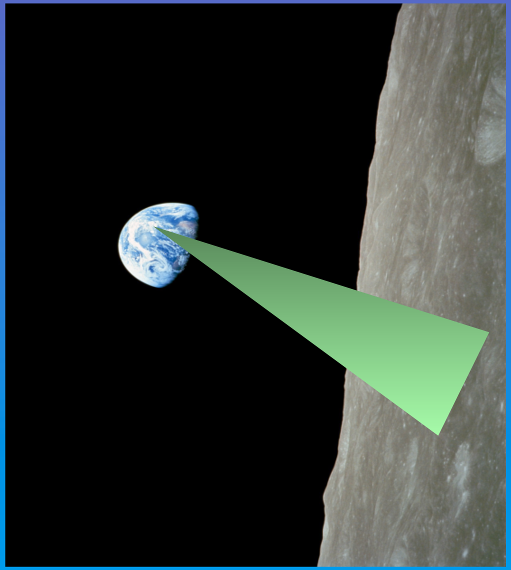
MoonLIGHT:

" A new Lunar Laser Ranging Retroreflector instrument"

Marco Garattini
for the "SCF_LAB Team"
LNF-INFN



Vulcano Workshop 2012

"Frotier Objects in Astrophysics and Particle Physics"

SCF_LAB Team, Collaborations

FRASCATI GROUP

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E. Ciocci

National Collaborations

ASI - Centro di Geodesia Spaziale - G. Bianco, SLR/LLR station and orbit sw

AMI - Aeronautica Militare Italiana - R. Vittori, co-PI of ETRUSCO

International Collaborations

Univ. of Maryland at College Park - D. Currie, inventor of LLR

Univ. of California at San Diego - T. Murphy, best LLR Station

Harvard-Smithsonian Center for Astrophysics - John Chandler, PEP lunar orbit sw

International Scientific Communities

ILRS - S. Dell'Agnello is member of Signal Processing WG

ILN - S. Dell'Agnello is member of Core Instrument WG

Laureandi: L. Palandra, S. Contessa, S. Rinaldi

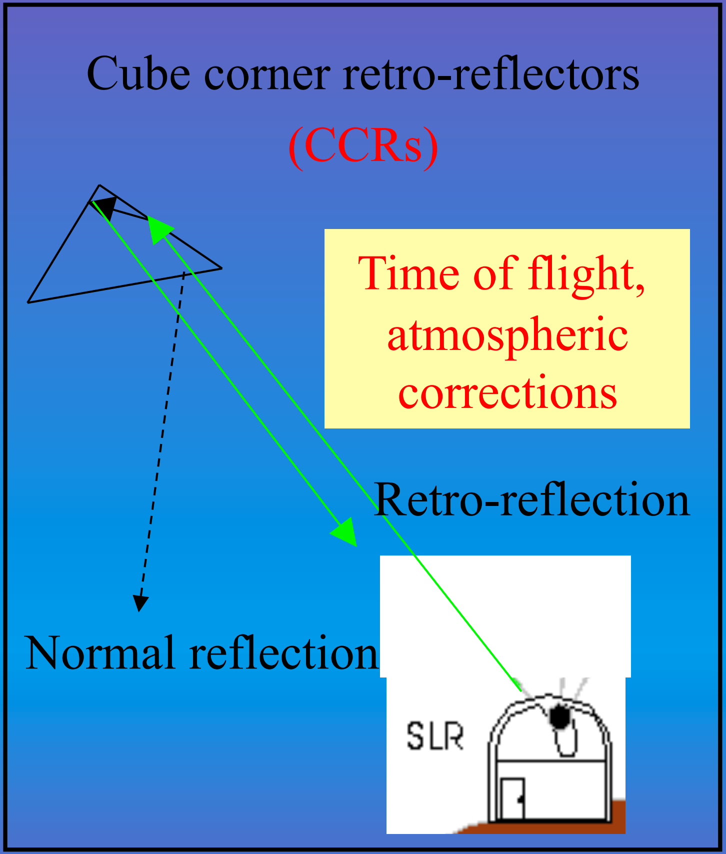
Outline

1. Introduction to Lunar Laser Ranging (LLR)
2. LLR Physics Objectives
3. 2^{nd} Generation of Lunar Laser Ranging
4. The New Maryland/Frascati Payload
5. Experimental results
6. Conclusions

Laser Ranging concept:

Laser - retroreflector - receiving telescope - time of flight

Total Internal Reflection

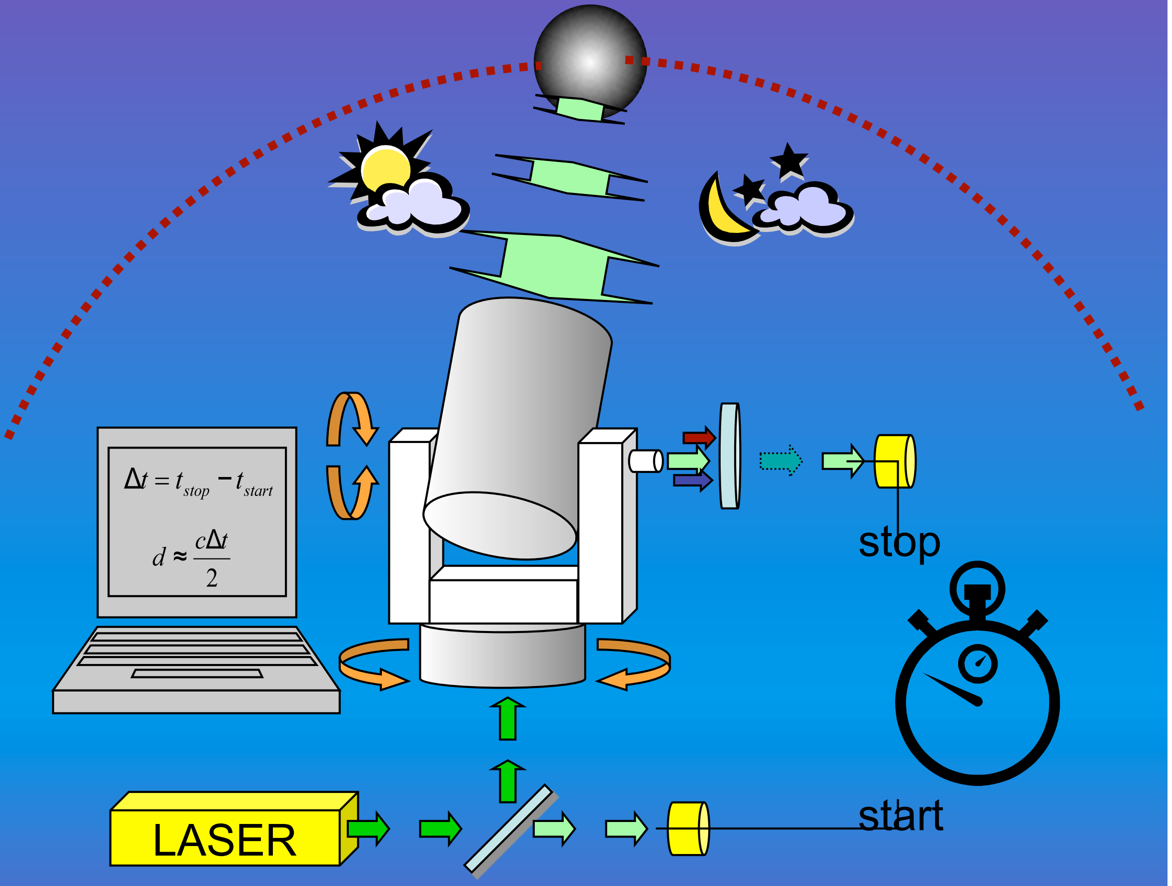

Cube corner retro-reflectors

(CCRs)

