MoonLIGHT-2

INFN-CSN2 Experiment: Test of Gravity in the Solar System
CSN2-LNF, 3rd July 2025

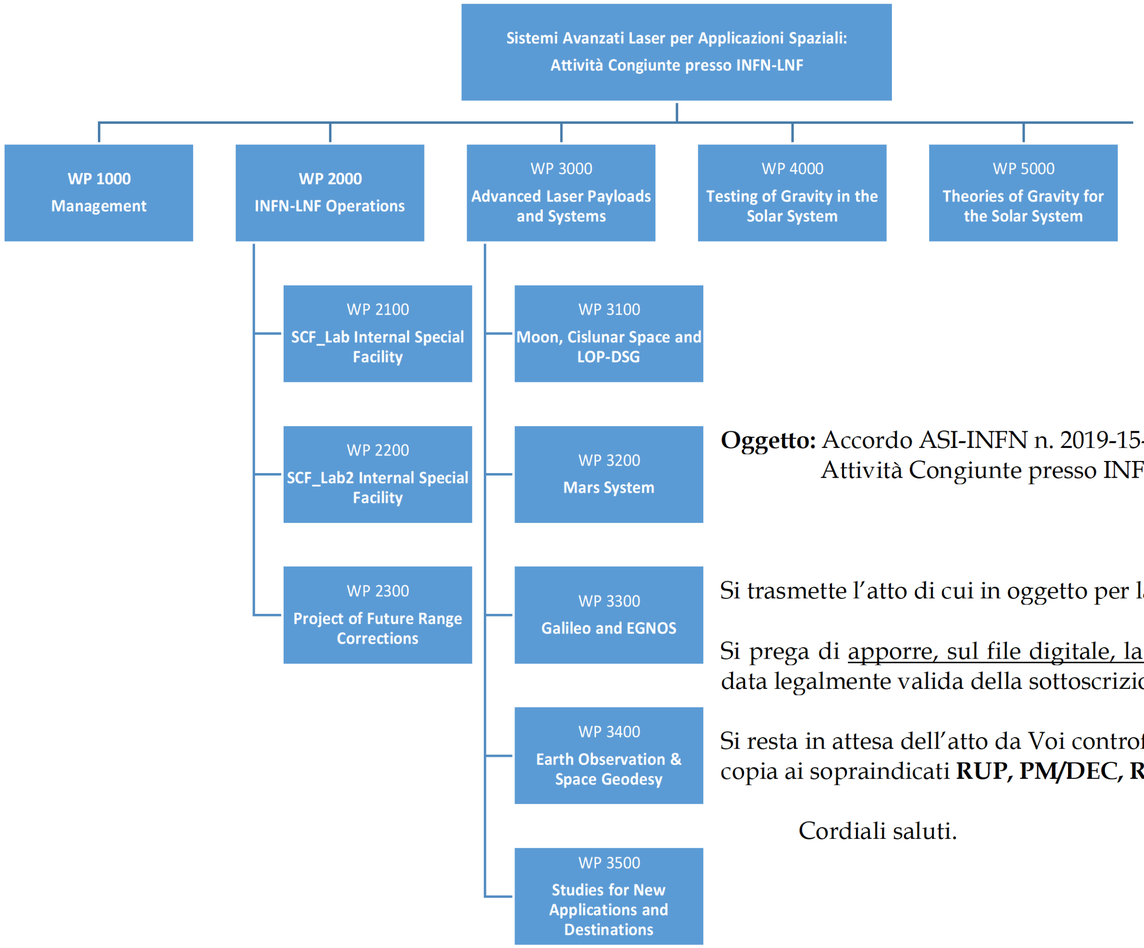
Italian Participants:
INFN-LNF ➔ ~ 7 FTE
INFN/University - Padova ➔ ~ 3 FTE
INFN/University - Naples ➔ ~ 7 FTE
INFN-RM2 - INAF-IAPS ➔ ~ 1 FTE
ASI-Matera Laser Ranging Observatory ➔ ~ 3 FTE

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

Approved Flights:
NASA (Prime = Firefly): early 2025 - LANDED!!!
ESA (Prime = Intuitive Machines): early 2026

Partner Space Agencies:

JointLab INFN-Frascati with ASI-Matera: 1 July 21 - 30 June 26: (delay/suspension due to COVID-19) 1.5M€



Spett.le
Istituto Nazionale di Fisica
Nucleare - INFN
Via Enrico Fermi, 40
00044 - Frascati

Att.ne
Prof. Fernando Ferroni
Presidente

PEC: presidenza@pec.infn.it

c.c.: RUP: Giuseppe Bianco
DEC /PM: Catia Benedetto
Unità Contratti: Francesca Paccagnini
Unità contratti – Segreteria Flora Leucci

Oggetto: Accordo ASI-INFN n. 2019-15-HH.0 per "Sistemi Avanzati Laser per Applicazioni Spaziali: Attività Congiunte presso INFN-LNF".

