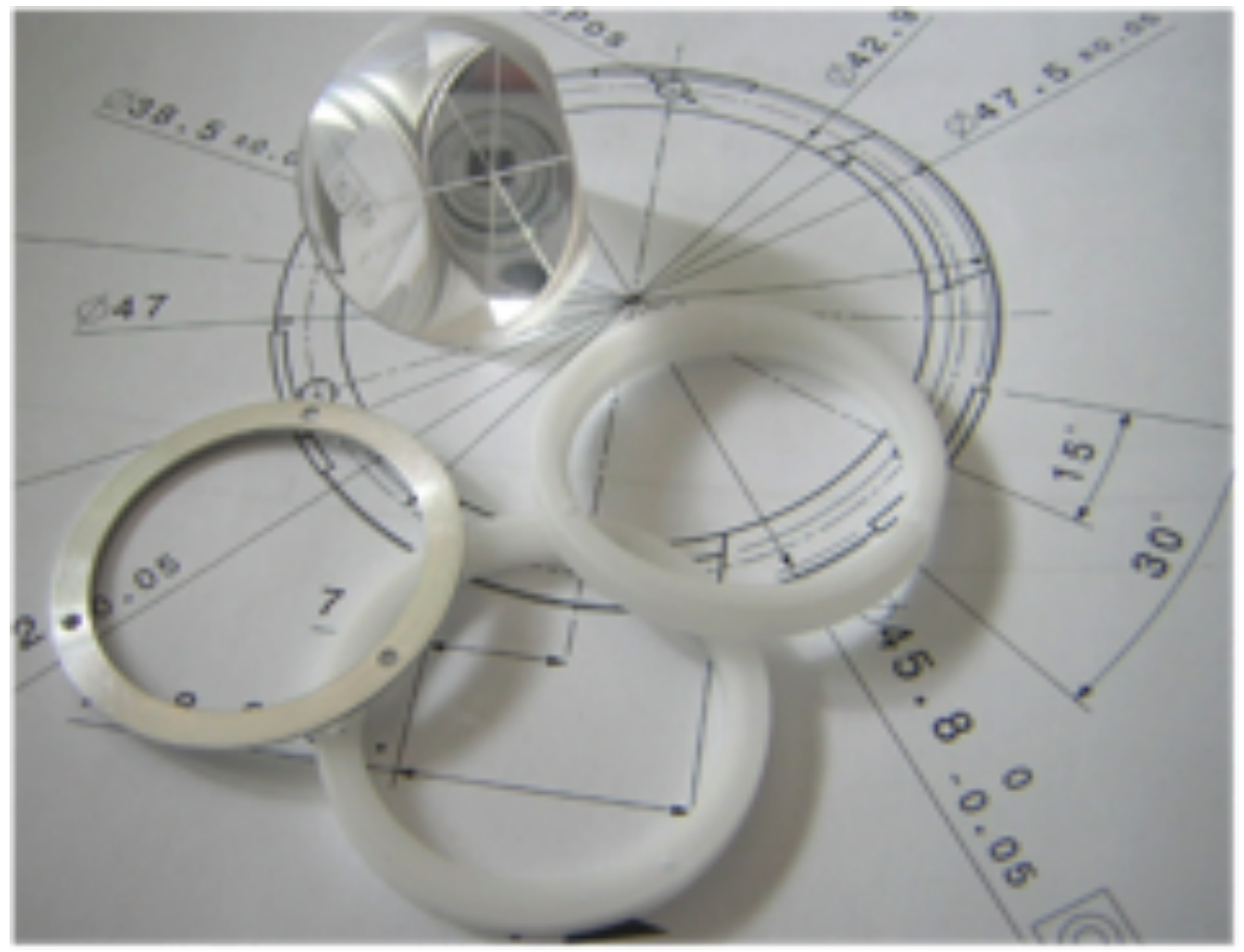


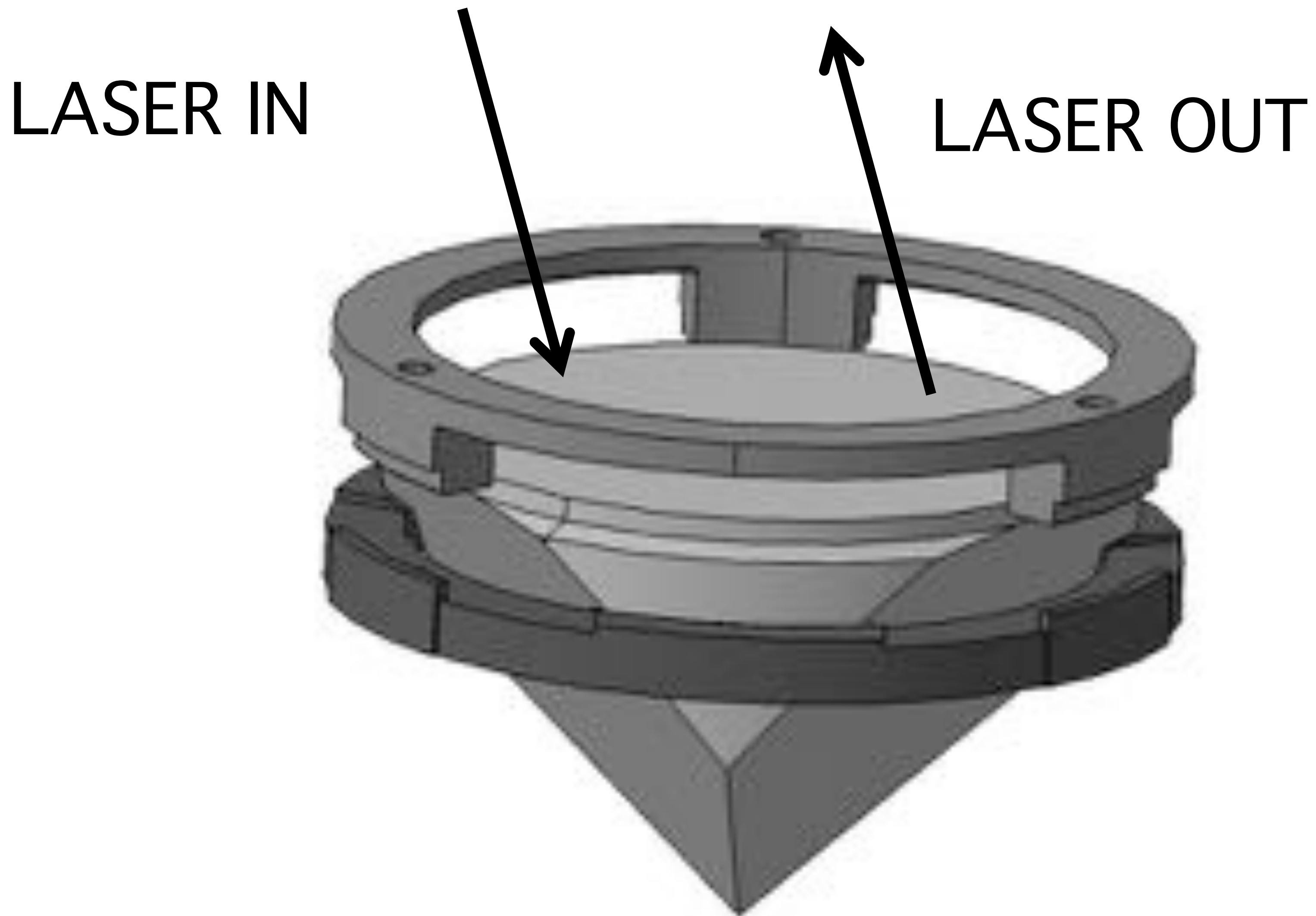
Lunar laser stations:

APOLLO (USA),
Grasse (France),
Matera (Italy).

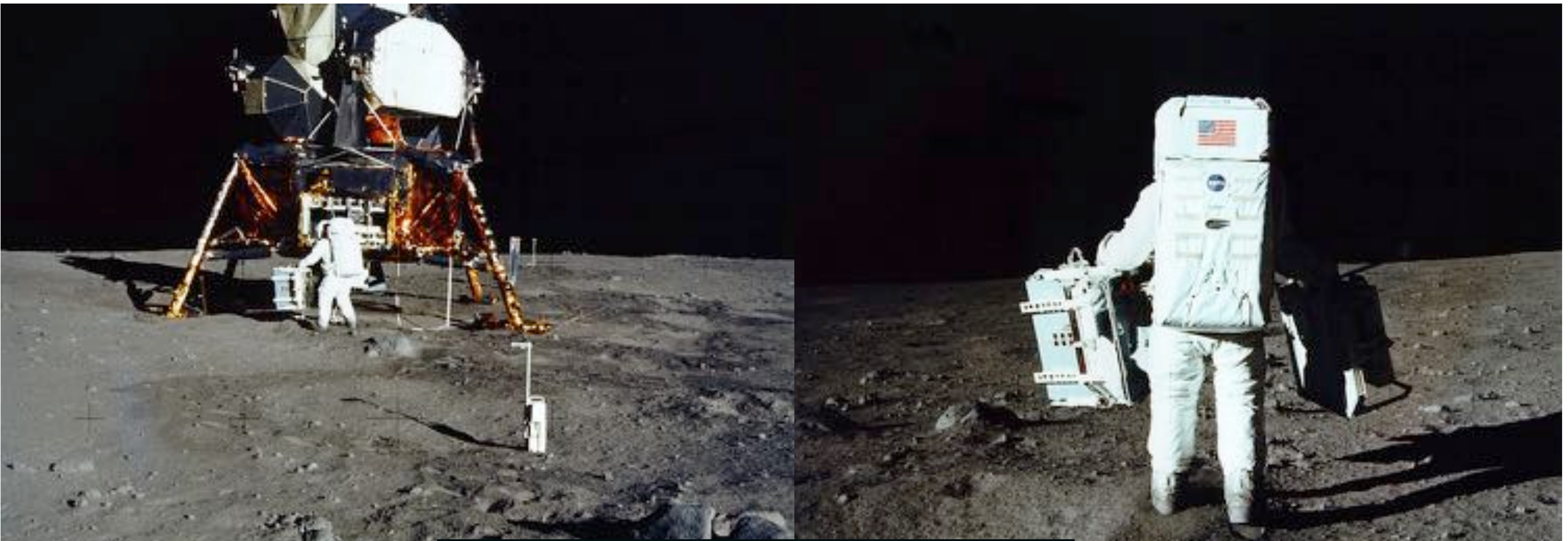
*Photo courtesy of ASI.*

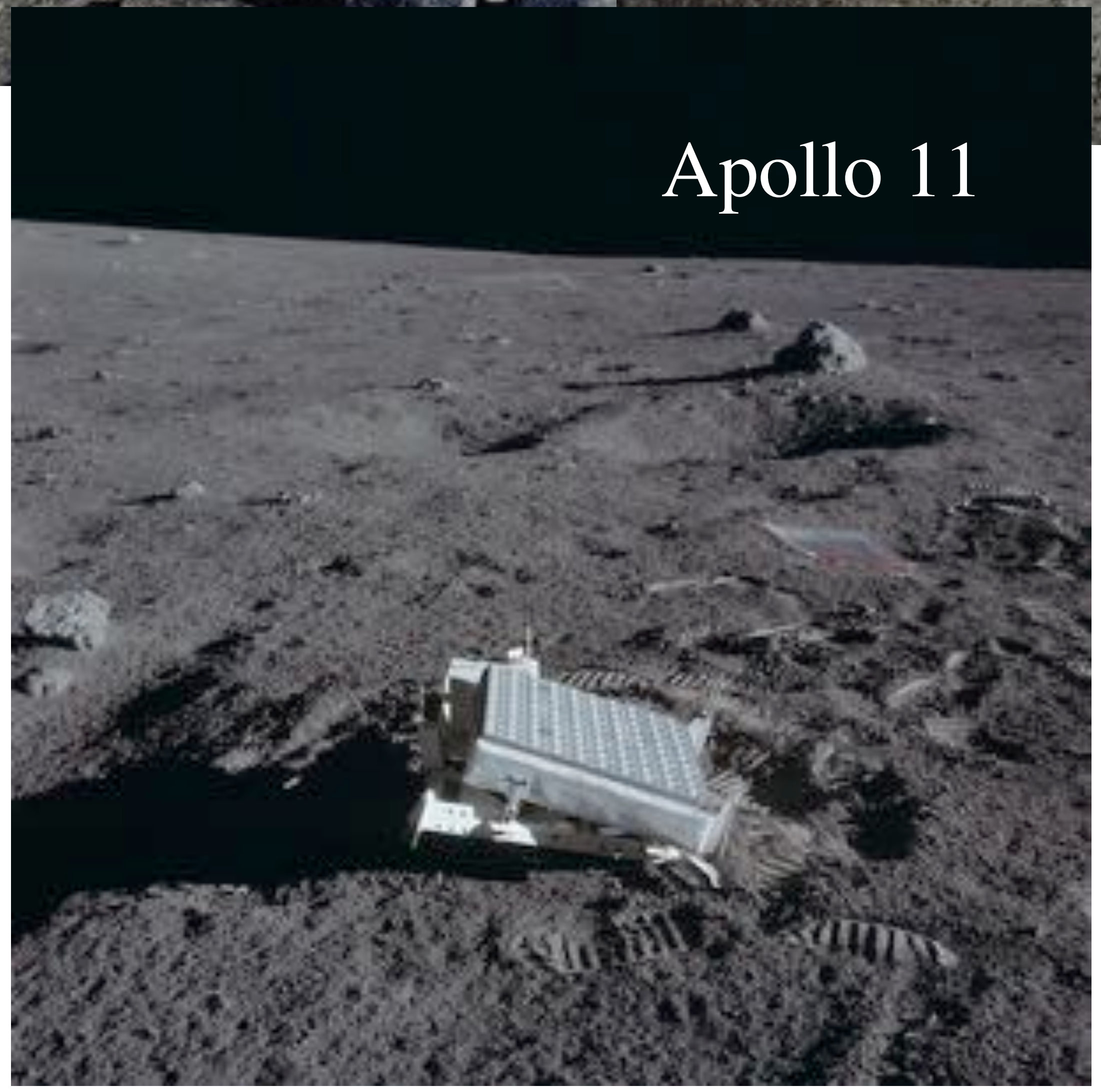
# Cube Corner Retroreflectors (CCRs)