Time of flight, atmospheric corrections

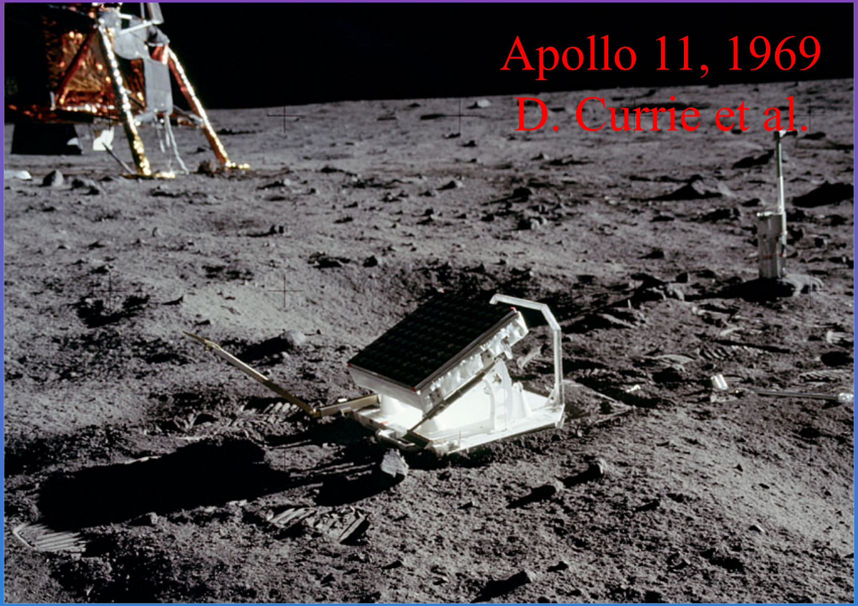
Retro-reflection

Normal reflection

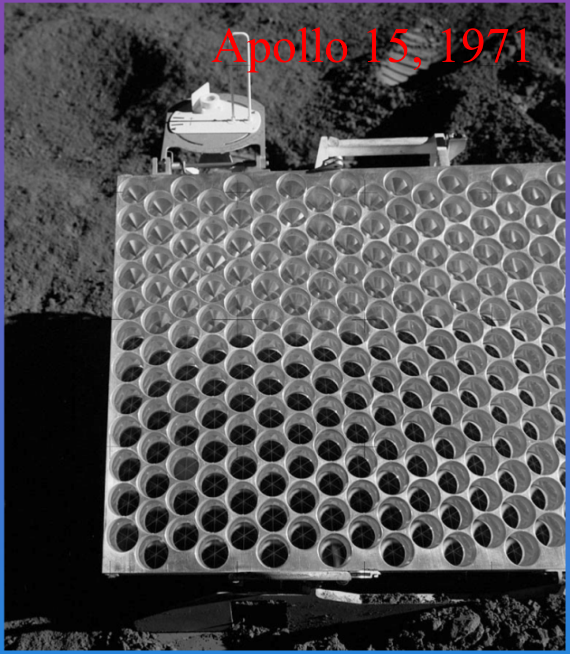

$$\Delta t = t_{stop} - t_{start}$$

$$d \approx \frac{c\Delta t}{2}$$

1st Gen. Lunar Reflector Arrays

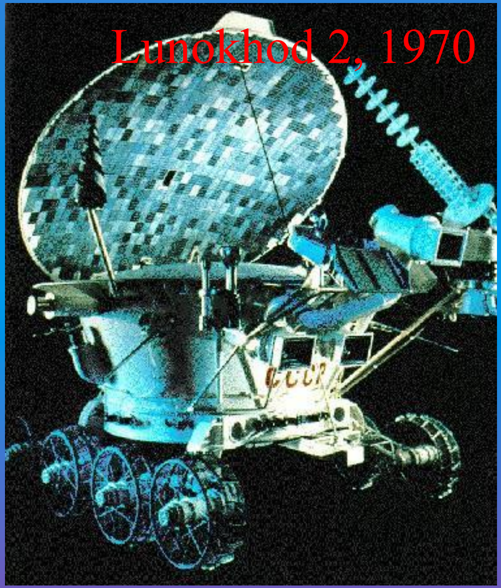


Apollo 11, 1969
D. Currie et al.

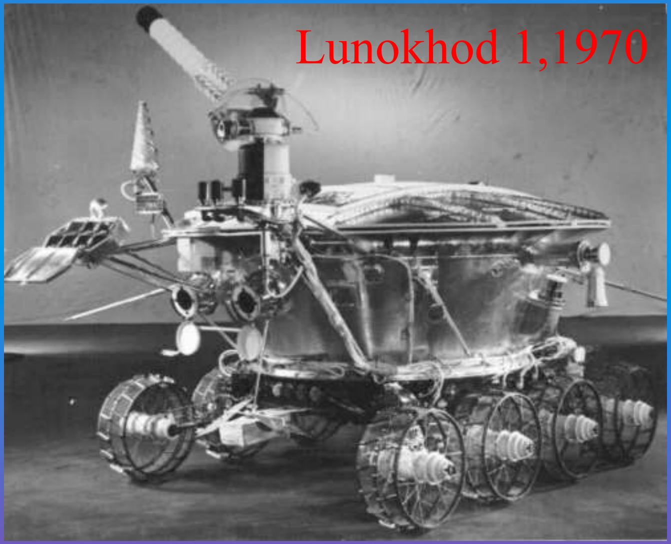


Apollo 15, 1971

Apollo 14, 1971



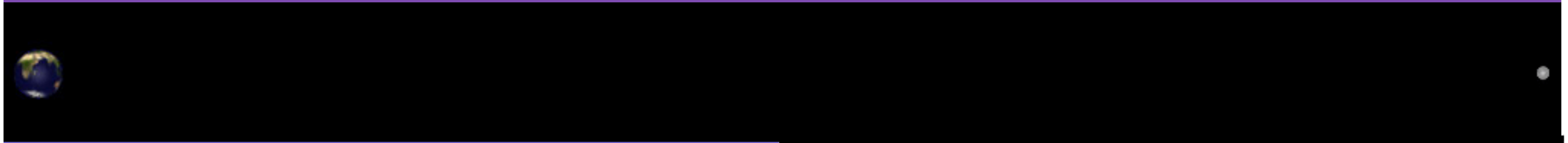
Lunokhod 2, 1970



Lunokhod 1,1970

1st Gen. Lunar Laser Ranging

accurate at ~ 10^{-11} of Earth-Moon distance

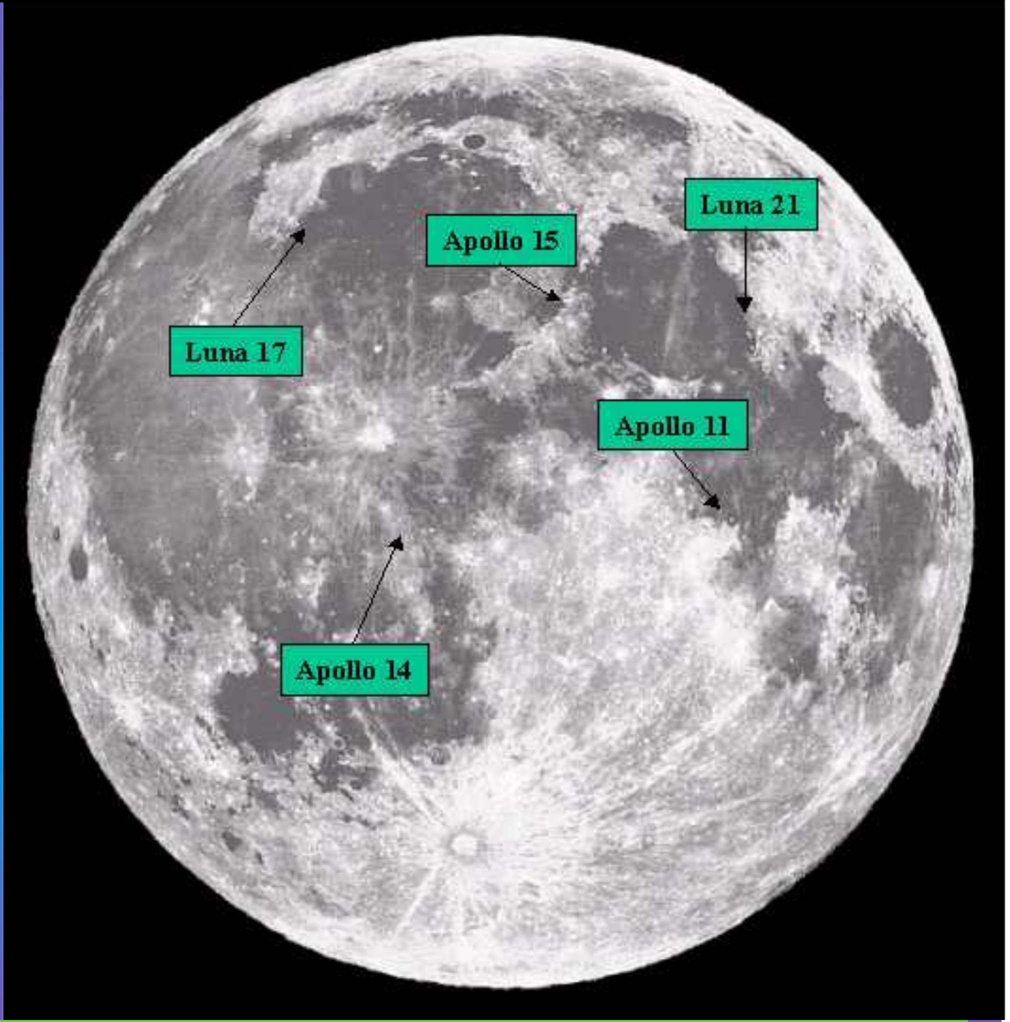


Relative sizes and separation of the Earth–Moon.