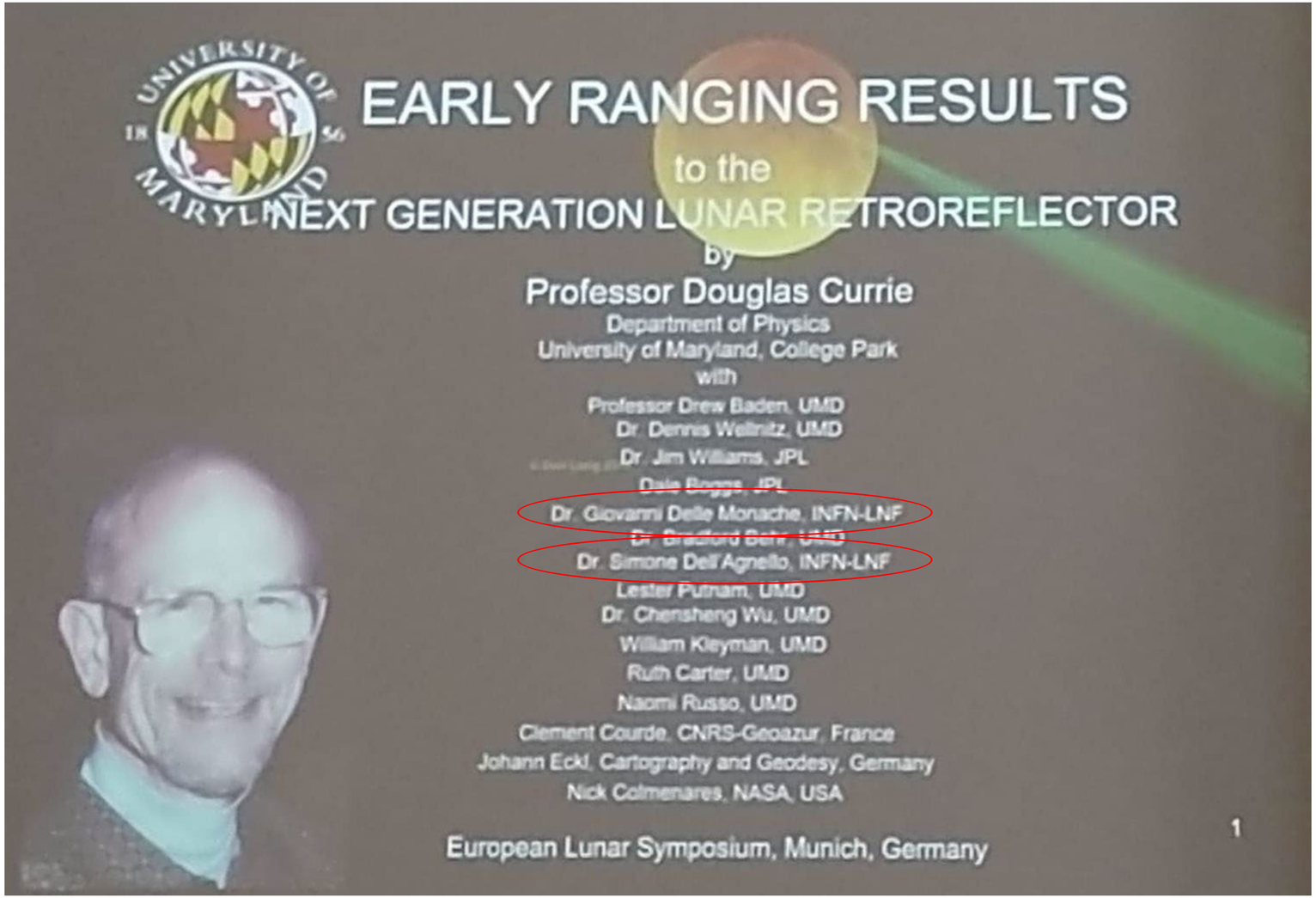
Si trasmette l'atto di cui in oggetto per la Vostra sottoscrizione.

Si prega di apporre, sul file digitale, la firma digitale, unitamente alla marca temporale, che attesta la data legalmente valida della sottoscrizione.

Si resta in attesa dell'atto da Voi controfirmato, da inviare ad asi@asi.postacert.it, con comunicazione in copia ai sopraindicati **RUP, PM/DEC, Responsabile Contrattuale ed Unità Contratti-Segreteria**.