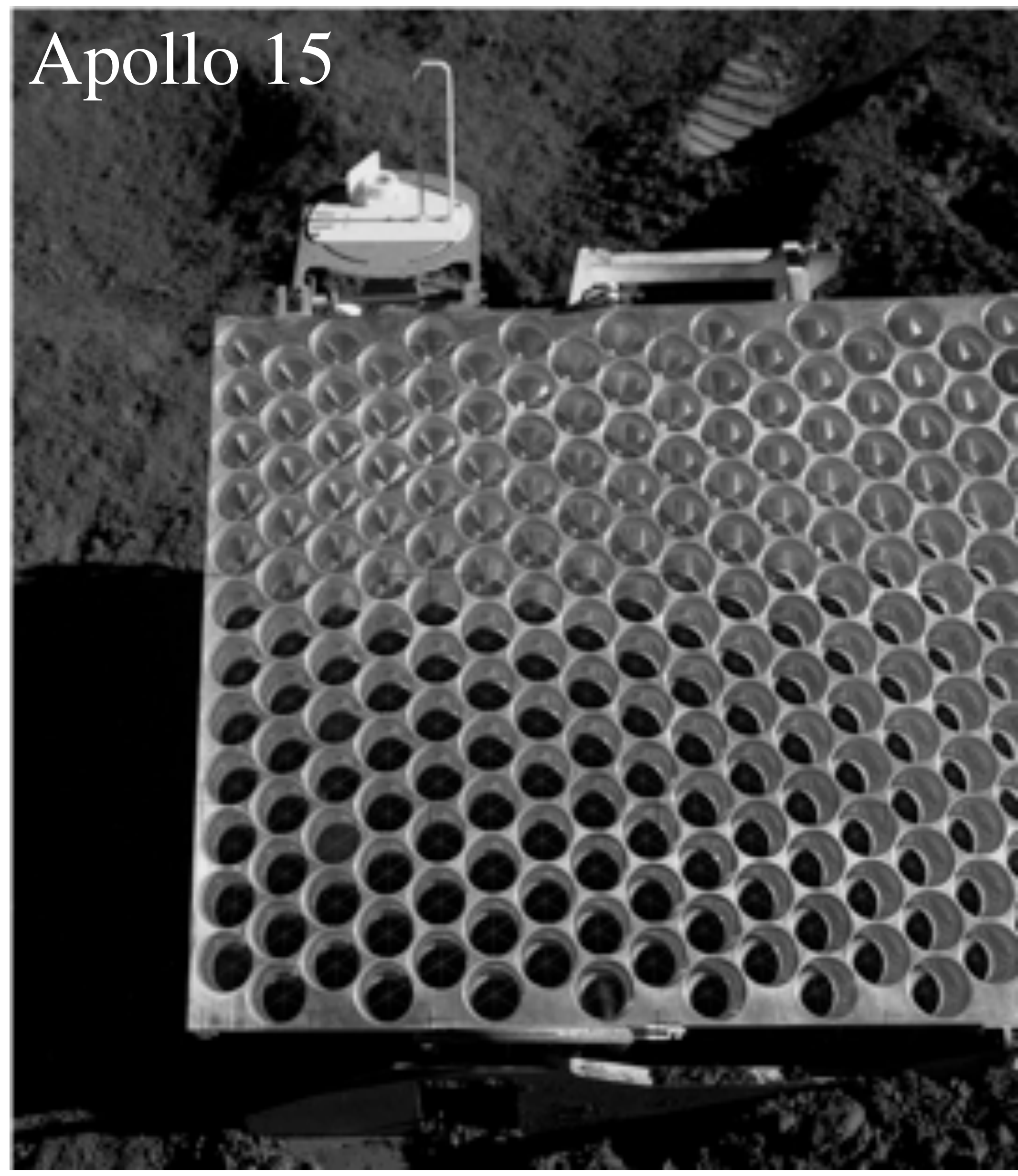


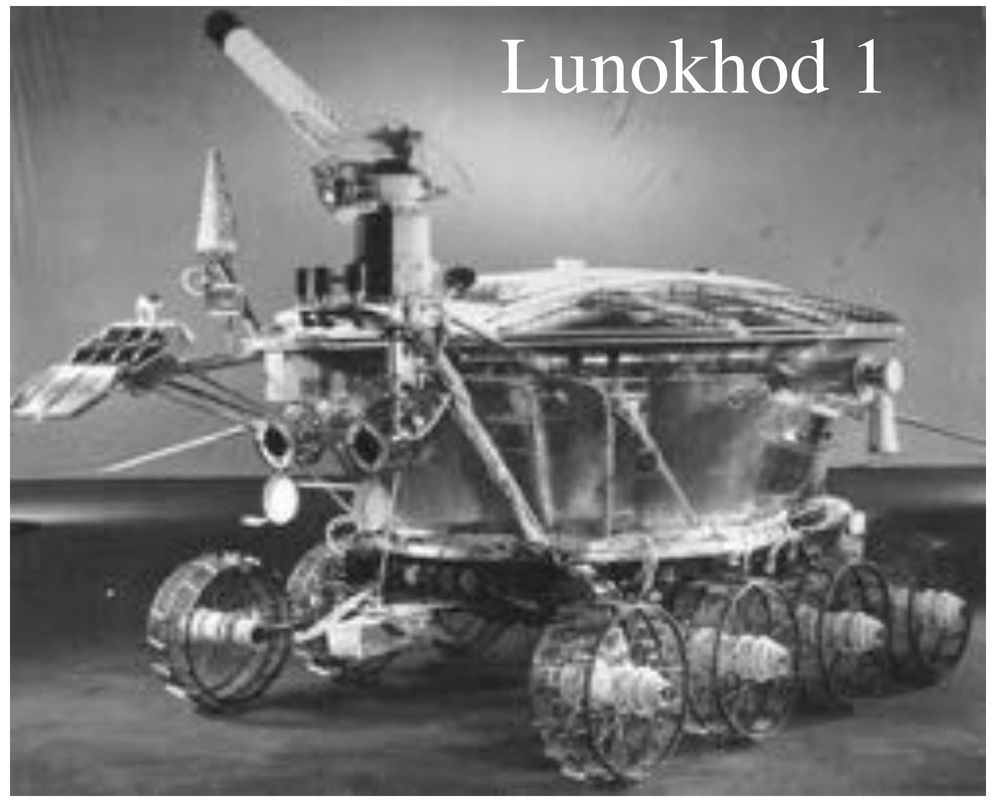


# Cube Corner Retroreflectors (CCRs)



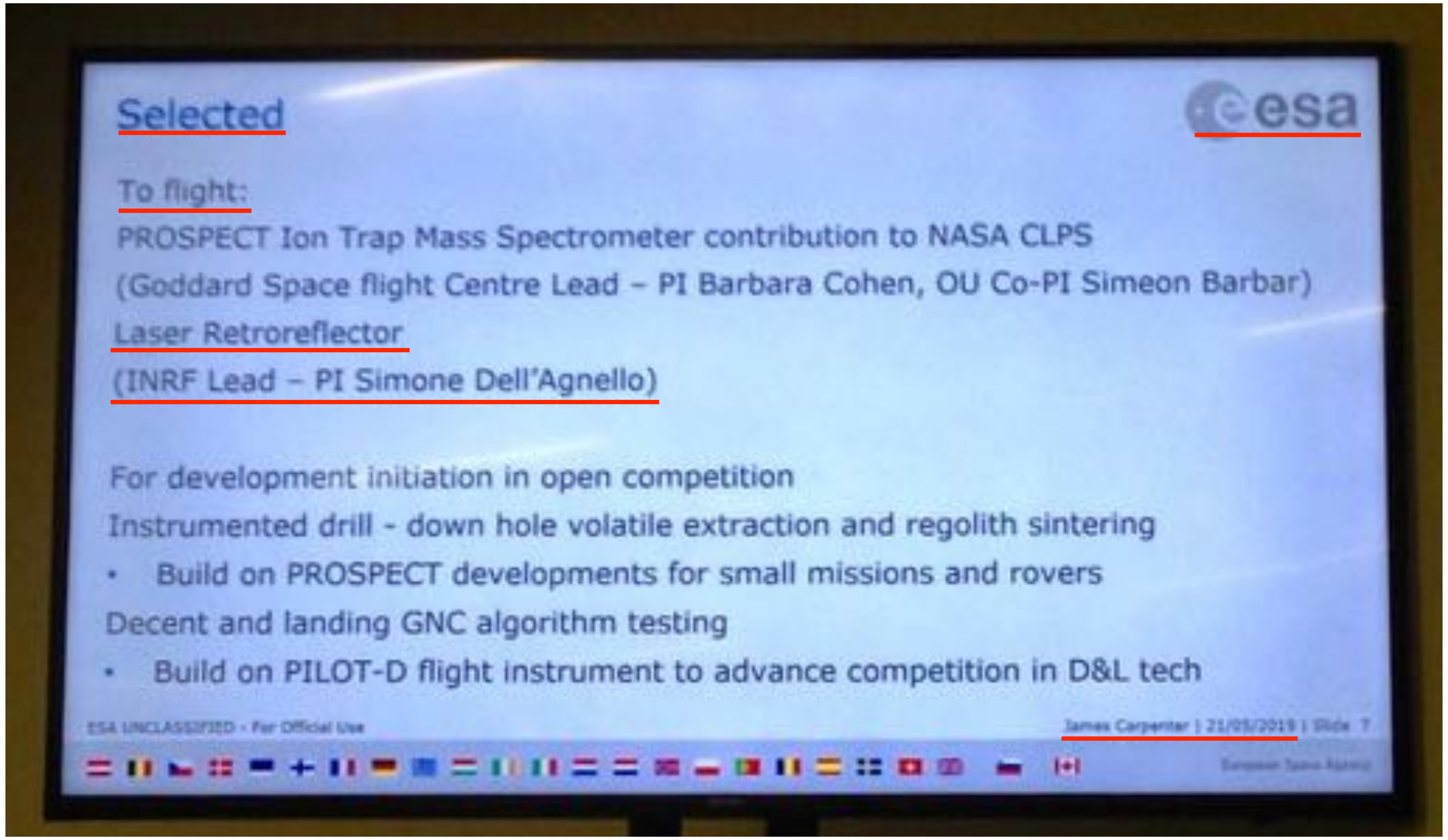






# MoonLIGHT

Selected for ESA MoO in May 2019 (response to the ESA RfI on Lunar Exploration Campaign Science and Technology Payloads due in late 2018):
- Publicly announced at the European Lunar Symposium 2019 by James Carpenter (ESA).
- INRF = INFN Retroreflector Frascati (one more acronym ☹).
- Flight will be a NASA-CLPS (w/ MPAc = MoonLIGHT Pointing Actuator).
- Also in 2019, arose a NASA-LSITP/CLPS (for fixed pointing hardware).



Selected

To flight:

PROSPECT Ion Trap Mass Spectrometer contribution to NASA CLPS

(Goddard Space flight Centre Lead – PI Barbara Cohen, OU Co-PI Simeon Barbar)

Laser Retroreflector

(INRF Lead – PI Simone Dell'Agnello)

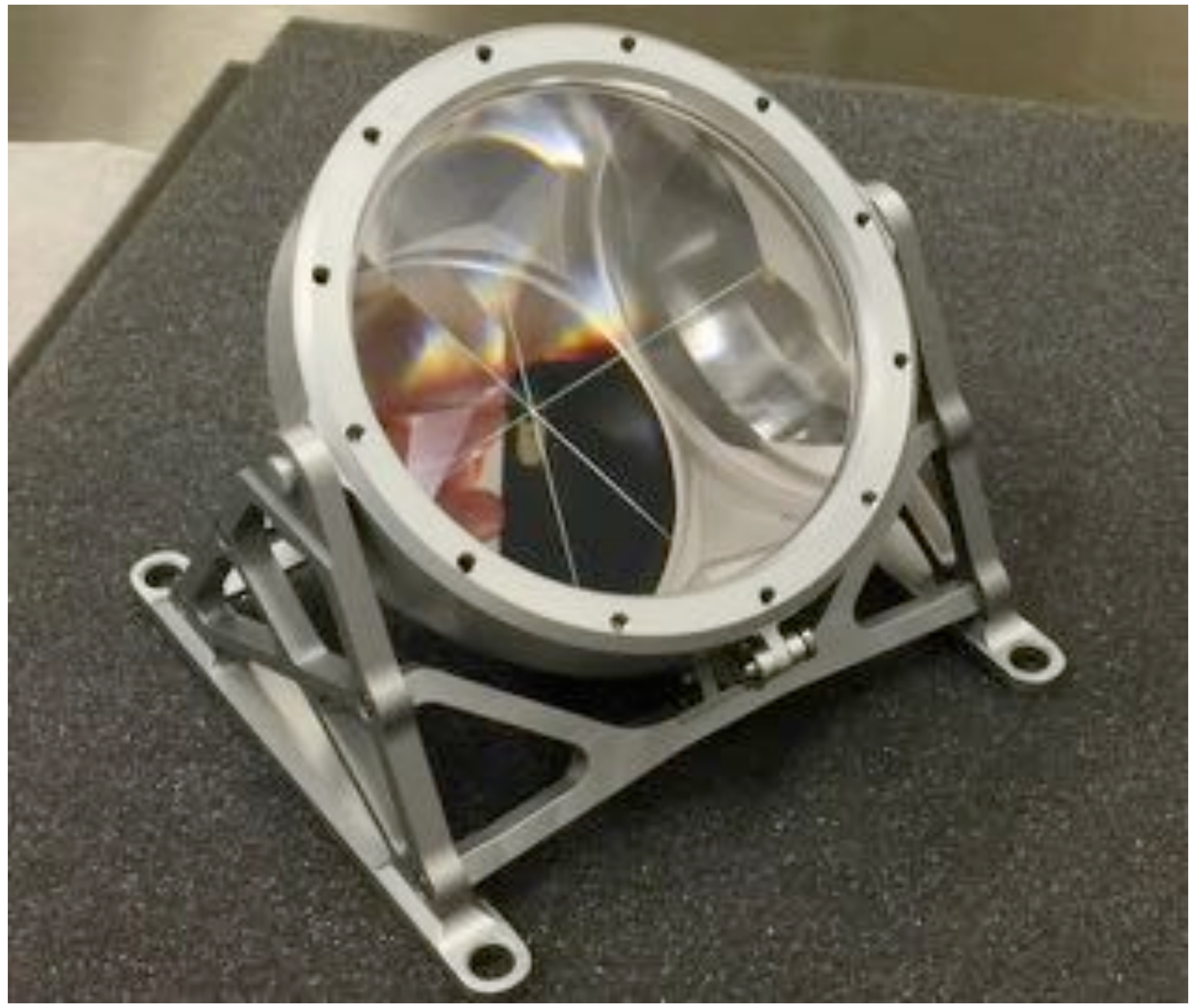
For development initiation in open competition