A LLR pulse takes 1.255 sec for the mean orbital distance

Distance Earth-Moon ~ 384,000 km

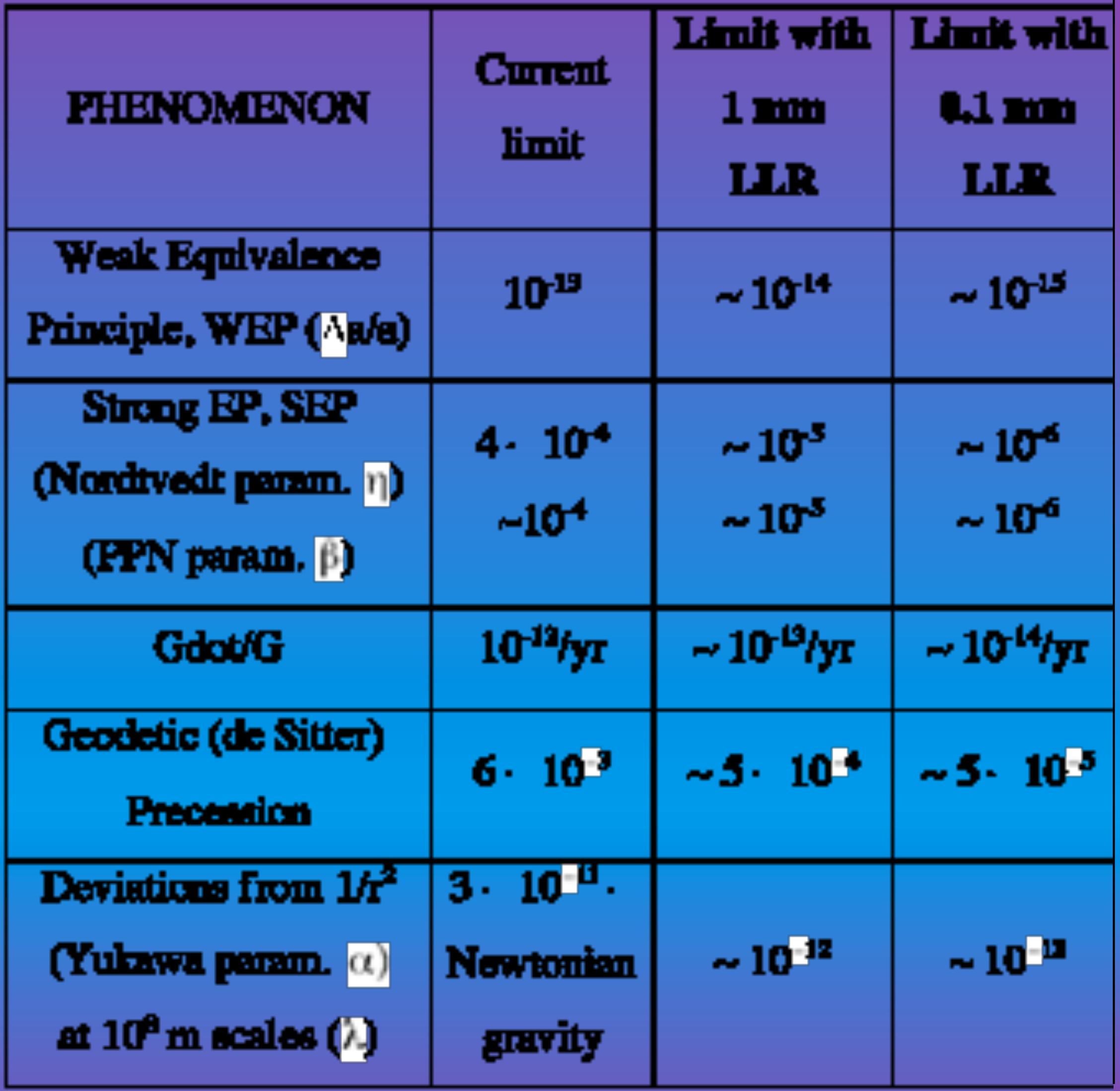
Locations of 1^{st} Gen. Lunar Retroreflector Arrays



LLR PHYSICS OBJECTIVES

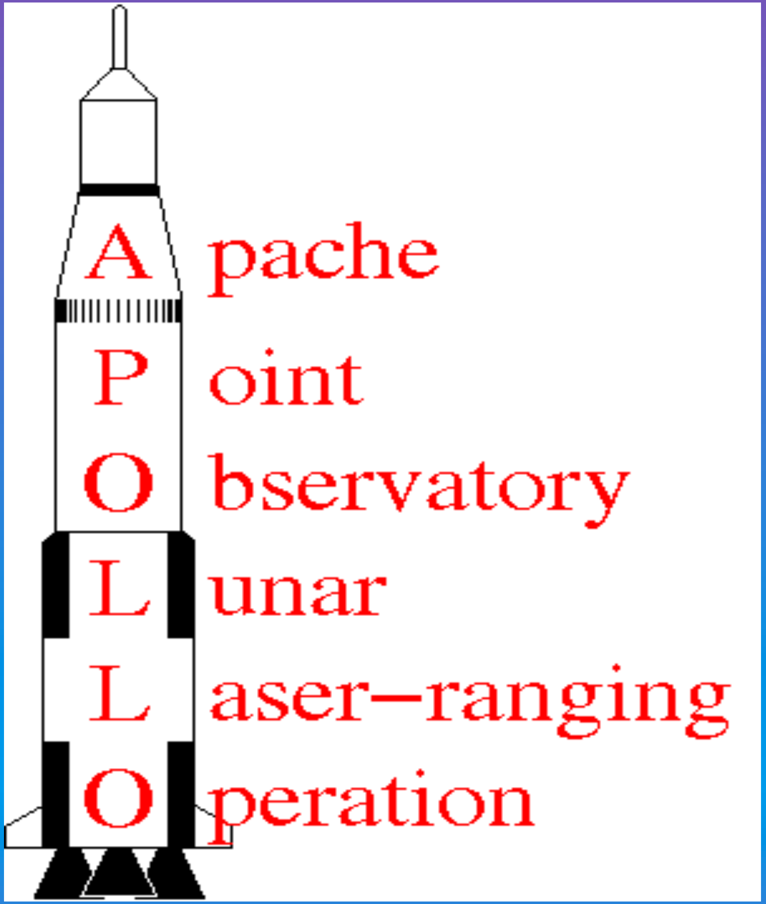
(for up to factor 100 improvement over 1st Gen. LLR)