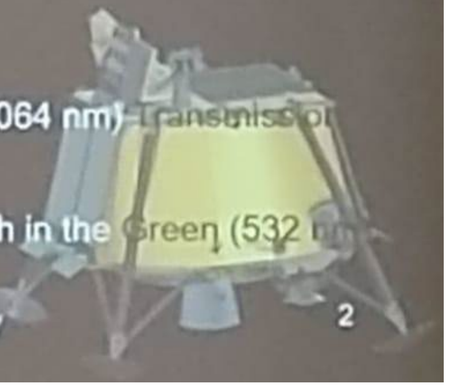
Cordiali saluti.

U.O. Contratti
Il Responsabile
Dott.ssa Luciana Gentile


EARLY RANGING RESULTS
to the
NEXT GENERATION LUNAR RETROREFLECTOR
by
Professor Douglas Currie
Department of Physics
University of Maryland, College Park
with
Professor Drew Baden, UMD
Dr. Dennis Wellnitz, UMD
Dr. Jim Williams, JPL
Dr. Giovanni Delle Monache, INFN-LNF
Dr. Simone Dell'Agnello, INFN-LNF
Lester Putnam, UMD
Dr. Chensheng Wu, UMD
William Kleyman, UMD
Ruth Carter, UMD
Naomi Russo, UMD
Clement Courde, CNRS-Geoazur, France
Johann Eckl, Cartography and Geodesy, Germany
Nick Colmenares, NASA, USA
European Lunar Symposium, Munich, Germany
1

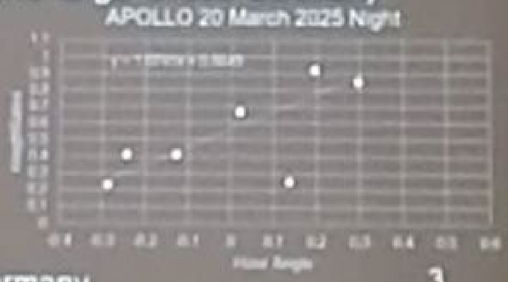
Preliminary Accomplishments

- Lunar Landing of Blue Ghost
  - Built by Firefly Aerospace Landing on 2nd March in Mare Crisium
- NGLR-1 Deployed 2nd March
  - Ready for Lunar Laser Ranging
- MeO Lunar Laser Ranging Observatory (LLRO)
  - Obtained Returns 3rd of March in Infra Red for First Range Measurement
- Wettzell LLRO in Wettzell, Germany
  - Obtained Returns on the 4th of March
- MeO LLRO
  - On the 4th of March Using Both Green (532 nm) and IR (1064 nm) Transmission
- APOLLO LLRO in Apache Point NM, USA
  - Obtained Many Range Measurements on the 20th of March in the Green (532 nm)



Success of NGLR-1

- Very Early Results from the First Month
  - Data is Preliminary.
- Primary Objective of Our NGLR Project
  - Provide and Demonstrate Very Low Dispersion (i.e., very small Target Signature)
  - Wettzell Demonstrated Dispersion Much Less than 24 ps
  - Standard Deviation of the Mean – 0.79 & 1.14 mm
  - NGLR-1 Will Fully Support Current and Later Improvements in LLRO Capacities
- Second Objective of Our NGLR Project
  - Provide and Demonstrate High Rate of Returns (i.e., the large Cross-Section)
  - Objective is Similar to Apollo 11 Retroreflector Array
  - APOLLO Demonstrated a Rate of Return
    - Statistical the Same as Apollo A11 Retroreflector Array
  - When Transmitting the Design Polarization
    - During Lunar Night on 20 March