Instrumented drill - down hole volatile extraction and regolith sintering
- Build on PROSPECT developments for small missions and rovers

Decent and landing GNC algorithm testing
- Build on PILOT-D flight instrument to advance competition in D&L tech

ESA UNCLASSIFIED - For Official Use

James Carpenter | 21/05/2019 | Slide 7



**MoonLIGHT-100/NGLR = Moon Laser Instrumentation for General relativity High accuracy test (INFN-LNF)/Next Generation Laser Retroreflector (UMD). This 100 mm single, solid, large reflector is intended for direct lunar laser ranging from stations in USA, Italy (ASI-CGS) and France (Grasse). Its main applications are the Lunar Geophysical Network (LGN) and precision tests of General Relativity and new theories of fundamental relativistic gravity.**

# Next-Gen Lunar CCR Select. by NASA for LSITP

PI = D. Currie of University of Maryland
Co-PI group = SCF_Lab of INFN

**July 2, 2019**: Next-Gen Lunar Reflector selected by NASA for LSITP

"... target for lasers on Earth to precisely measure the Earth-Moon distance ... and address questions of fundamental physics."

# MoonLIGHT + MPAc

## LUNAR LASER RETROREFLECTOR POINTING ACTUATOR

proposal for ESA

**ESA RFP/3-16160/19/NL/TFD**

SCF_Lab

INFN Laboratori Nazionali di Frascati

Negotiation Meeting with ESA

Doc. Number: INFN-LNF-MPAc-2019-10-09-NMP - place: telecon - date: Oct. 9th, 2019

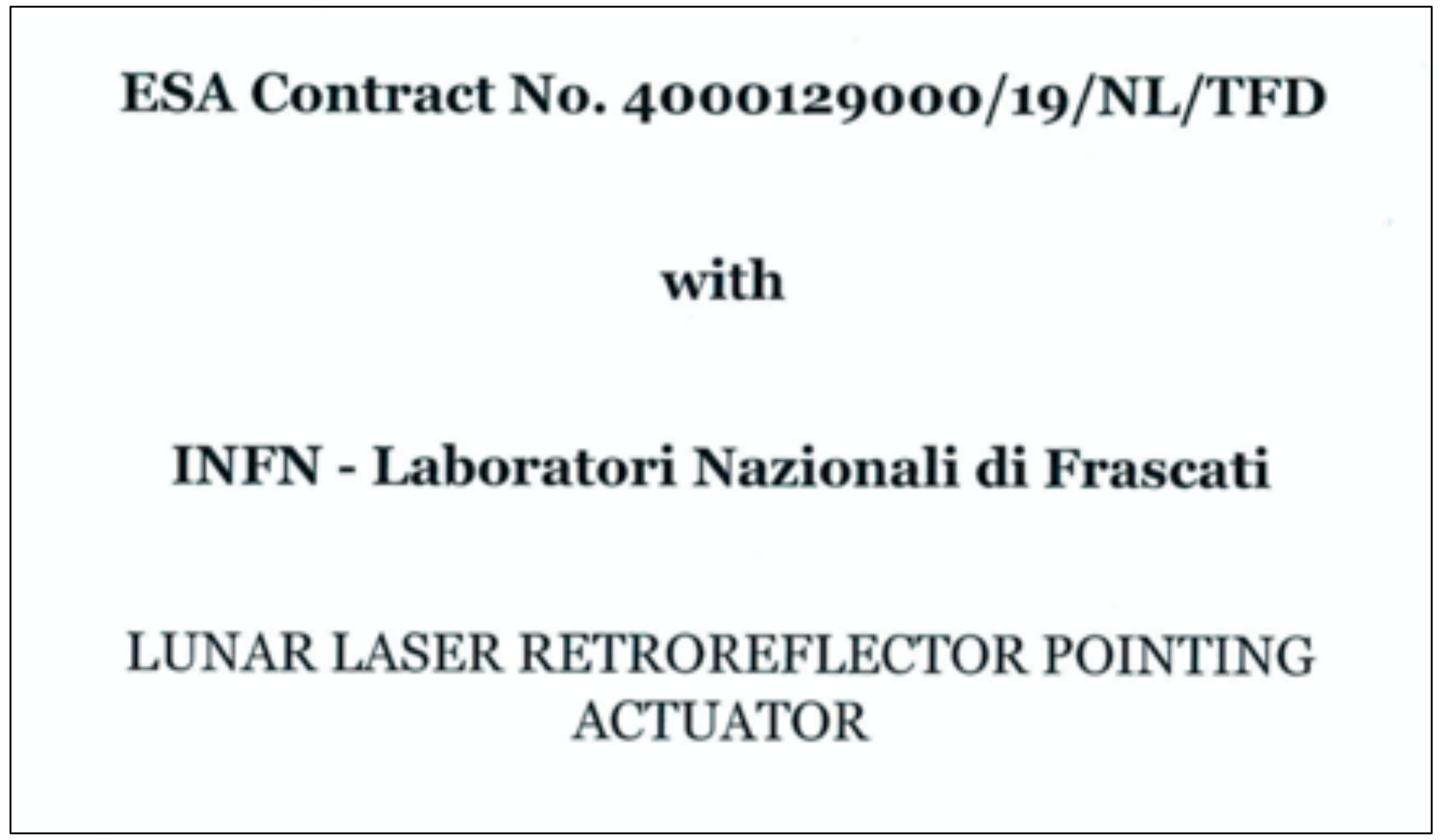
## ML100 Pointing Actuator (MPAc) – Goal and Design

New design – Stage Mass about 2.6 kg

The goal of this requirement is to develop an actuator system that will be integrated on an already existing laser retroreflector (ML100) and capable of an accurate alignment according to an accuracy to be defined by the science team.

Contract for development of MPAc (MoonLIGHT Pointing Actuator)