LLR data
triggered
2000 papers
10000 refs



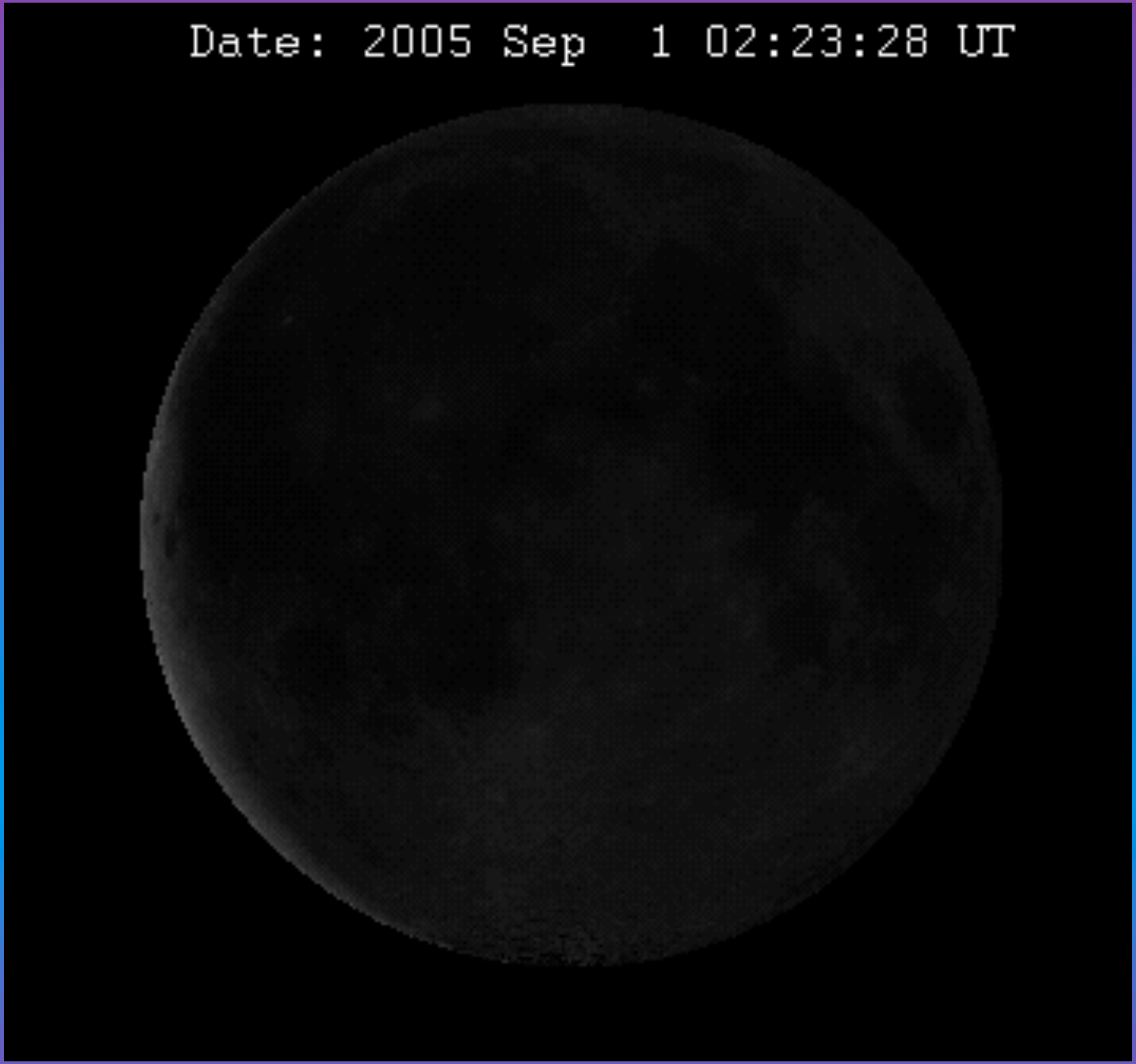
PHENOMENON	Current limit	Limit with 1 mm LLR	Limit with 0.1 mm LLR
Weak Equivalence Principle, WEP ($\Delta a/a$)	10^{-13}	$\sim 10^{-14}$	$\sim 10^{-15}$
Strong EP, SEP (Nordtvedt param. η)	$4 \cdot 10^{-4}$	$\sim 10^{-5}$	$\sim 10^{-6}$
(PPN param. β)	$\sim 10^{-4}$	$\sim 10^{-5}$	$\sim 10^{-6}$
Gdot/G	10^{-12}/yr	$\sim 10^{-13}$/yr	$\sim 10^{-14}$/yr
Geodetic (de Sitter) Precession	$6 \cdot 10^{-3}$	$\sim 5 \cdot 10^{-4}$	$\sim 5 \cdot 10^{-5}$
Deviations from $1/r^2$ (Yukawa param. α) at 10^8 m scales (λ)	$3 \cdot 10^{-11}$ · Newtonian gravity	$\sim 10^{-12}$	$\sim 10^{-13}$

APOLLO: Achieving the 1 *mm* Goal



- APOLLO offers an order-of-magnitude improvements (mm-level) to LLR by:
  - Using a 3.5 m telescope at a high elevation site (southern New Mexico)
  - Using a 16-element APD array
  - Operating at 20 Hz pulse rate
  - Multiplexed timing capable of detecting multiple photons per shot
  - Tight integration of experiment with analysis
  - Having a fund-grabbing acronym
    - APOLLO is jointly funded by the NSF and by NASA
- Started operations in 2007
- Leader: Tom Murphy, UCSD

Lunar Librations



Date: 2005 Sep 1 02:23:28 UT

Libraptions: the main limitation of 1st Gen. LLR

MLRO

Matera Laser Ranging Observatory (leader G. Bianco)

agenzia spaziale italiana

2nd Gen. Lunar Reflectors

In the US:

A LUNAR LASER RANGING RETRO-REFLECTOR ARRAY for the 21st CENTURY

LLRRA21

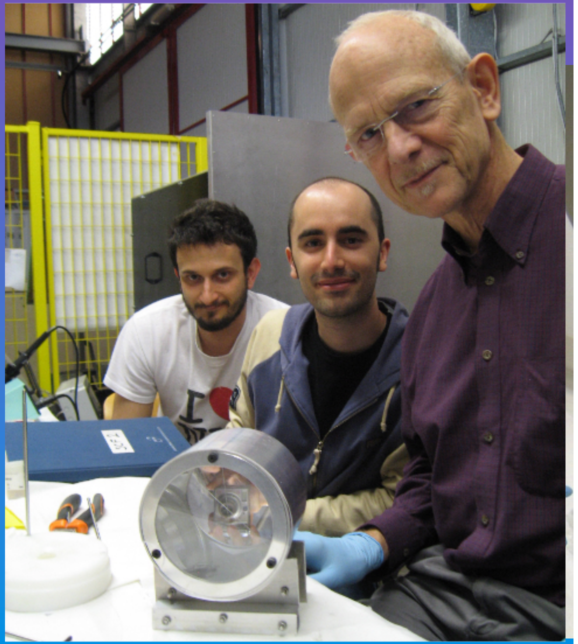
An Approved NASA Project
"Lunar Sortie Scientific Opportunities"
NASA Lunar Science Institute

In Italy:

Moon Laser Instrumentation for High-accuracy General relativity Tests

MoonLIGHT

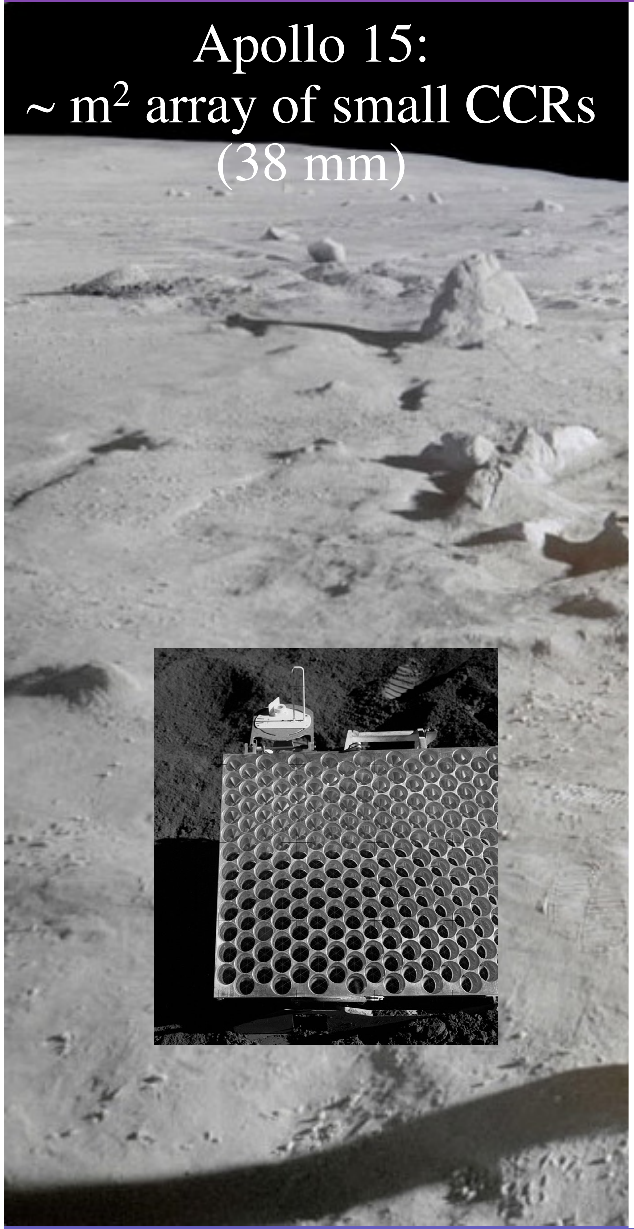
Mainly supported by INFN-LNF
In part supported by ASI for the Studies
"Observation of the Universe from the Moon"
Phase A of the lunar mission "MAGIA"