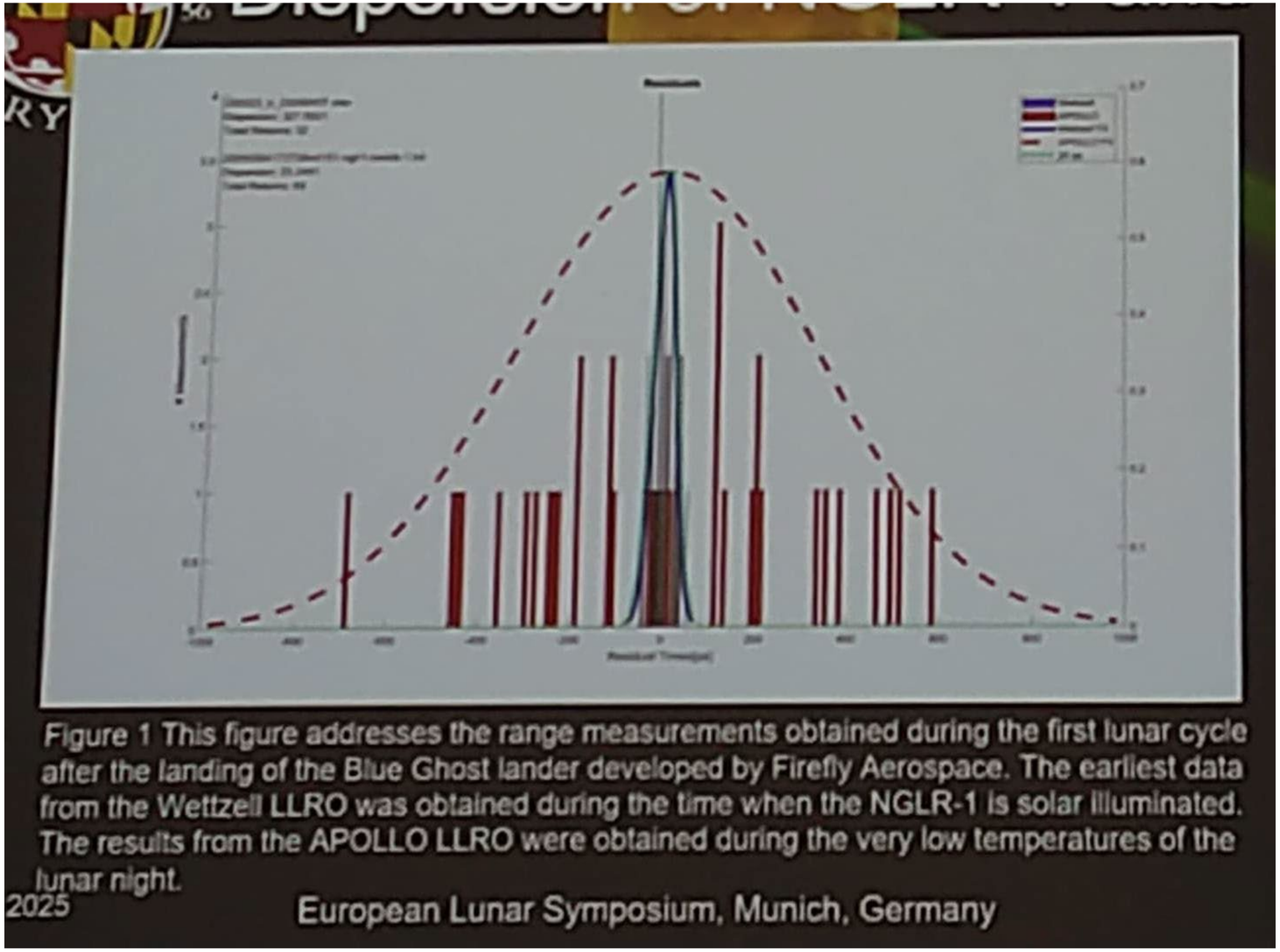


Figure 1 This figure addresses the range measurements obtained during the first lunar cycle after the landing of the Blue Ghost lander developed by Firefly Aerospace. The earliest data from the Wettzell LLRO was obtained during the time when the NGLR-1 is solar illuminated. The results from the APOLLO LLRO were obtained during the very low temperatures of the lunar night.

2025 European Lunar Symposium, Munich, Germany

Testing relativistic gravity with lunar laser retroreflectors and PEP

G.Bargiacchi[1], R. Campagnola[1], S.Capozziello[3,4,5], S. Dell'Agnello[1], E. Battista[1], L. Porcelli[1], R. March[1], M. Muccino[1,2], R. Rodriquez[1], L. Salvatori[1], M. Tibuzzi[1], M. Trigilio[1,2], B. Villalba[1,2]

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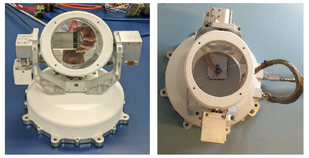
- Enhance tests of **General Relativity (GR)**
- Improve understanding of the Moon's internal structure
- Constrain alternative theories of gravity

Technological Innovations

MoonLIGHT (Moon **L**aser **I**nstrumentation for General relativity **H**igh–accuracy **T**ests**)**: a 100 mm retroreflector unaffected by lunar **librations**, which are a major current source of measurement error.

- **MPAc (MoonLIGHT Pointing Actuator)**: enables precise orientation of MoonLIGHT to maximize accuracy.
- **INRRI (**INstrument for landing–Roving Laser Retroreflector Investigations**)**: a micro retroreflector deployed on China's **Chang'e-6** lander, now on the Moon's far side.



The PFM1 of the MPAc payload: side view (left); zenithal view (right).

LRR (Laser RetroReflector)	Total Attempts	Total Successes	Success Rate	Day/Night Success Rate
Apollo 11	11	9	82%	Day: 67% Night: 100%
Apollo 14	20	16	80%	Day: 78% Night: 82%
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Chandrayaan-3 (microreflector)	96	15	16%	Day: 24% Night: 10%
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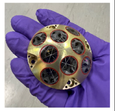
Observations by laser altimeter LOLA on NASA-LRO
7 observations with 28% efficiency – March 2025



Italian microreflector INRRI on Chang'e-6.