INFN Resp.: M. Muccino

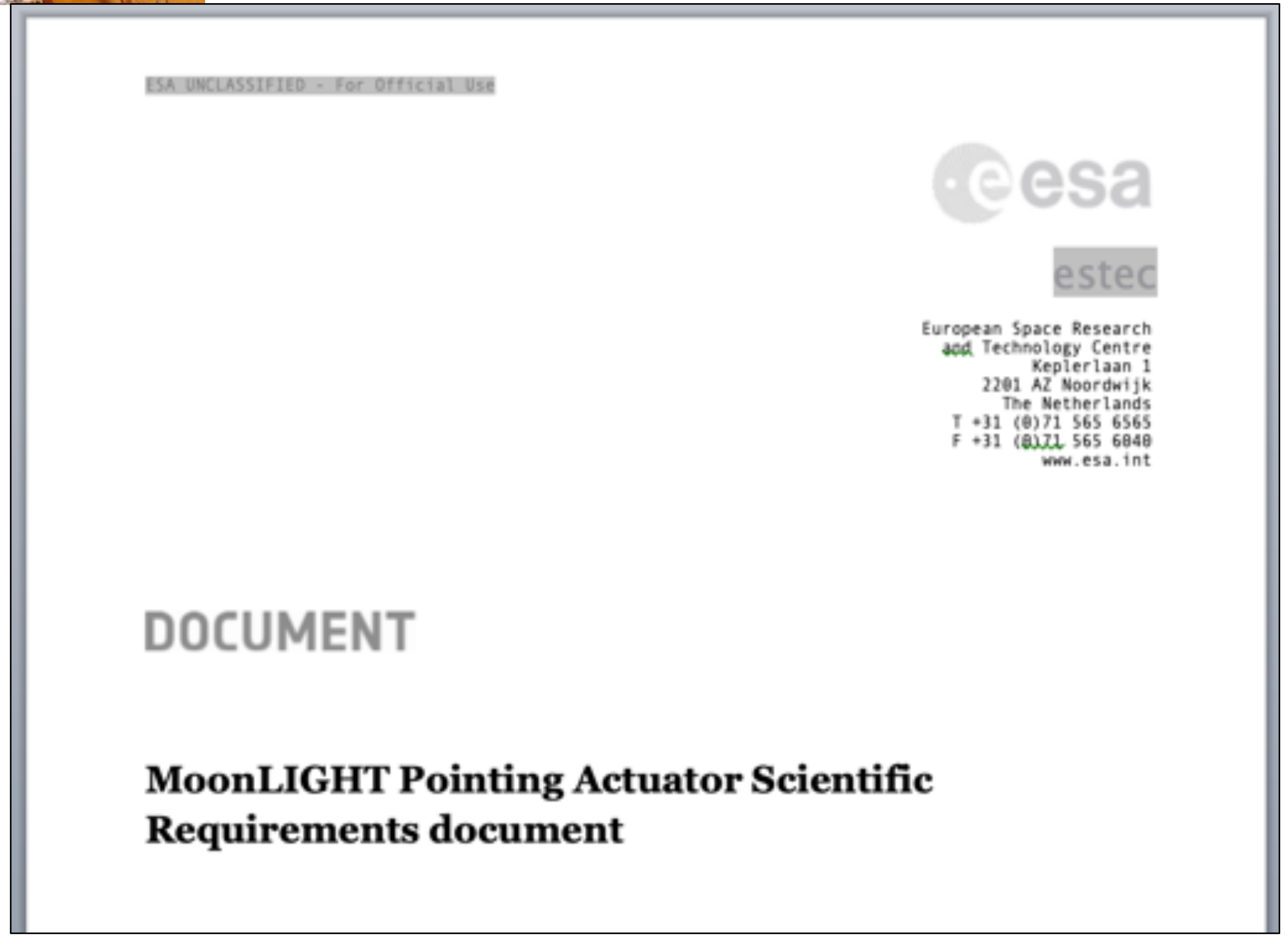


**ESA Contract No. 4000129000/19/NL/TFD**

**with**

**INFN - Laboratori Nazionali di Frascati**

LUNAR LASER RETROREFLECTOR POINTING ACTUATOR



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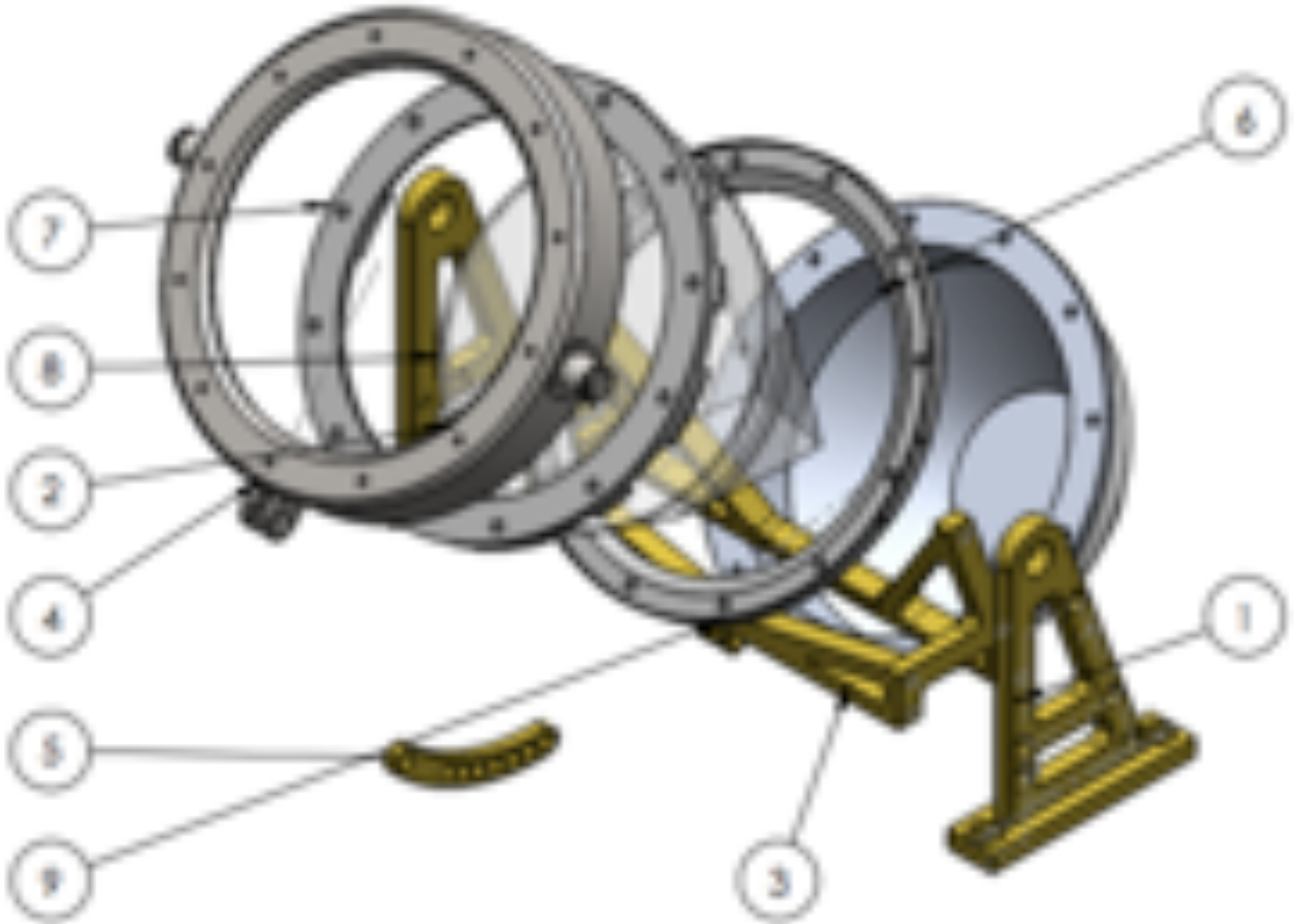
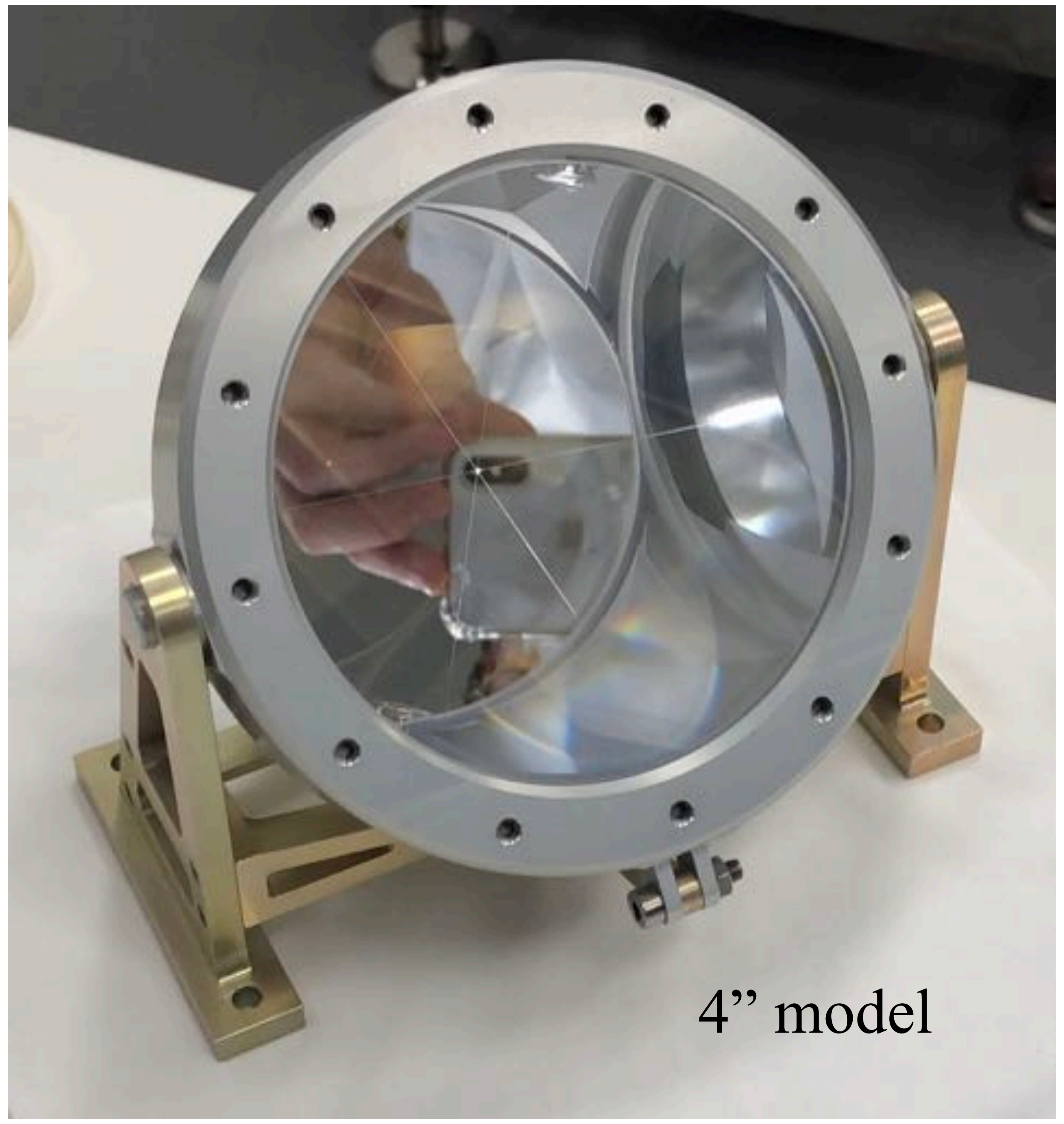
**DOCUMENT**

**MoonLIGHT Pointing Actuator Scientific Requirements document**

# MoonLIGHT




4” model

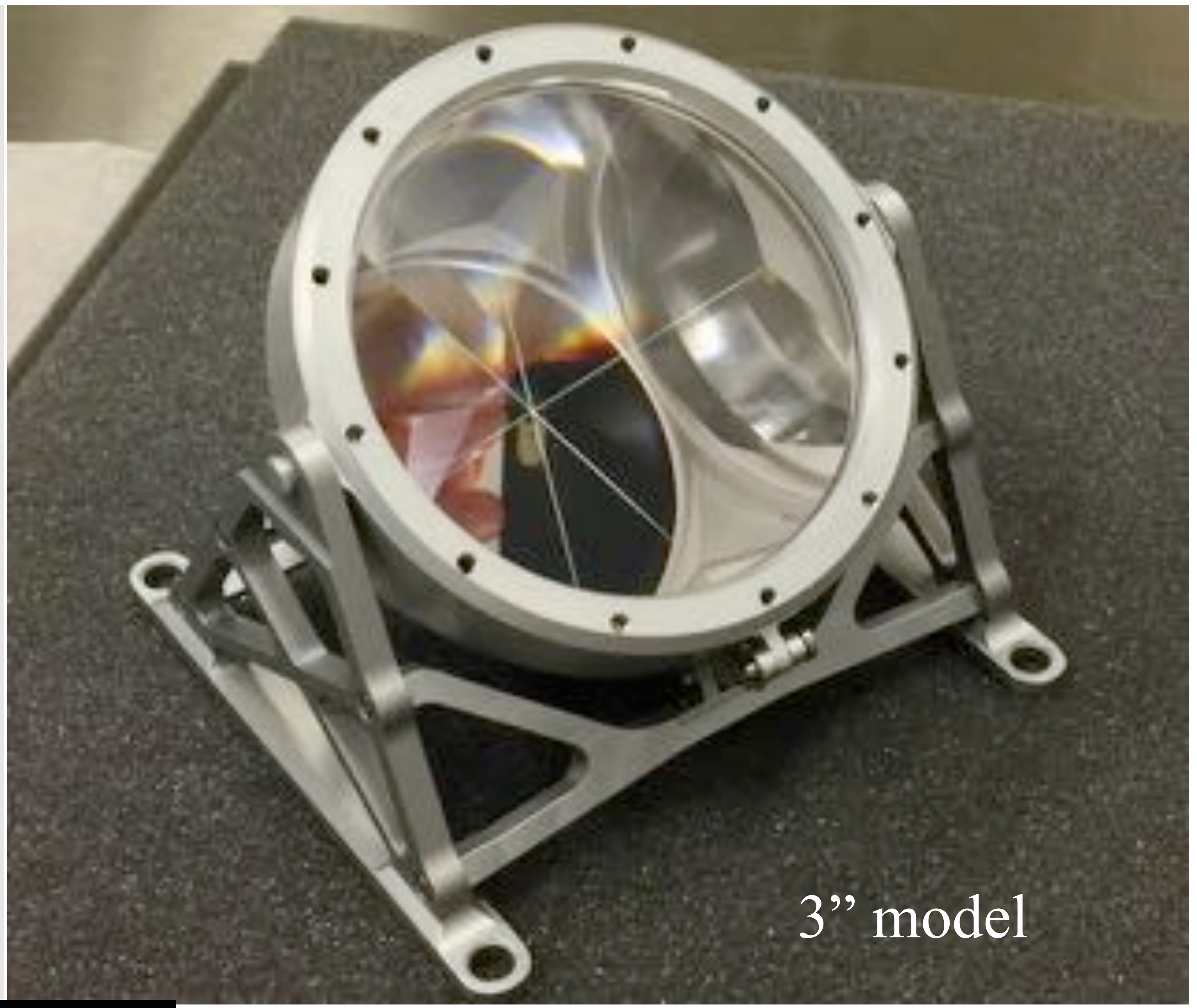
# MoonLIGHT-75 for Intuitive Machines

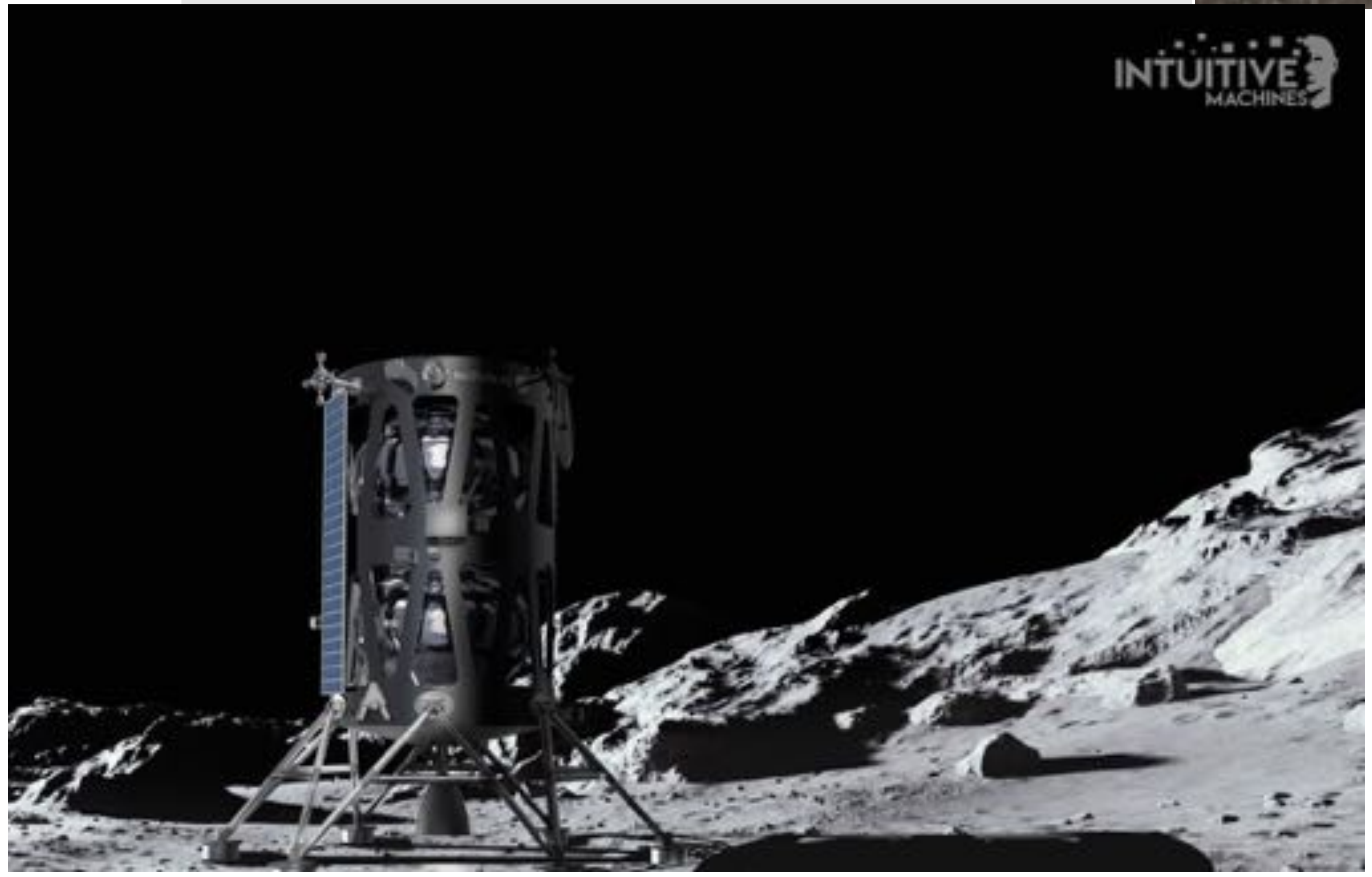
## What are the minimum acceptable mass and dimension for lunar science?

MoonLIGHT 75 is a 0.5 kg, 75 mm payload designed to fit within weight constraint required by launching partners. 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 ($\lambda$ = 532 nm, linear H-polarization).