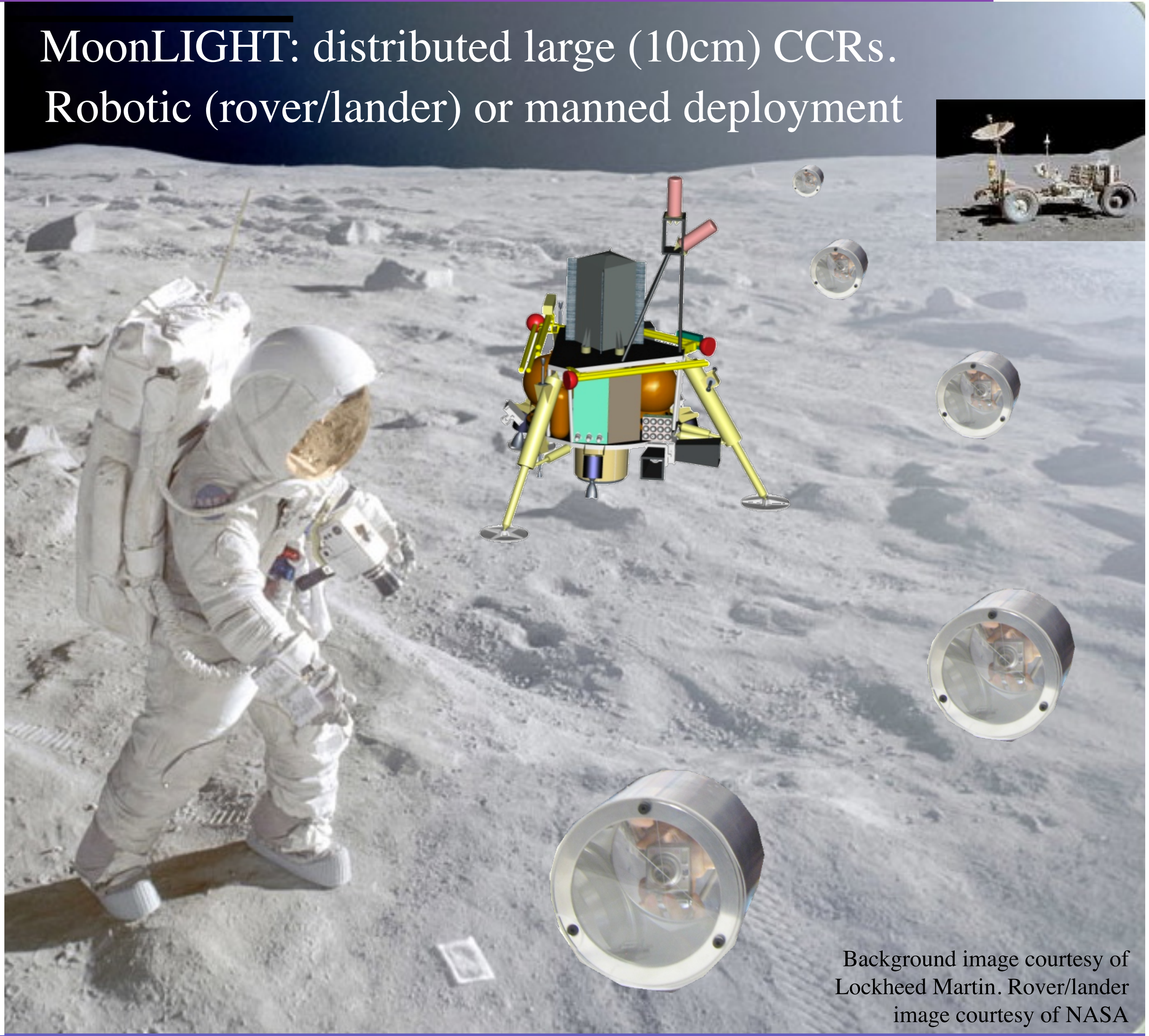
Our PI, Doug Currie of UMD, is one of the inventors of LLR. S. Dell'Agnello (LNF) is Co- PI

MoonLIGHT 2G LLR: distributed, large CCRs

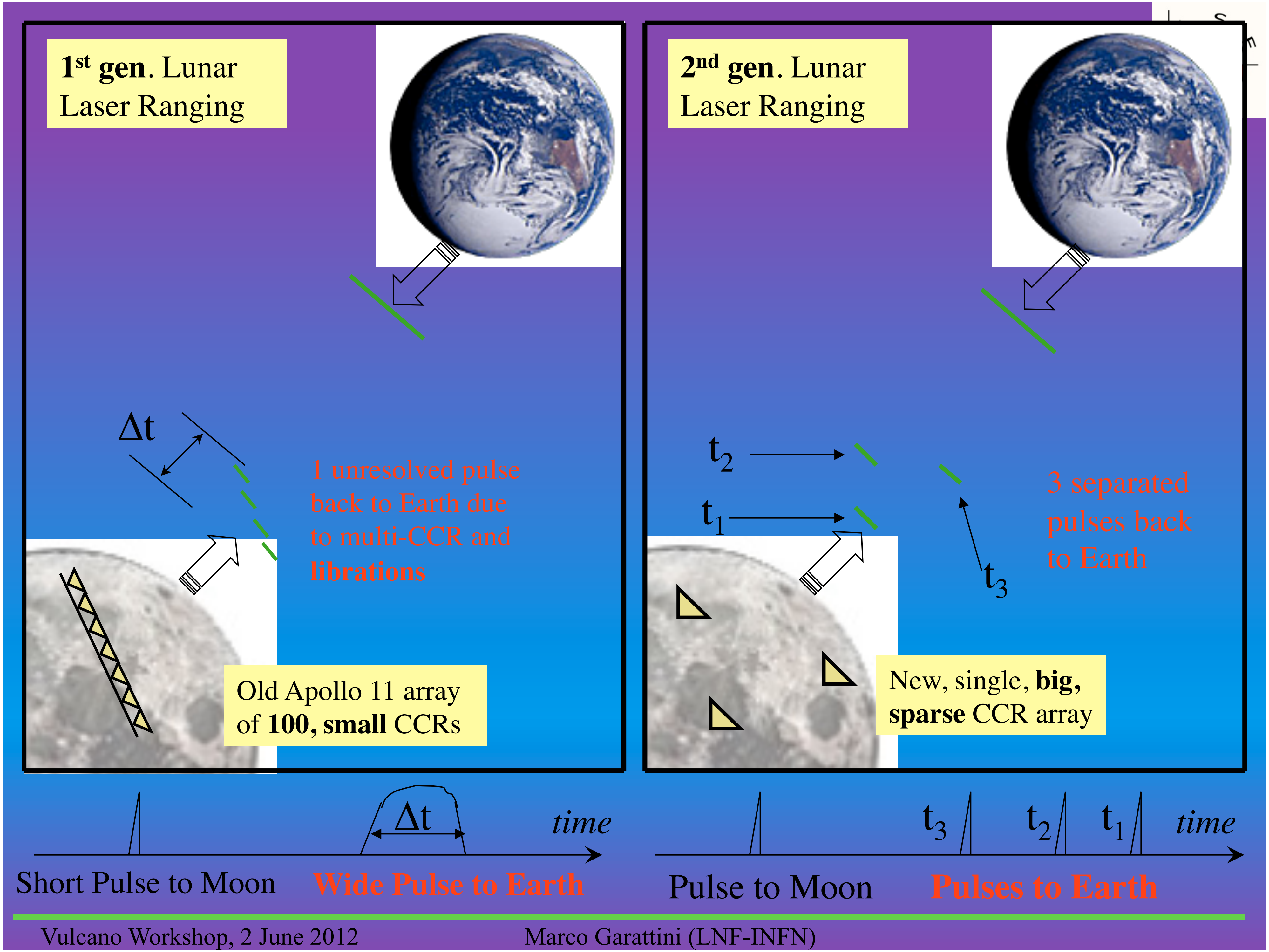
Apollo 15:
~ m^2 array of small CCRs
(38 mm)