Scientific results and PEP

The **Planetary Ephemeris Program (PEP)**, developed by the **Harvard-Smithsonian Center for Astrophysics**, analyzes LLR data from Apollo, Lunokhod, and MoonLIGHT reflectors to:

- Refine estimates of key gravitational parameters
- Test time variation of the **gravitational constant**, **geodetic precession**, and **Yukawa-type deviations** from Newtonian gravity
- Place tighter bounds on alternative gravity models such as **spacetime torsion**, **f(R) gravity**, **non-minimally coupled theories**, and **Lorentz invariance violations**

Fundamental Physics Measurement	Current LLR Accuracy of ~1 cm, Supported by Apollo/Lunokhod LRAs	LLR Accuracy of ~1mm (Contribution of Next-Generation CCRs)	Ultimate LLR Accuracy ~0.1mm (Contribution of Next-Generation CCRs)
WEP	$\lvert\Delta a/a\rvert < 2.4 \times 10^{-14}$	$<10^{-14}$	10^{-15}
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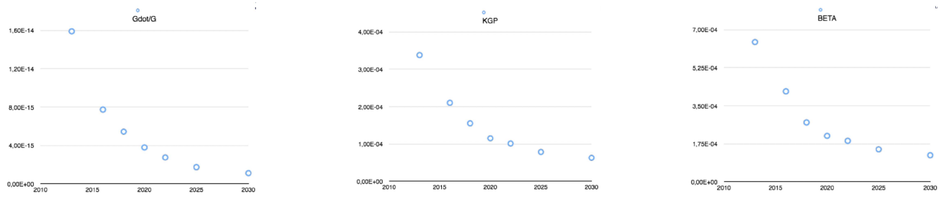
PEP Simulations



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The ultimate goal: **narrow the scope of viable non-standard theories** by tightening experimental constraints.

Conclusion & Outlook

By analyzing LLR data with PEP, we can tighten constraints on fundamental physics, narrowing the range of viable gravitational theories and identifying possible deviations from General Relativity.

PEP continues to refine these tests, playing a key role in the ongoing search for new physics.

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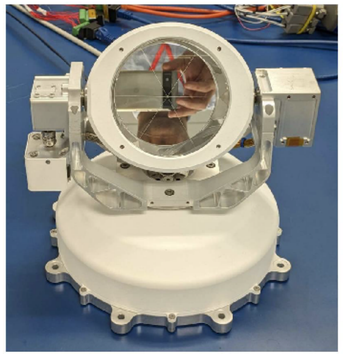

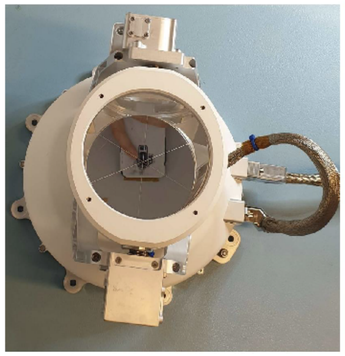

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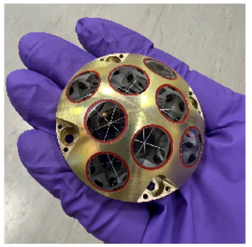

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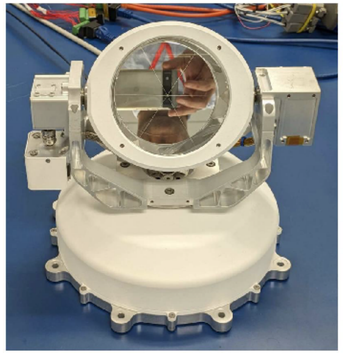

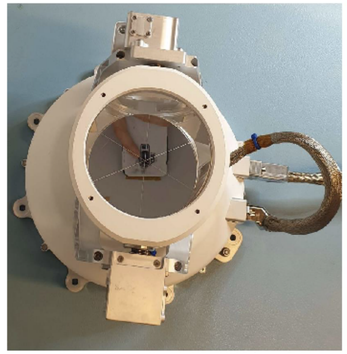

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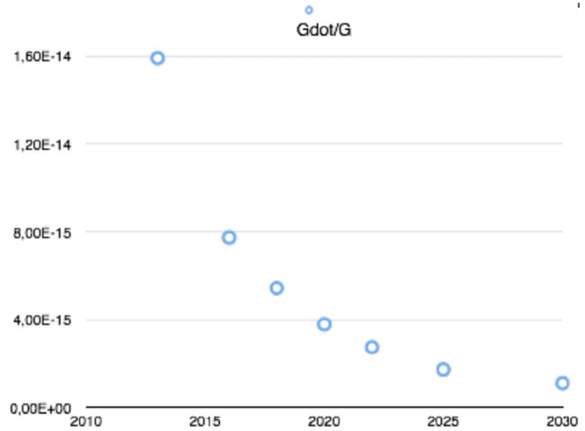