$OCS_{CCR} \approx D^4$
$OCS_{75mm} = OCS_{100mm} \times (75/100)^4$
… but there are also thermal effects to take into account, basically because $n(\lambda) = n(\lambda,T)$...
$OCS_{75mm} = OCS_{100mm} \times (75/100)^4 \times (100/75)^3$

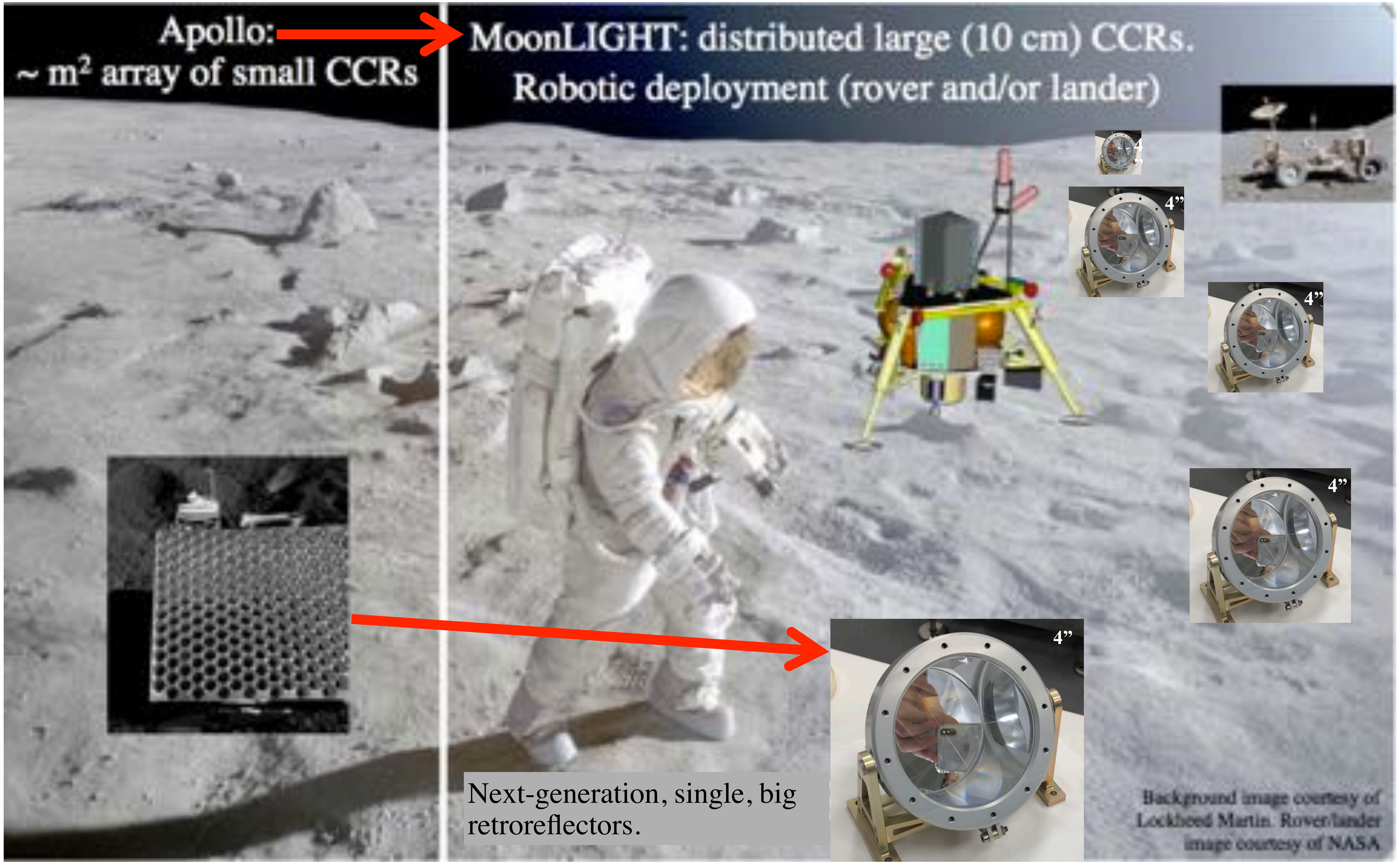
https://doi.org/10.1016/j.asr.2010.10.022


3” model



Launch scheduled by (end of) 2021.

# MoonLIGHT

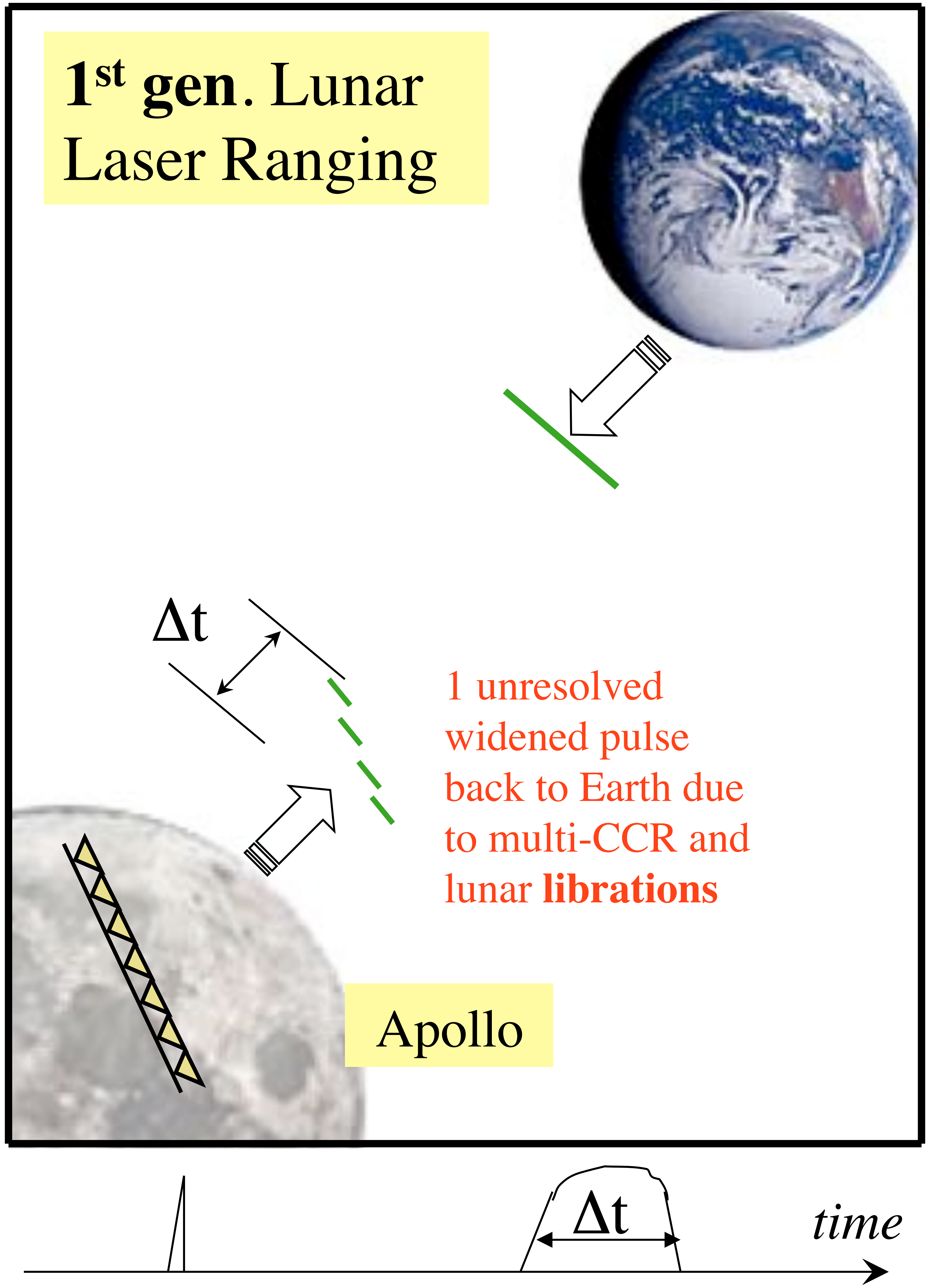


Apollo:
~ m$^2$ array of small CCRs

MoonLIGHT: distributed large (10 cm) CCRs.
Robotic deployment (rover and/or lander)

Next-generation, single, big retroreflectors.

Background image courtesy of Lockheed Martin. Rover/lander image courtesy of NASA

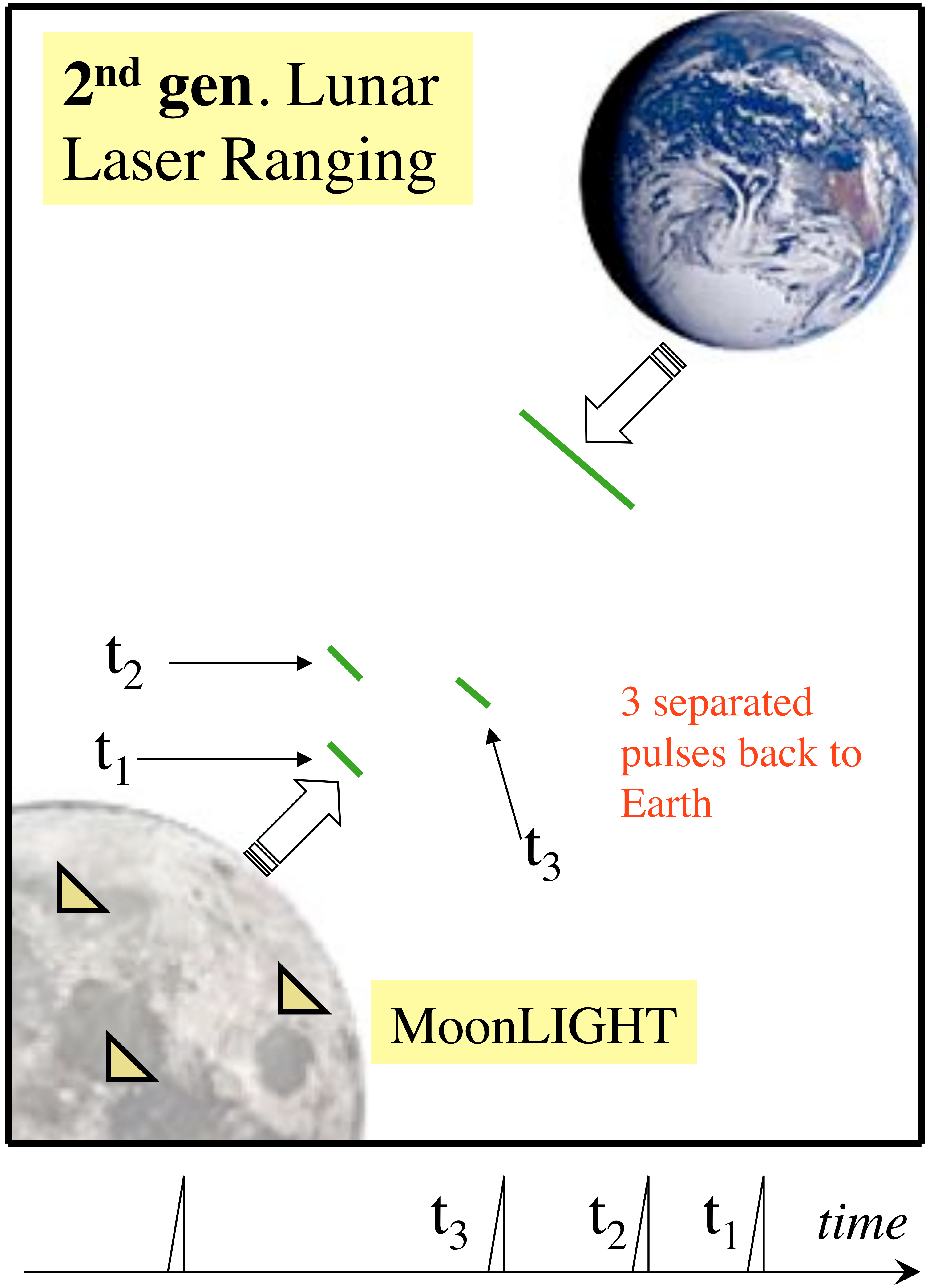


**1st gen.** Lunar Laser Ranging

1 unresolved widened pulse back to Earth due to multi-CCR and lunar **libravions**