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



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



1st gen. Lunar Laser Ranging

1 unresolved pulse back to Earth due to multi-CCR and **librations**

Old Apollo 11 array of **100, small** CCRs

2nd gen. Lunar Laser Ranging

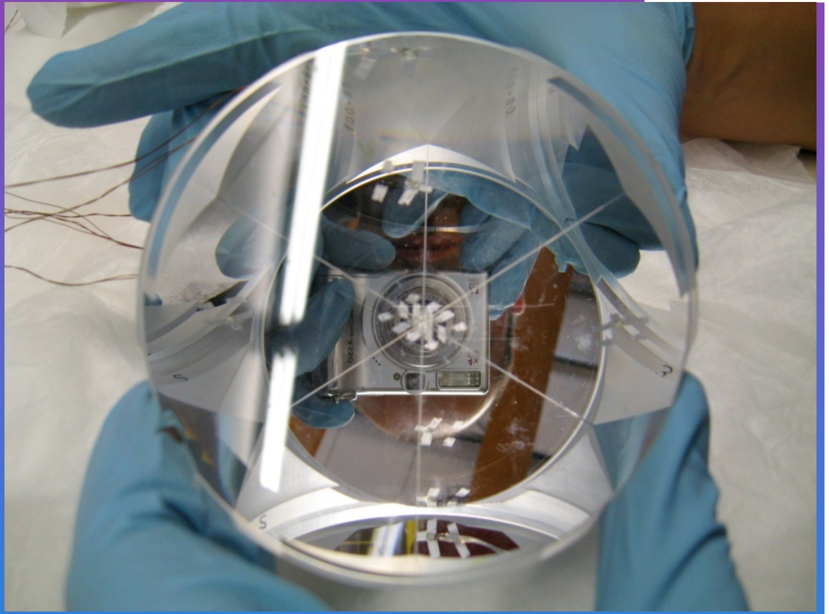
3 separated pulses back to Earth

New, single, **big, sparse** CCR array

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

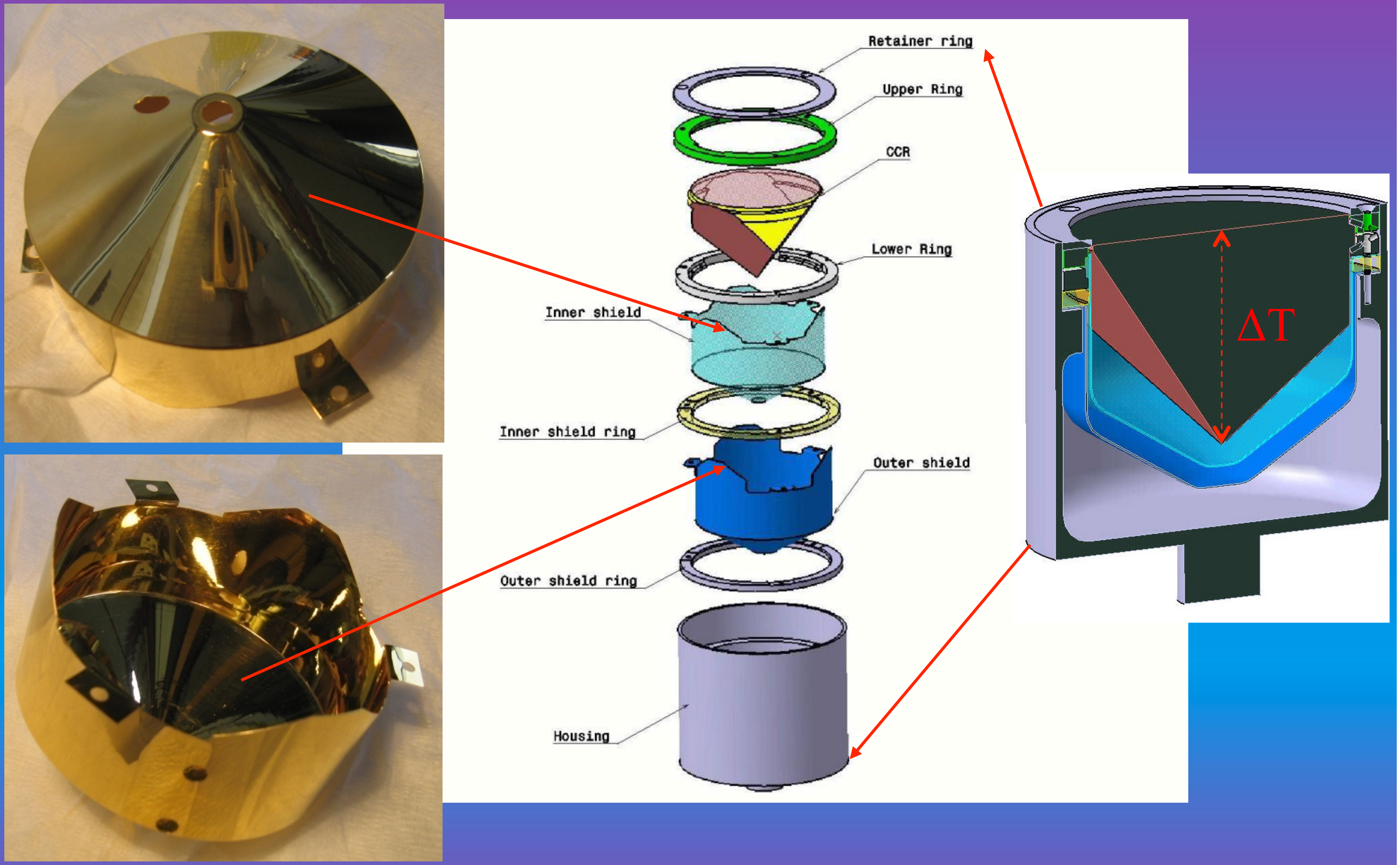
Pulse to Moon **Pulses to Earth**

Intuitive laser link equation

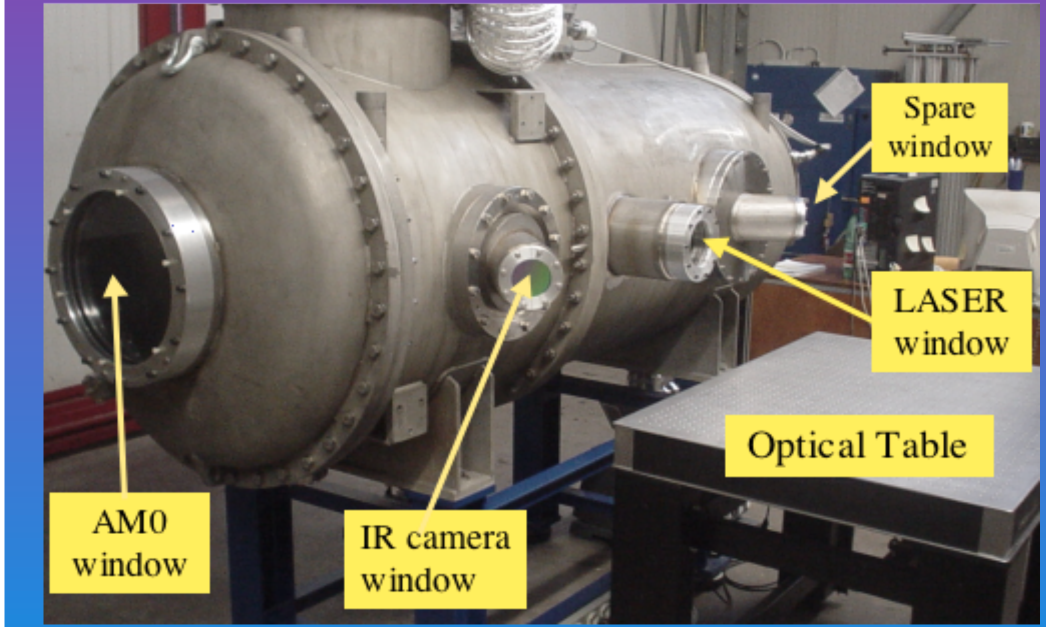


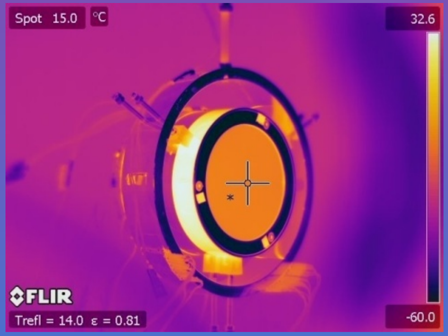
- **Laser Return Strength Goes as D^4**
  - On-Axis: that is, no velocity aberration
  - Iso-Thermal: that is, no thermal Distortion
- **Ratio $(100mm/38.1mm)^4 = 47.5$**
- **Single 100 mm CCR = 47 APOLLO CCRs**
- **Therefore ~ ½ return of APOLLO 11/14**
  - APOLLO Station "Always" gets more than 60 returns
  - We Expect >15 returns for most observations - plenty
  - Allows for any degradation that may have occurred for APOLLO