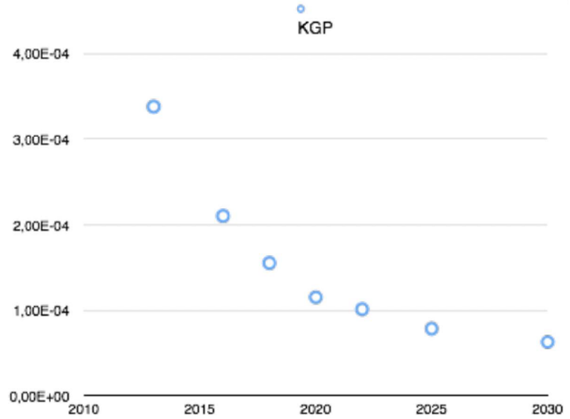

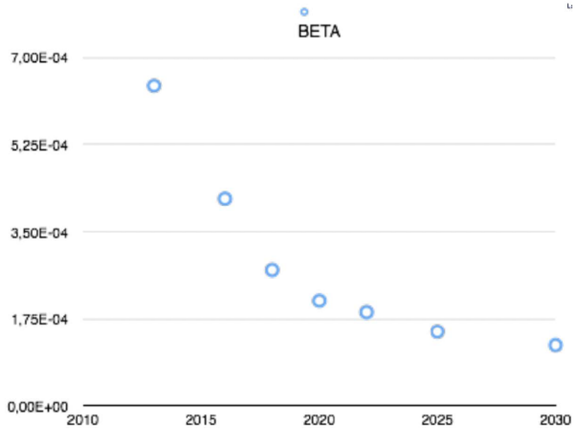

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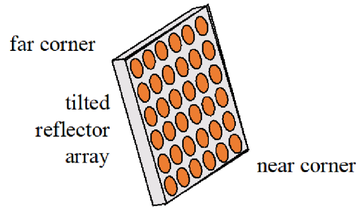
Why Next-Gen LLR CCRs

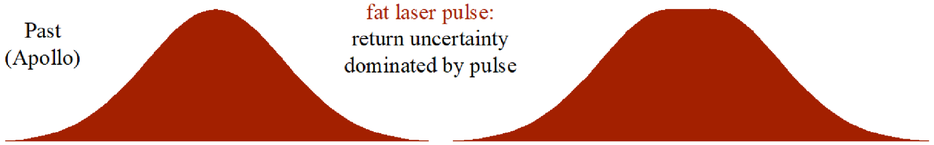
Libration rotations up to 10°.
Current accuracy ~ 2 cm



Laser Pulse

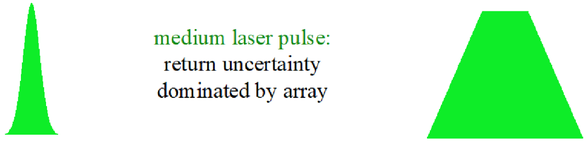
Past
(Apollo)

fat laser pulse:
return uncertainty
dominated by pulse



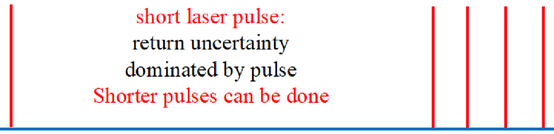
Present
(Apollo)