Apollo

Short Pulse to Moon **Wide Pulse to Earth**



**2nd gen.** Lunar Laser Ranging

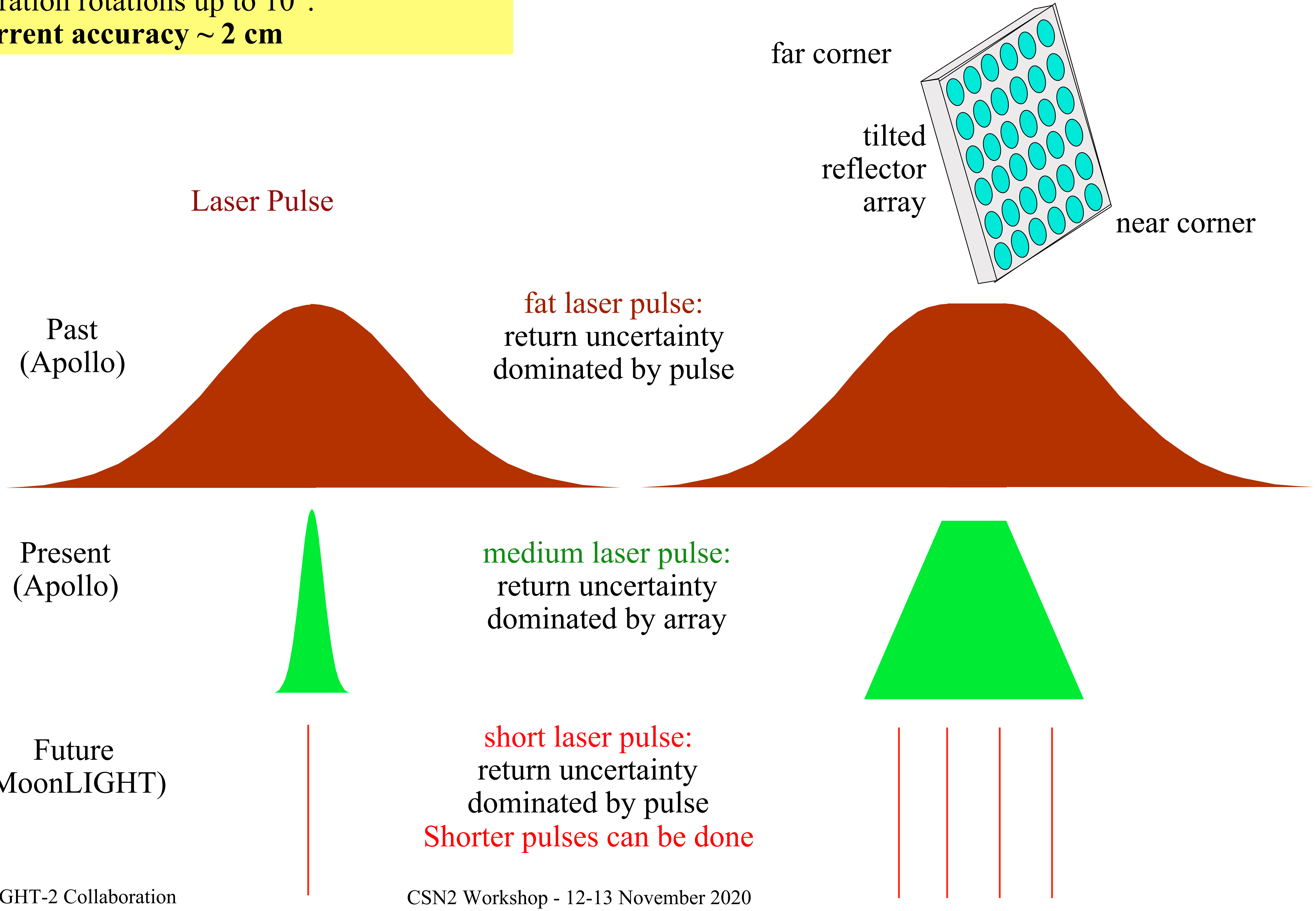
3 separated pulses back to Earth

MoonLIGHT

Pulse to Moon **Pulses to Earth**

# MoonLIGHT

Libration rotations up to 10°.
**Current accuracy ~ 2 cm**



far corner

tilted
reflector
array

near corner

Laser Pulse

Past
(Apollo)

fat laser pulse:
return uncertainty
dominated by pulse

Present
(Apollo)

medium laser pulse:
return uncertainty
dominated by array

Future
(MoonLIGHT)

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

# Lunar Exploration & Science Assets

- *Big, single* laser retroreflector observed from Earth
  - Italy/US: **MoonLIGHT** = Moon Laser Instrumentation for General relativity High accuracy Tests
- *Lunar Laser Ranging*
  - **APOLLO** (USA), **GRASSE** (France), **MLRO** (Matera Laser Ranging Observatory, ASI, Italy)
- *Orbital, positioning SW*
  - **PEP** (Planetary Ephemeris Program) for Moon/Mars positioning: developed since 1960/70s at the Harvard Smithsonian Center for Astrophysics (CfA), by Shapiro, Reasenberg, Chandler (now at UCSD, with T. Murphy). PEP is an open source sophisticated software package to estimate the orbits of the solar system natural bodies and of many artificial satellites.

# Lunar Exploration & Science Assets

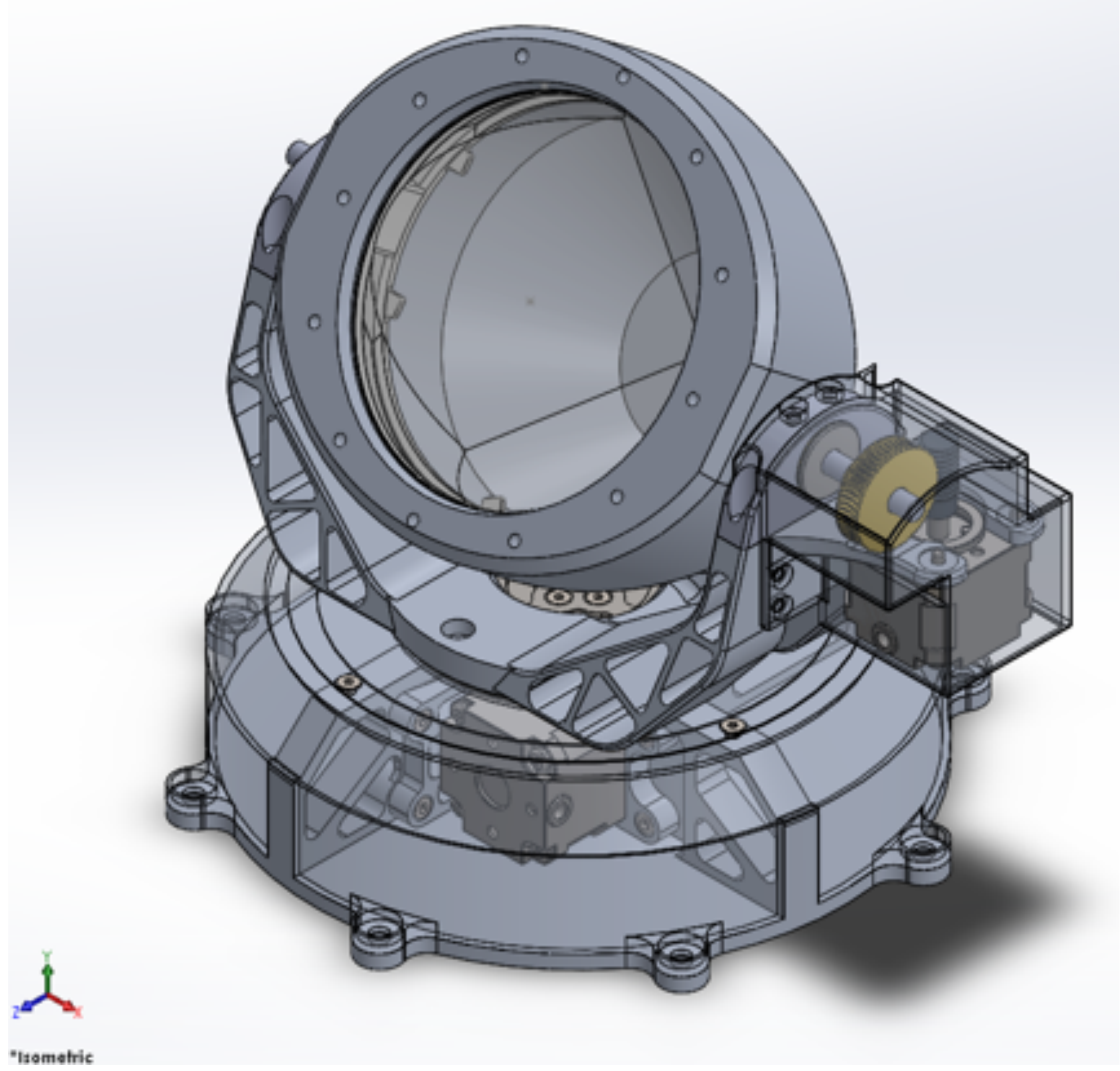
The laser ranging technique consists in ToF measurements performed through short laser pulses fired from ground stations to orbiting payloads equipped with CCRs.

Since 1969, LLR provides accurate measurements of the Moon orbit through high-precision data collected for decades by ground stations and retroreflected by LRAs currently deployed onto the Moon (Apollo 11, 14 and 15, and Lunokhod 1 and 2). The first LLR measurements had a precision of about 20 cm. Since then, significant improvements have been achieved by upgrading the ground segment with the most advanced ranging technology and partly by improving the model and data fits.

Nowadays, because of the old generation lunar LRA design, the current level of range precision is largely limited by the effect of the lunar librations in longitude, produced by the eccentricity of the Moon orbit around the Earth [1]. Currently this effect is estimated to be as large as ~ 15-50 mm [2], but by averaging over a large number N of lunar returns to a laser ground station, the range of uncertainty reduces by a factor sqrt(N), leading to the declared level of accuracy of ~ 1 cm [3] down to a ~ few mm [4].

After the great efforts in the past years, further upgrades in the ranging technology would not significantly improve the range precision as LRAs are still affected by lunar librations, which dominate the range error budget.

[1] Martini et al., Planetary and Space Science, 74, 276-282 (2012), doi:10.1016/j.pss.2012.09.006.
[2] Murphy et al., Classical and Quantum Gravity, 29, 184005 (2012), doi:10.1088/0264-9381/29/18/184005.
[3] Williams, Turyshev, Boggs, Ratcliff, Advances in Space Research, 37, 67-71 (2006).
[4] Battat et al., PASP, 121, 29 (2009), doi:10.1086/596748.



# Lunar Exploration & Science Assets

To this aim, INFN-LNF, built the SCF_Lab. Among all its activities, the SCF_Lab started a project to develop, design, manufacture, and space qualify innovative payloads for performing laser ranging operations in the Earth-Moon system. The SCF_Lab Team, with the support by ASI, intends to reach the afore-mentioned goals by deploying onto the Moon a big CCR, i.e., ML100 (Figure), about 50 years after the last deployment onto the Moon of devices of the same kind [5-6].

The MPAc project [7-8] is the natural continuation of the above SCF_Lab activities aiming at the deployment of innovative payloads onto the Moon. MPAc has been developed for the lunar environment to perform unmanned pointing operations of ML100. The deployment of modern retroreflectors, such as ML100, on the lunar surface is a specific target of ESA's Strategy for Science on the Moon [9-10].

[5] Fournet, Le réflecteur laser de Lunokhod., in: S. A. Bowhill, L.D. Jaffe, M.J. Rycroft (Eds.), Space Research Conference, Vol. 1 of Space Research Conference, pp. 261–277 (1972).
[6] Bender et al., Science, 182, 229–238 (1973), doi:10.1126/science.182.4109.229.
[7] ESA Contract No. 4000129000/19/NL/TFD with INFN Laboratori Nazionali di Frascati "Lunar Laser Retroreflector Pointing Actuator" .
[8] ESA RFP/3- 16160/19/NL/TFD, "LUNAR LASER RETROREFLECTOR POINTING ACTUATOR" - INFN-LNF SCF_Lab Proposal - AO 3-16160.
[9] ESA UNCLASSIFIED - Releasable to the Public, "ESA Strategy for Science at the Moon".
[10] Request for Proposal for Lunar Laser Retroreflector Pointing Actuator, EUROPEAN SPACE AGENCY - ESA EXPRESS PROCUREMENT PROCEDURE - "EXPRO"/"EXPRO+" TENDERING CONDITIONS ("EXPRO/TC").

# Lunar Exploration & Science Assets

## Lunar Science Case

### Primary Goals

LLR determination of the lunar ephemeris with an increasing accuracy represents a unique laboratory for gravitational physics since:

1. verifies to a very high accuracy terms in the relativistic PPN equations of motion;
2. provides the only current solar system means for testing the SEP;
3. constraints the time variation of Newton constant Gdot/G and the geodetic precession.

Future data with higher accuracy from the new generation lunar CCRs will continue to improve the LLR tests/constraints of gravitational physics.

### Secondary Goals

LLR technique can also contribute in defining a LGN and in determining the interior structure of the Moon.

# Lunar Exploration & Science Assets

- Improvements of space segment up to ×100 with MoonLIGHTs plus current Apollo/Lunokhods arrays.

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

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

** Martini et al., Plan. & Space Sci. 74 (2012), 276-282.

** Ciocci et al., Adv. Space Res. 60 (2017), 1300-1306.

** Dell'Agnello et al., in Frascati Physics Series Vol. 66 (2018).

# WEP and SEP Tests

The EP, i.e. the exact correspondence of gravitational and inertial masses, is a central assumption of GR. Its weak form, the WEP, states that the gravitational properties of strong and electro-weak interactions obey the EP. WEP can be tested in laboratory or with astronomical bodies because the relevant differences are in the test-body compositions (i.e., feather vs. hammer). The SEP extends the WEP by including gravitational self-energy of a body, addressing the way that gravity begets gravity (i.e., small hammer vs. big hammer), i.e. about the non-linear property of gravitation. The EP must hold in GR, while alternative theories of gravity predict a violation of the EP at some level. Therefore, probing the validity of the EP is one of the most powerful ways to test GR and search for new physics beyond the standard model [Damour, Class. Quantum Grav., 13, A33–A41 (1996); doi: 10.1088/0264-9381/13/11A/005].