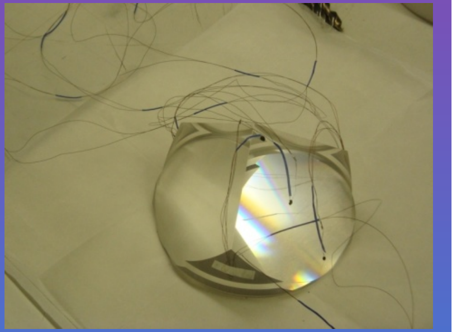
Big CCR Housing



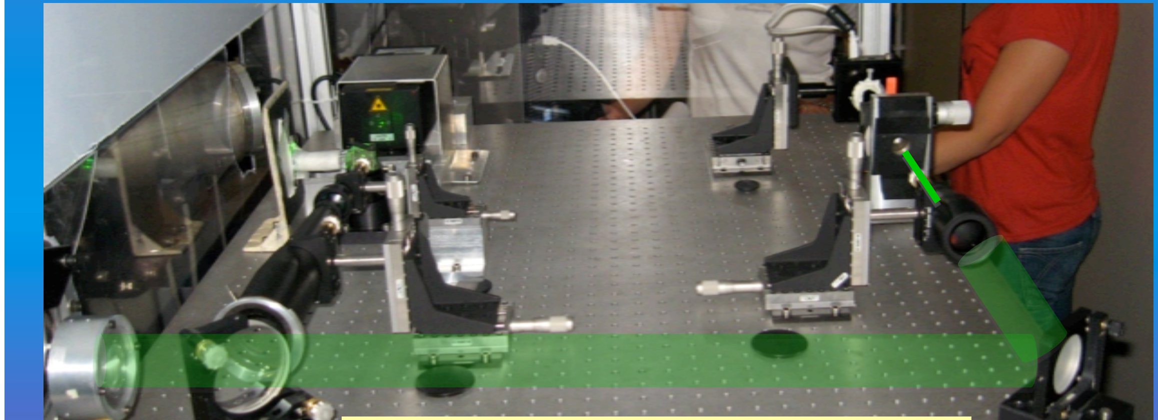
SCF: Satellite/Lunar laser ranging Characterization Facility



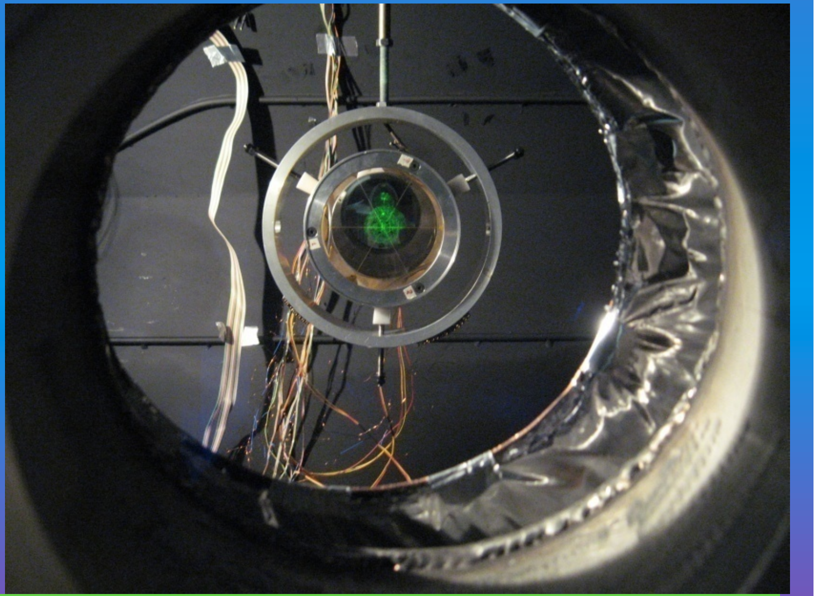




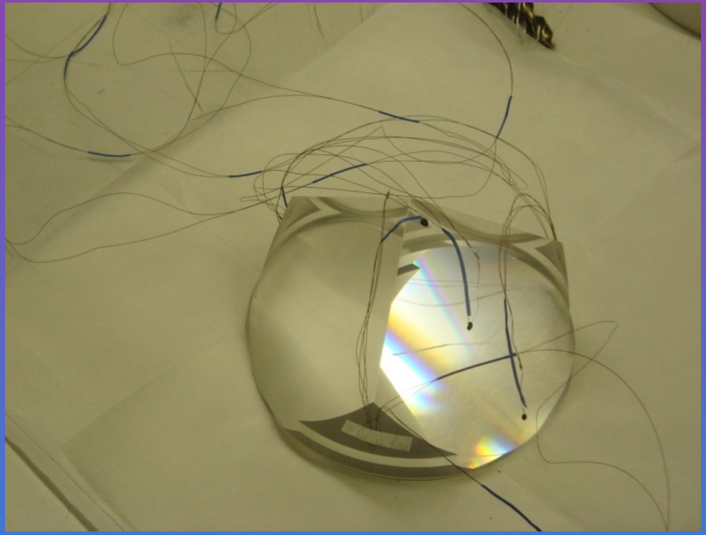
SCF-Test



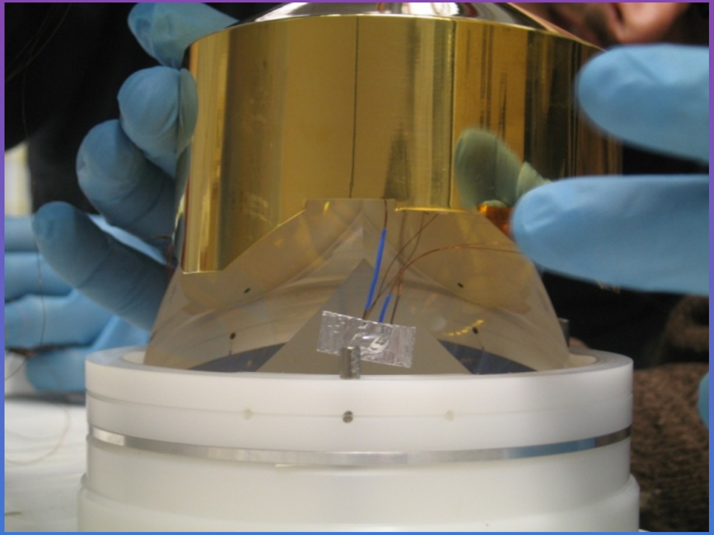
CCR Far Field Diffraction Pattern circuit
CCRs inside or outside the SCF