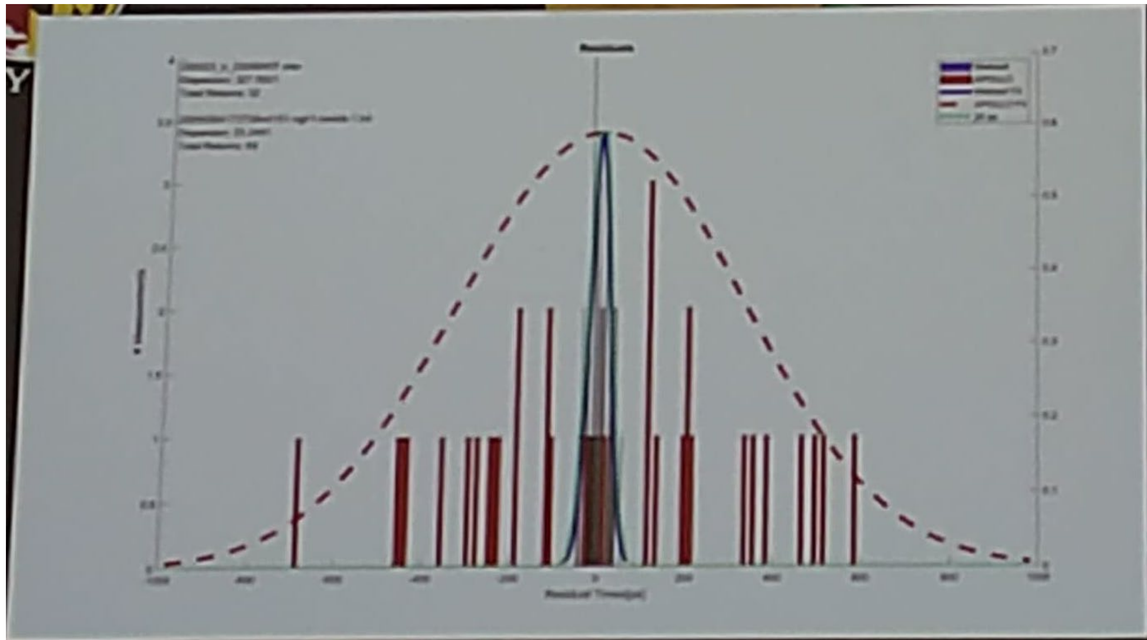
medium laser pulse:
return uncertainty
dominated by array



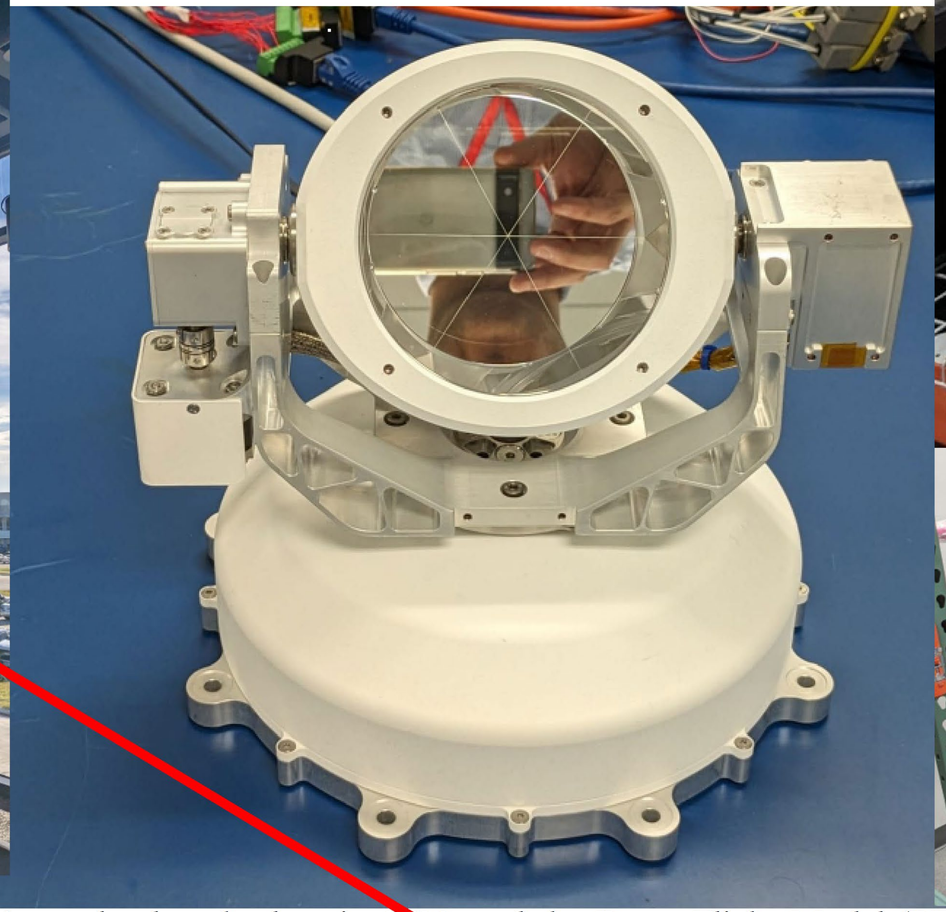
Future
(MoonLIGHT)