EP tests generally deal with the universality of free-fall acceleration of test-bodies in a uniform gravitational field. In classical Eötvös type experiments, laboratory masses lack measurable gravitational self-energy, so can only probe the WEP. LLR tests compare the relative free-fall acceleration of the Earth (E) and the Moon (M) toward the Sun:

$$\frac{\Delta a}{a} = \frac{2(a_E - a_M)}{a_E + a_M} = \left[\left(\frac{M_G}{M_I}\right)_E - \left(\frac{M_G}{M_I}\right)_M\right]_{WEP},$$

where $M_G$ and $M_I$ are the gravitational and inertial masses, respectively. Any EP violation would cause the Earth and the Moon to fall at different rates toward the Sun and produce a lunar orbit displacement along the Earth-Sun line with a synodic period signature of 29.53 days [Nordtvedt, Phys. Rev., 170, 1186 (1968); doi: 10.1103/PhysRev.170.1186]. Fitting LLR data with the solutions to the equations of motion for the Earth-Moon-Sun system, the radial perturbation of the Earth-Moon distance writes as

$$\Delta r = S\left[\left(\frac{M_G}{M_I}\right)_E - \left(\frac{M_G}{M_I}\right)_M\right]_{WEP} \cos D = (2.8 \pm 4.1)\times \cos D \quad [mm],$$

where $S=-2.9427\times10^{13}$ mm is a scaling factor and D is the angle between the mean longitude of the Moon and the mean longitude of the Sun as observed from the Earth. From this result it easy to obtain the WEP test

$$\left[\left(\frac{M_G}{M_I}\right)_E - \left(\frac{M_G}{M_I}\right)_M\right]_{WEP} = (-1.0 \pm 1.4)\times 10^{-13}.$$

# WEP and SEP Tests

LLR is sensitive to EP violations due to the different compositions and gravitational self-energies $U(<0)$ of the Earth and the Moon. However, LLR alone does not provide a pure test of SEP. To separate WEP and SEP effects and eliminate the possibility of a cancellation effect, a UW laboratory performed a torsion balance experiment using test masses of similar composition to the Earth and Moon [Baeßler, et al., Phys. Rev. Lett., 83, 3585–3588 (1999); doi: 10.1103/PhysRevLett.83.3585]. The UW test result is insensitive to self-energy and provides a relative acceleration $(1.0 \pm 1.4)\times10^{-13}$ (systematic and random uncertainties are combined). Combining the UW and LLR WEP test results yields the SEP test result

$$\left[\left(\frac{M_G}{M_I}\right)_E - \left(\frac{M_G}{M_I}\right)_M\right]_{SEP} = (-2.0 \pm 2.0)\times10^{-13}.$$

SEP can be also tested by the ratio $U/(Mc^2)$. Since $U \sim M^2$ and $U/(Mc_2) \sim M$, SEP tests need astronomical bodies to be observable and the Earth-Moon system becomes a perfect laboratory for this kind of test. Because of their complex interior structure, gravitational self-energy for the Earth and the Moon are computed numerically. Detailed models for the Earth [Williams, et al., Phys Rev D Part Fields, 53, 6730-673 (1996)] and the Moon [Williams, et al., Lunar Laser Ranging Science, in: Garate, et al. (Eds.), 14th International Laser Ranging Workshop, Greenbelt, MD: CDDIS/NASA GSFC, pp. 155–161 (2005)] yield $U_E/(M_E c^2) = -4.64\times10^{-10}$ and $U_M/(M_M c^2) = -1.90\times10^{-11}$, respectively. In this fashion the SEP test writes as

$$\left[\left(\frac{M_G}{M_I}\right)_E - \left(\frac{M_G}{M_I}\right)_M\right]_{SEP} = \left(\frac{U_E}{M_E c^2} - \frac{U_M}{M_M c^2}\right)\eta = -4.45\times10^{-10}\eta\,,$$

where $\eta$ is a linear function of the PPN parameters $\beta$ and $\gamma$ and in GR yields $\eta=0$ [Nordtvedt, Phys. Rev., 170, 1186 (1968); doi: 10.1103/PhysRev.170.1186]. From the above SEP test results one can obtain

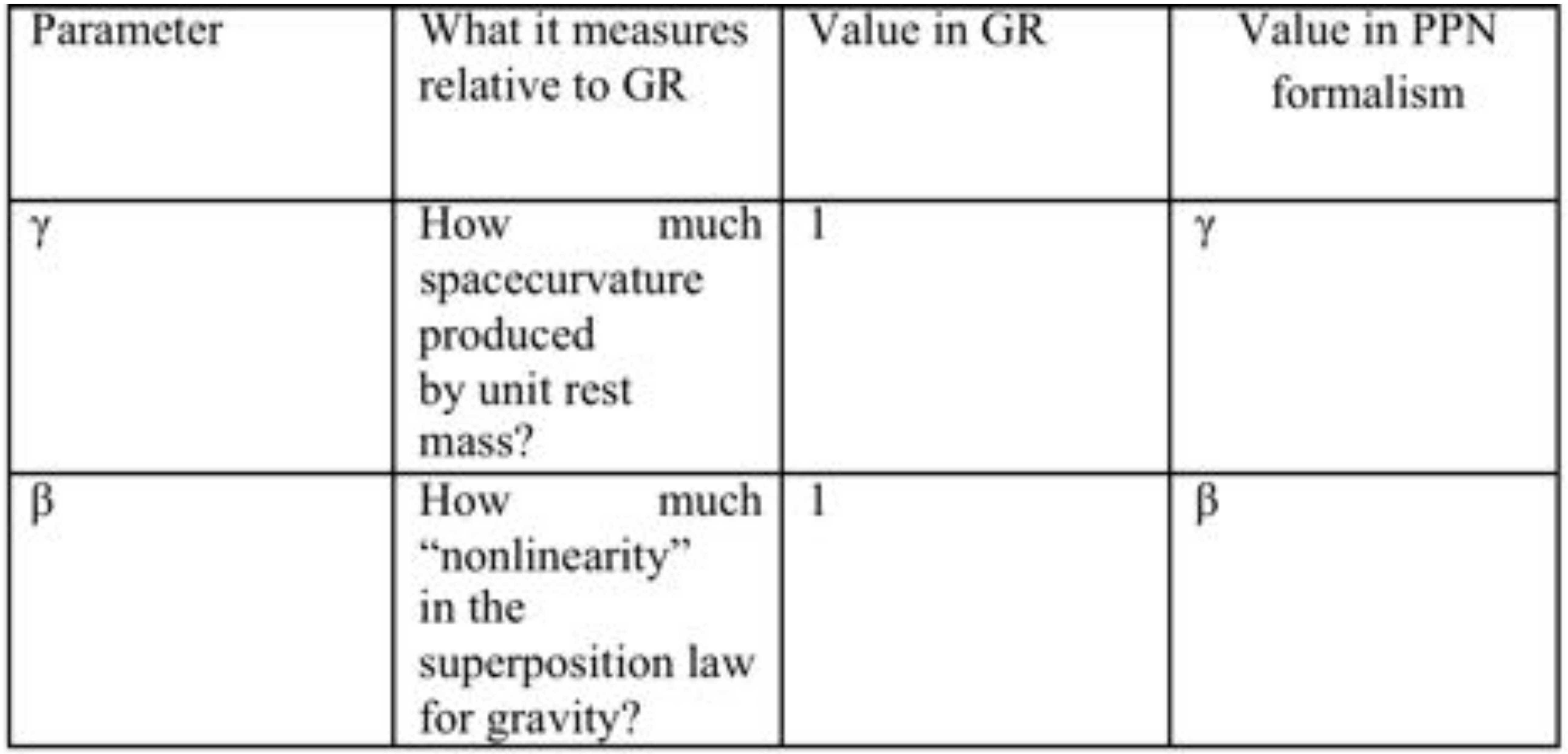
$$\eta = 4\beta - \gamma - 3 = (-4.4 \pm 4.5)\times10^{-4}.$$

# PPN Parameters

SEP relates the non-linearity of gravity to PPN parameter β and γ. The parameter γ has been measured independently by the Cassini mission at a solar conjunction through a time-delay experiment. This test led to a very high accuracy result of $\gamma - 1 = (2.1 \pm 2.3)\times 10^{-5}$ [Bertotti, Iess, Tortora, Nature, 425, 374 (2003)] and to a significant improvement on β derived from η determined from LLR WEP test, i.e.

$$\beta - 1 = (-1.2 \pm 1.1)\times 10^{-4},$$

resulting to a non-significant deviation of β from unity.



| Parameter | What it measures relative to GR | Value in GR | Value in PPN formalism |
|---|---|---|---|
| γ | How much spacecurvature produced by unit rest mass? | 1 | γ |
| β | How much "nonlinearity" in the superposition law for gravity? | 1 | β |

# Variation in the Strength of Gravity

While in GR the coupling strength of gravity G is a constant, in alternative theories it may vary with time. A time variation of G is detectable from an anomalous evolution of the orbital periods of astronomical bodies. From the time derivative of Kepler's third law we have

$$\frac{\dot{G}}{G} = 3\frac{\dot{a_M}}{a_M} - 2\frac{\dot{P}}{P} - 2\frac{\dot{M}}{M},$$

where $a_M$ and P are the semi-major axis and the period of the body orbit, respectively. For solar system bodies (excluding the Sun) the mass loss term can be neglected. Both tidal friction and a G variation influence $a_M$. However, one can separate the effects by taking into account their different contributions to P. Using LLR data it is possible to set as a limit [Williams, et al., Phys. Rev. Lett., 93, 261101 (2004)]

$$\dot{G}/G = (4 \pm 9)\times 10^{-13}\ yr^{-1},$$

which corresponds to less than a 1% variation of G over the 13.7 Gyrs age of the universe. Secular change in the annual orbital period is a dominant effect for a variation of G and evolves quadratically with time, therefore continued and more precise LLR measurements will significantly improve this limit [Nordtvedt, Class. Quantum Grav., 16, A101–A112 (1999); doi: 10.1088/0264-9381/16/12A/305].

# ISL Test and Deviation from Geodetic Precession

ISL tests are often based on Yukawa additional contribution to the gravitational potential

$$V(r) = -G\frac{M_1 M_2}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right),$$

where α is the dimensionless strength and λ is the length scale. At the scale of LLR such a potential would generate a precession of the lunar perigee with frequency δω [Adelberger, et al., Annu. Rev. Nucl. Part. Sci., 53, 77–121 (2003); doi: 10.1146/annurev.nucl.53.041002.110503]

$$\frac{\delta\omega}{\omega} = \frac{\alpha}{2}\left(\frac{\rho}{\lambda}\right)^2 e^{-\frac{\rho}{\lambda}},$$

where ρ is the mean radius of the lunar orbit. GR prediction on the geodetic precession is 19.2 msec/yr [Bertotti, et al., Phys. Rev. Lett., 58, 1062-1065 (1987)] and from LLR measurements the current limit on the deviation of the geodetic procession from the GR prediction is KGP =$(1.9 \pm 6.4)\times10^{-3}$ [Williams, et al., Phys. Rev. Lett., 93, 261101 (2004)]. This result leads to a limit of $\delta\omega/\omega < 1.6\times10^{-11}$. Recent fits of LLR data including Yukawa perturbation terms in the equations of motion leads to a measurement $\alpha = (3 \pm 2)\times10^{-11}$ at $\lambda = 4\times10^{8}$ m. While intriguing, this possible non-null result has yet to be thoroughly investigated [Müller, et al., Lunar Laser Ranging Contributions to Relativity and Geodesy, in: Dittus, et al. (Eds.), Lasers, Clocks and Drag-Free Control: Exploration of Relativistic Gravity in Space, Berlin, Springer, pp. 457–472 (2008)].

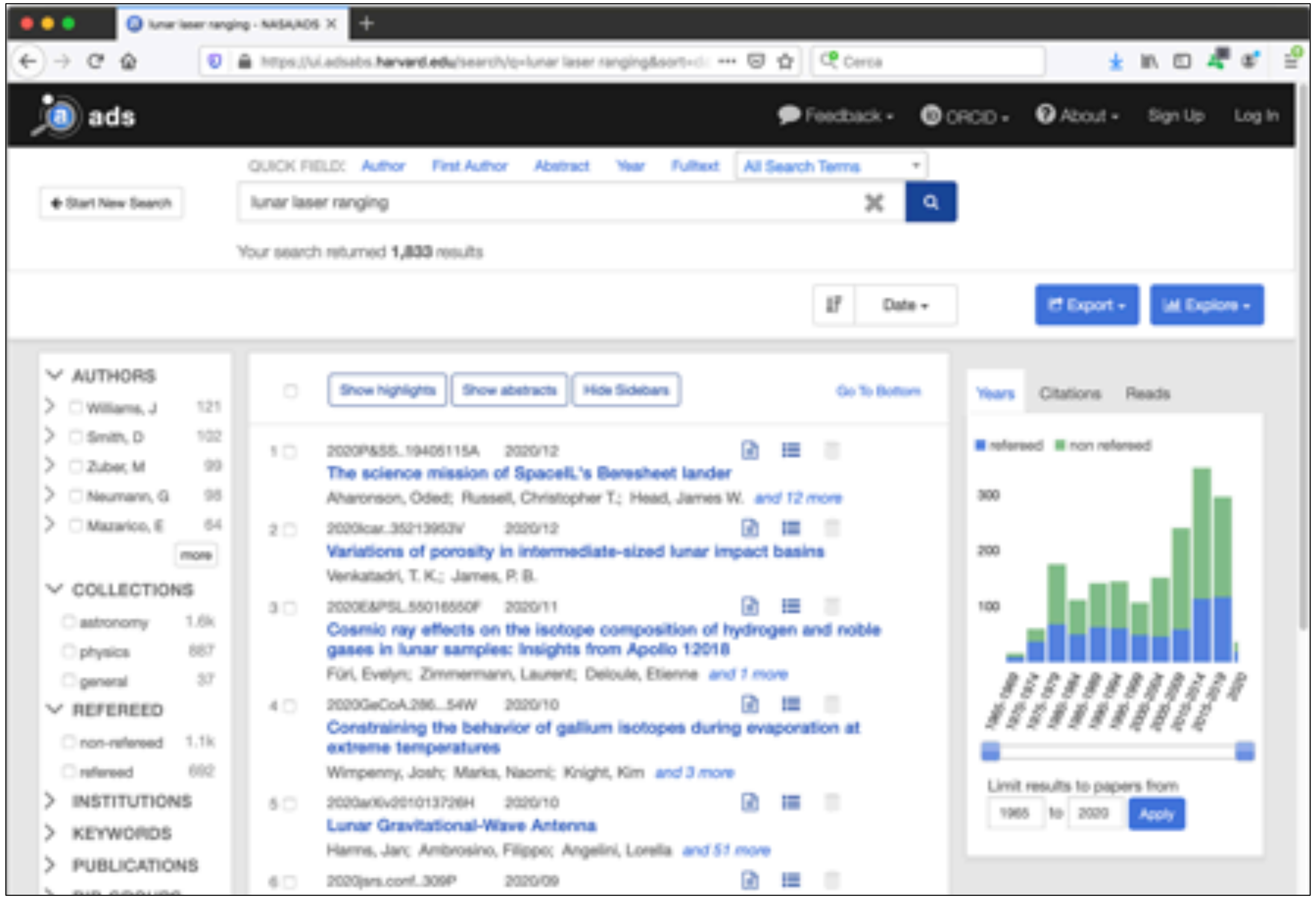
# Lunar Exploration & Science Assets

Lunar Laser Ranging and Selenodesy

- LLR provided the best data for the deep interior of the Moon. Complementary to the analysis of NASA GRAIL and other orbiter missions, which measure from the crust down:
  - ✓ In 1998, analysis of the LLR data discovered and measured the size, shape and dissipation of the liquid core of the Moon (Williams et al.).
  - ✓ Confirmed by re-analysis of Apollo Seismometry (Weber et al. 2011).
- Next-Gen reflectors will increase/improve this consolidated synergism for better understanding the lunar interior:
  - ✓ By allowing for more accurate data, from more stations of the International Laser Ranging Service (ILRS, part of IAG).

# References and International Framework

[19] Viswanathan et al., Extending Science from Lunar Laser Ranging, arXiv:2008.09584.
[20] Dell'Agnello et al., in Frascati Physics Series Vol. 66 (2018).
[21] Ciocci et al., Adv. Space Res. 60 (2017), 1300-1306.
[1] Martini et al., Plan. & Space Sci. 74 (2012), 276-282.



lunar laser ranging

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# References and International Framework

[19] Viswanathan et al., Extending Science from Lunar Laser Ranging, arXiv:2008.09584.

[20] Dell'Agnello et al., in Frascati Physics Series Vol. 66 (2018).

[21] Ciocci et al., Adv. Space Res. 60 (2017), 1300-1306.

[1] Martini et al., Plan. & Space Sci. 74 (2012), 276-282.

[22] Viswanathan et al., Next-Generation Geodesy at the Lunar South Pole: An Opportunity Enabled by the Artemis III Crew, arXiv: 2009.03985.

[23] Viswanathan et al., Scientific Exploration of the Lunar South Pole with Retro-reflectors, Lunar Surface Science Workshop 2020 (LPI Contrib. No. 2241).

[24] Mazarico et al., First two-way laser ranging to a lunar orbiter: infrared observations from the Grasse station to LRO's retro-reflector array, Planets and Space (2020) 72:113, doi: 10.1186/s40623-020-01243-w.

[25] Brock, Millimetre Moon Measurement: 50 Years of Lunar Laser Ranging Since Apollo 11!, doi:10.5194/isprs-archives-XLIII-B3-2020-1105-2020.

[26] Hofmann and Müller, Relativistic tests with lunar laser ranging, Class. Quantum Grav. 35 (2018) 035015 (26pp), doi: 10.1088/1361-6382/aa8f7a.

[27] He et al., Manufacture of a hollow corner cube retroreflector for next generation of lunar laser ranging, RAA 2018, Vol. 18, No. 11, 136 (8pp), doi: 10.1088/1674–4527/18/11/136.

[28] He et al., Development of a 170-mm hollow corner cube retroreflector for the future lunar laser ranging, Chin. Phys. B, Vol. 27, No. 10 (2018), 100701, doi: 10.1088/1674-1056/27/10/100701.

[29] Courde et al., Lunar laser ranging in infrared at the Grasse laser station, arXiv:1704.06443.

[30] Araki et al., Thermo-optical simulation and experiment for the assessment of single, hollow, and large aperture retroreflector for lunar laser ranging, Planets and Space (2016) 68:101, doi: 10.1186/s40623-016-0475-4.

[31] Murphy, Lunar Laser Ranging: The Millimeter Challenge, arXiv:1309.6294.

[32] Preston and Merkowitz, Next-generation hollow retroreflectors for lunar laser ranging, Applied Optics, Vol. 52, Issue 36, pp. 8676-8684 (2013), doi: 10.1364/AO.52.008676.

[33] Merkowitz, Tests of Gravity Using Lunar Laser Ranging, Living Rev. Relativity, 13, (2010), 7.

[34] Murphy et al., Testing Gravity via Next-Generation Lunar Laser-Ranging, Nuclear Physics B (Proc. Suppl.) 134 (2004), 155-162, doi: 10.1016/j.nuclphysbps.2004.08.025.

# References and International Framework

[19] Viswanathan et al., Extending Science from Lunar Laser Ranging, arXiv:2008.09584.
[20] Dell'Agnello et al., in Frascati Physics Series Vol. 66 (2018).
[21] Ciocci et al., Adv. Space Res. 60 (2017), 1300-1306.
[1] Martini et al., Plan. & Space Sci. 74 (2012), 276-282.

[27] He et al., Manufacture of a hollow corner cube retroreflector for next generation of lunar laser ranging, RAA 2018, Vol. 18, No. 11, 136 (8pp), doi: 10.1088/1674–4527/18/11/136.
[28] He et al., Development of a 170-mm hollow corner cube retroreflector for the future lunar laser ranging, Chin. Phys. B, Vol. 27, No. 10 (2018), 100701, doi: 10.1088/1674-1056/27/10/100701.
[30] Araki et al., Thermo-optical simulation and experiment for the assessment of single, hollow, and large aperture retroreflector for lunar laser ranging, Planets and Space (2016) 68:101, doi: 10.1186/s40623-016-0475-4.
[32] Preston and Merkowitz, Next-generation hollow retroreflectors for lunar laser ranging, Applied Optics, Vol. 52, Issue 36, pp. 8676-8684 (2013), doi: 10.1364/AO.52.008676.
[33] Merkowitz, Tests of Gravity Using Lunar Laser Ranging, Living Rev. Relativity, 13, (2010), 7.

# Summary

Lunar 'big' single-CCR retroreflector payload:

- Comes in two 'versions':

  1. The fully-fledged 4" (100 mm) model, approved for flight by ESA Selection (w/ active MPAc) and NASA-LSITP (Fixed Pointing).
  2. The 3" (75 mm) on board IM 2021 mission.

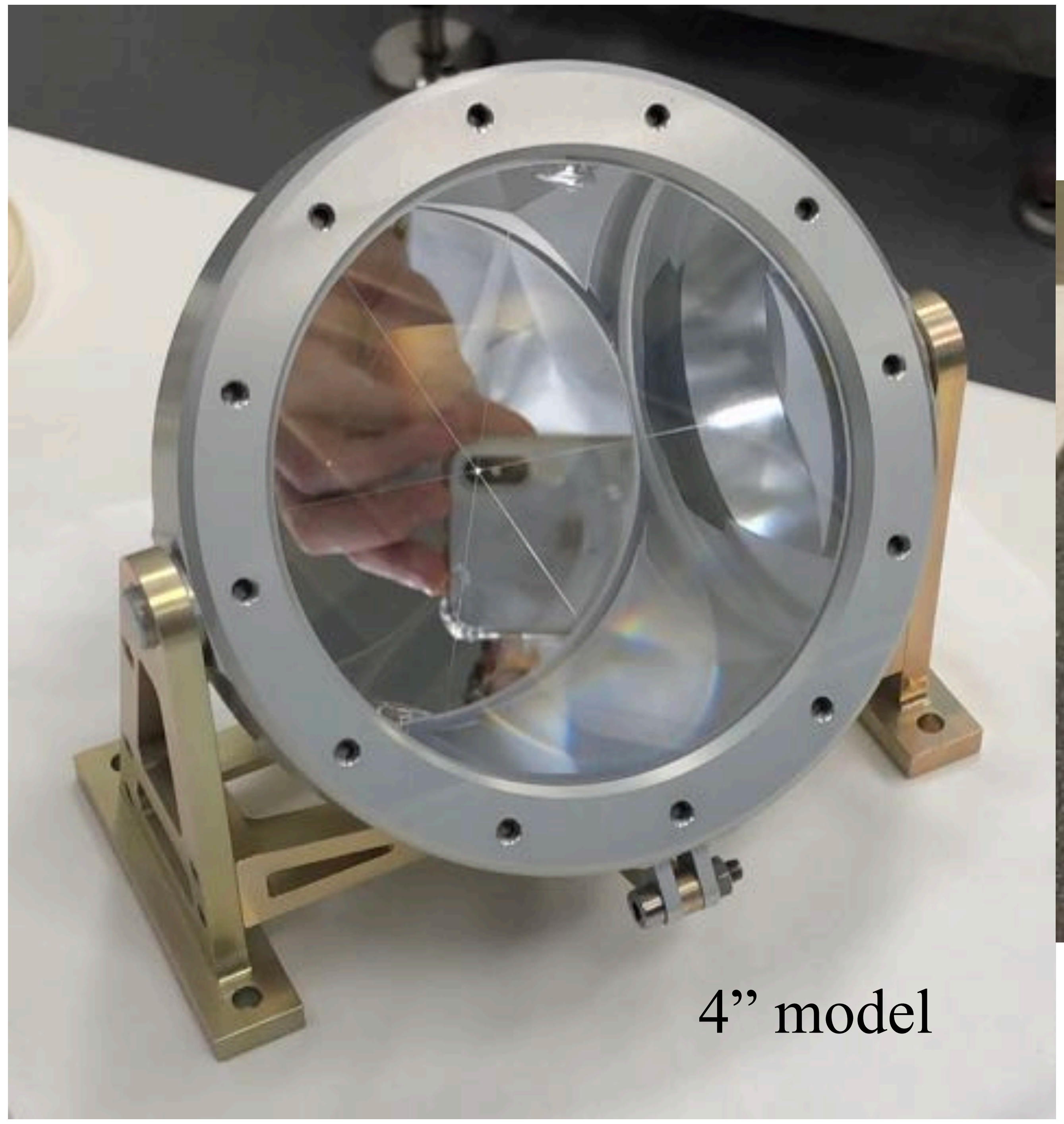
- At least three flights approved from 2021 onwards.

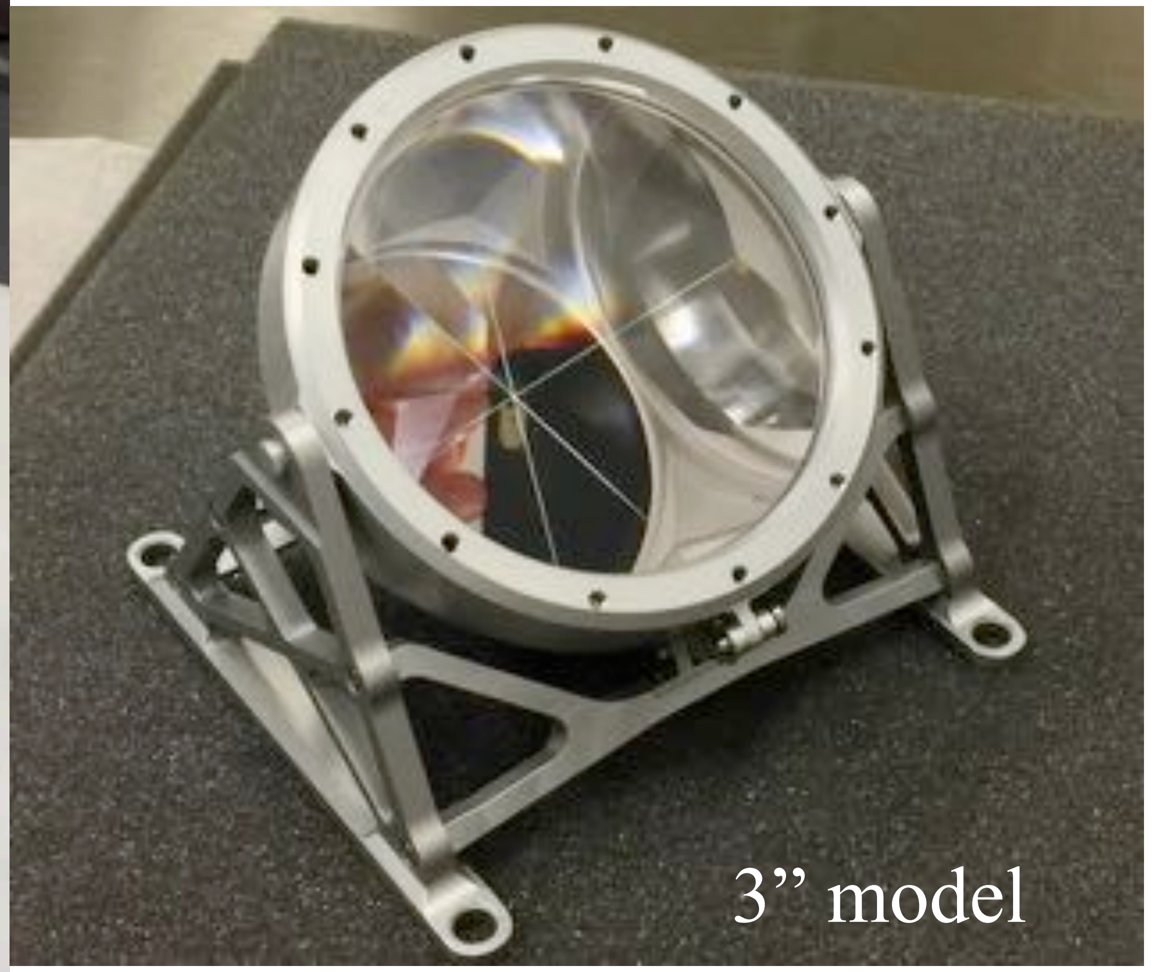
- Passive, 50-year lifetime, laser retroreflector-based enhancement of the Lunar Geophysical Networks (LGN).

- Improved 'use' of the Moon as a test body for:

  1. Lunar surface geodesy and deep lunar interior studies.
  2. Accurate test of General Relativity (and beyond).

European Lunar Symposium 2020 (https://els2020.arc.nasa.gov/)


4" model


3" model