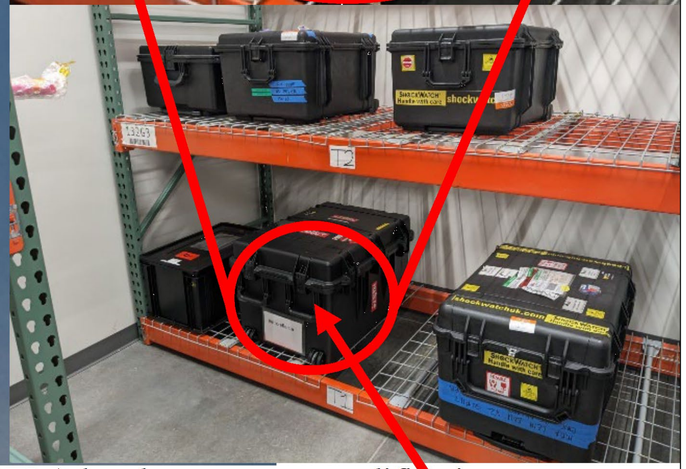
short laser pulse:
return uncertainty
dominated by pulse
Shorter pulses can be done





MoonLIGHT+MPA





Final integration of the MoonLIGHT+MPAc payload took place in 2023, and the Proto Flight Model (PFM) hardware space qualification tests were successfully passed in late 2023. The MoonLIGHT+MPAc payload was finally delivered to ESA, and NASA, and IM; it is in storage since 6th December 2023, after acceptance, and waiting for final integration on board IM's CP-11 lander.

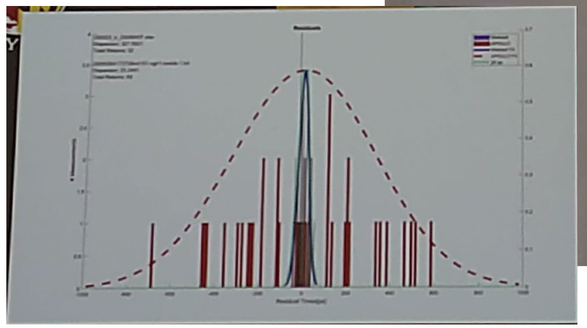
European Lunar Symposium 2025:
https://sservi.nasa.gov/els2025/

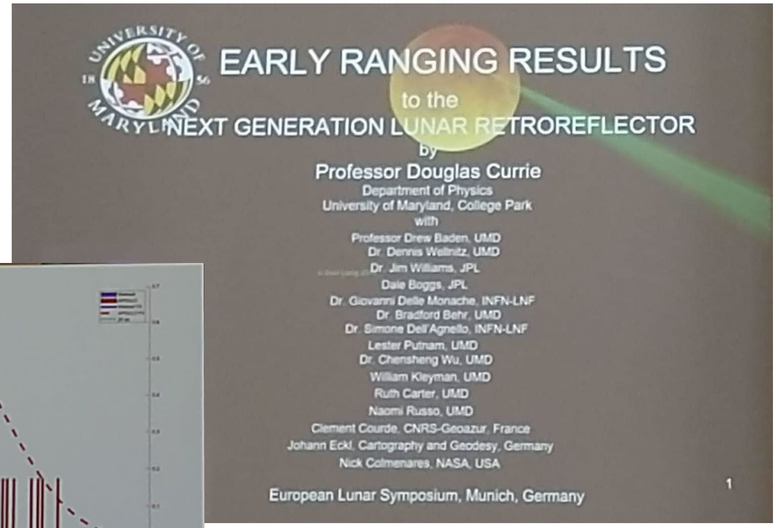
EUROPEAN LUNAR SYMPOSIUM

MoonLIGHT-2 x 2026

Objective: launch of ‘first’ MoonLIGHT+MPAc (…yet ‘second’ next generation lunar retroreflector…) to the Moon and continuation of data taking/analysis.

- **2025 Results:**
  - Landing of NGLR-1 (MoonLIGHT with Fixed Pointing) on the Moon.
  - Success of NGLR-1 (very low dispersion, high rate of returns).
  - European Lunar Symposium 2025 (https://sservi.nasa.gov/els2025/).
- **2026 Objectives:**
  - Launch of the ‘first’ MoonLIGHT+MPAc to the Moon.
  - Continuation of data taking/analysis.
  - European Lunar Symposium 2026.





MoonLIGHT-2 x 2026

Objective: launch of ‘first’ MoonLIGHT+MPAc (…yet ‘second’ next generation lunar retroreflector…) to the Moon and continuation of data taking/analysis.

- **FTE (LNF):** G. Bargiacchi (100%), G. Bellettini (50%), G. Bianco (50%), S. Dell’Agnello (100%), M. Maiello (100%), L. Porcelli (50%), R. Vittori (50%), …
- **Richieste CSN2 2025 (overall, TBD):** ~~missioni 20k, consumo 5k, altri cons 5k, inventario …k, license SW …k, apparati …k, servizi …k~~
- **Richieste LNF 2025 (mesi-uomo):** richieste fatte dal Joint Lab
- **Fondi Esterni:** Joint Lab INFN-Frascati with ASI-Matera, 1.5 MEuro; ESA Contract for Pointing Actuator (MPAc), 500kEuro