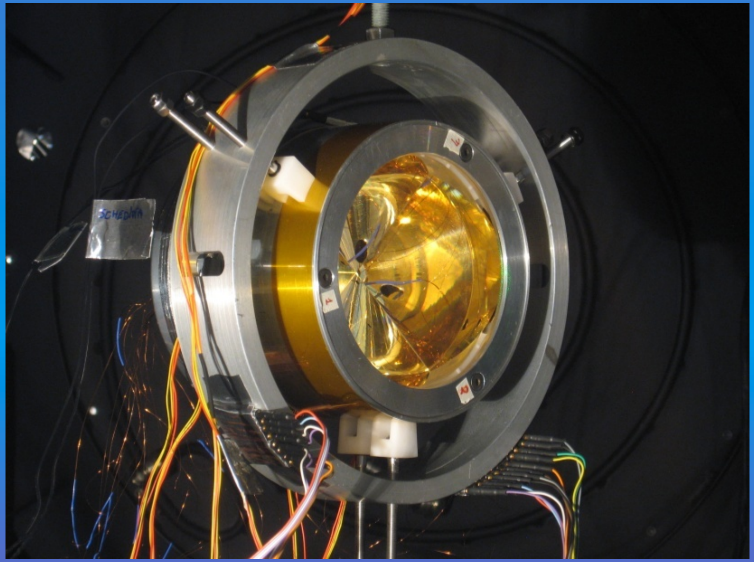
Big CCR Housing and Thermal Shields



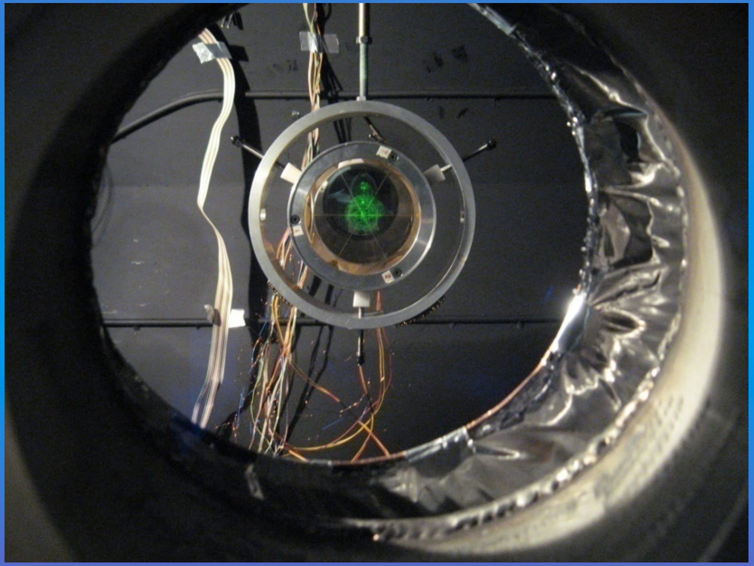
Temperature Probes on CCR's back face



Gold thermal shield



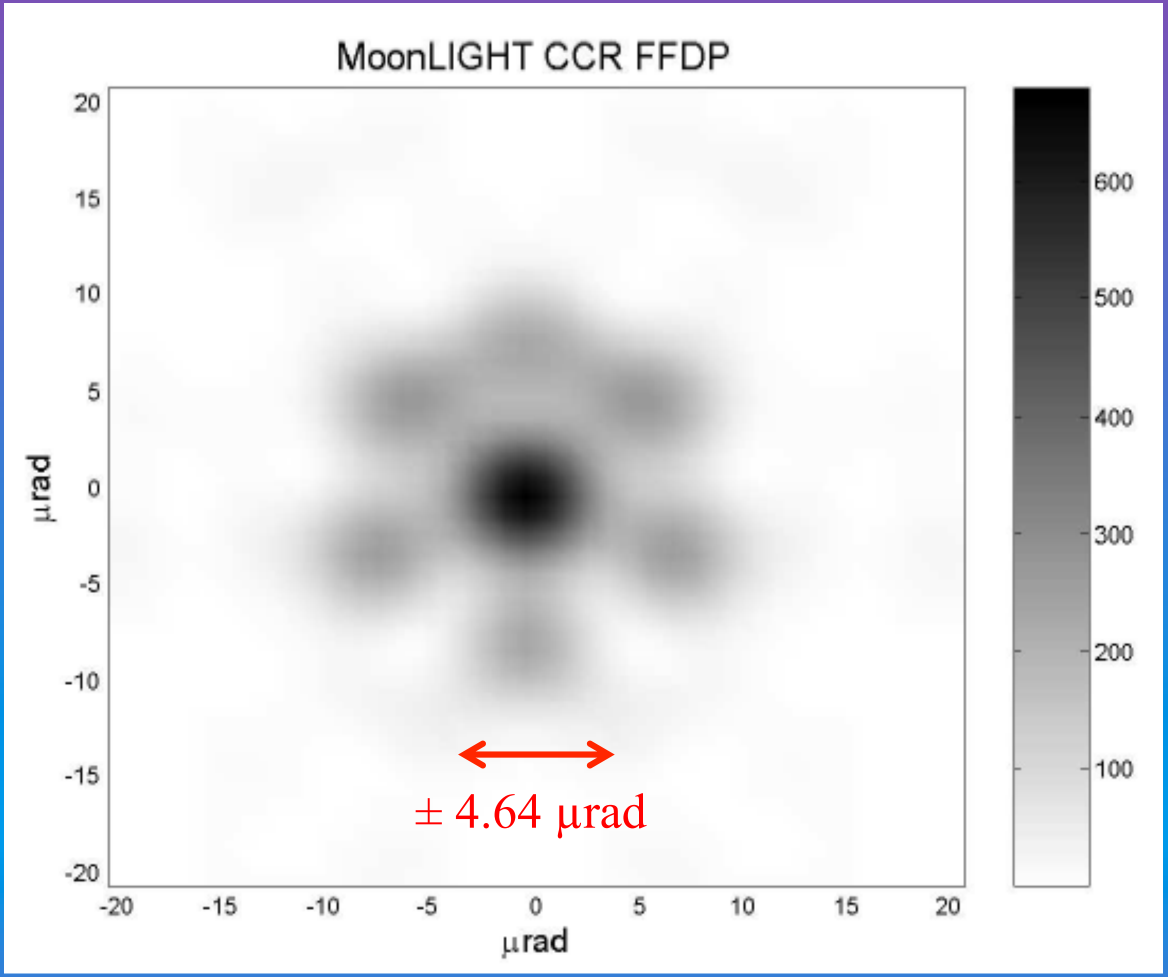
Assembly in SCF



Laser beam hits the CCR in SCF

Far Field Diffraction Pattern (FFDP)

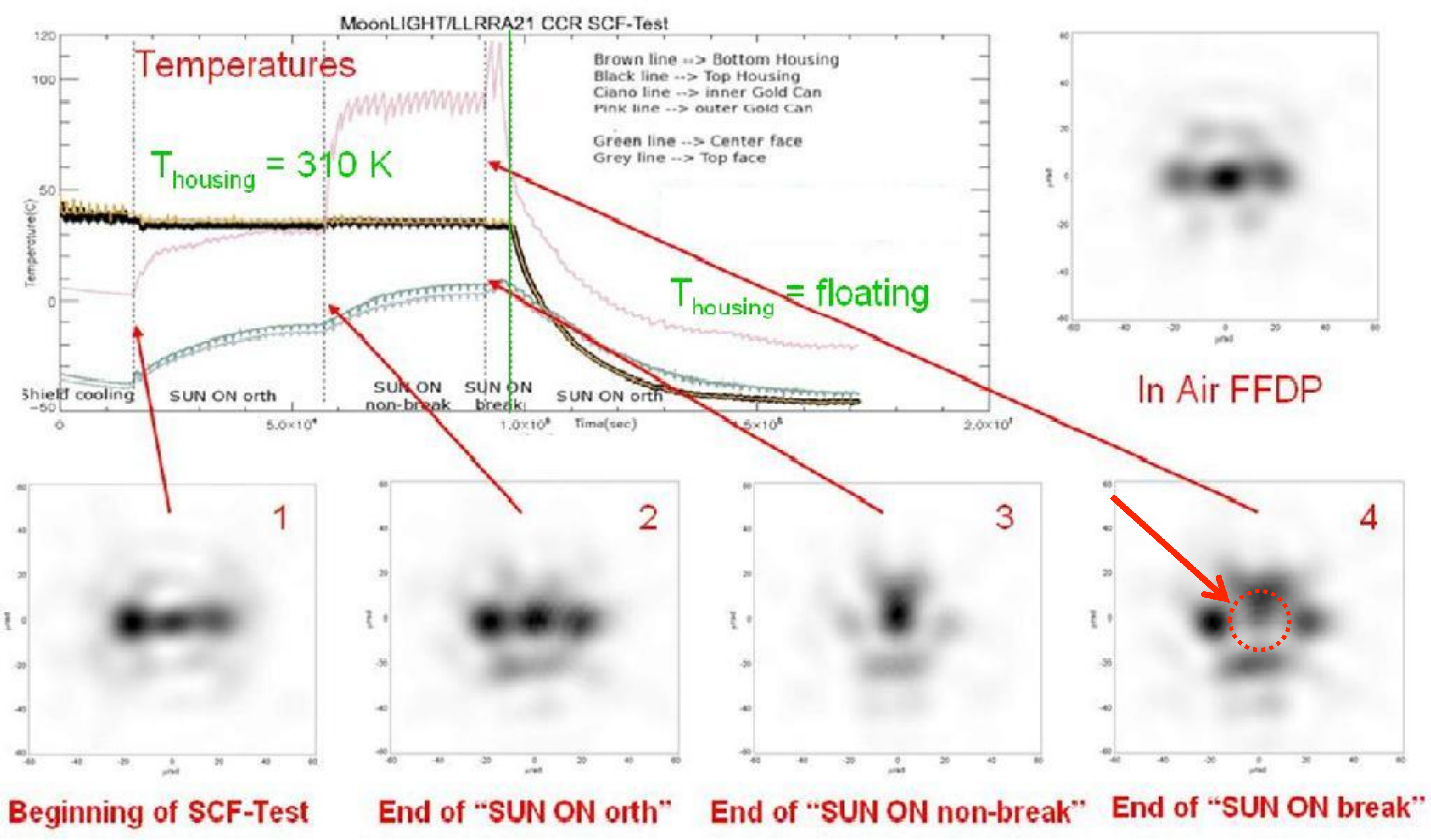
FFDP of
MoonLIGHT
CCR
Offset angles
(0,0” 0.0” 0,0”)



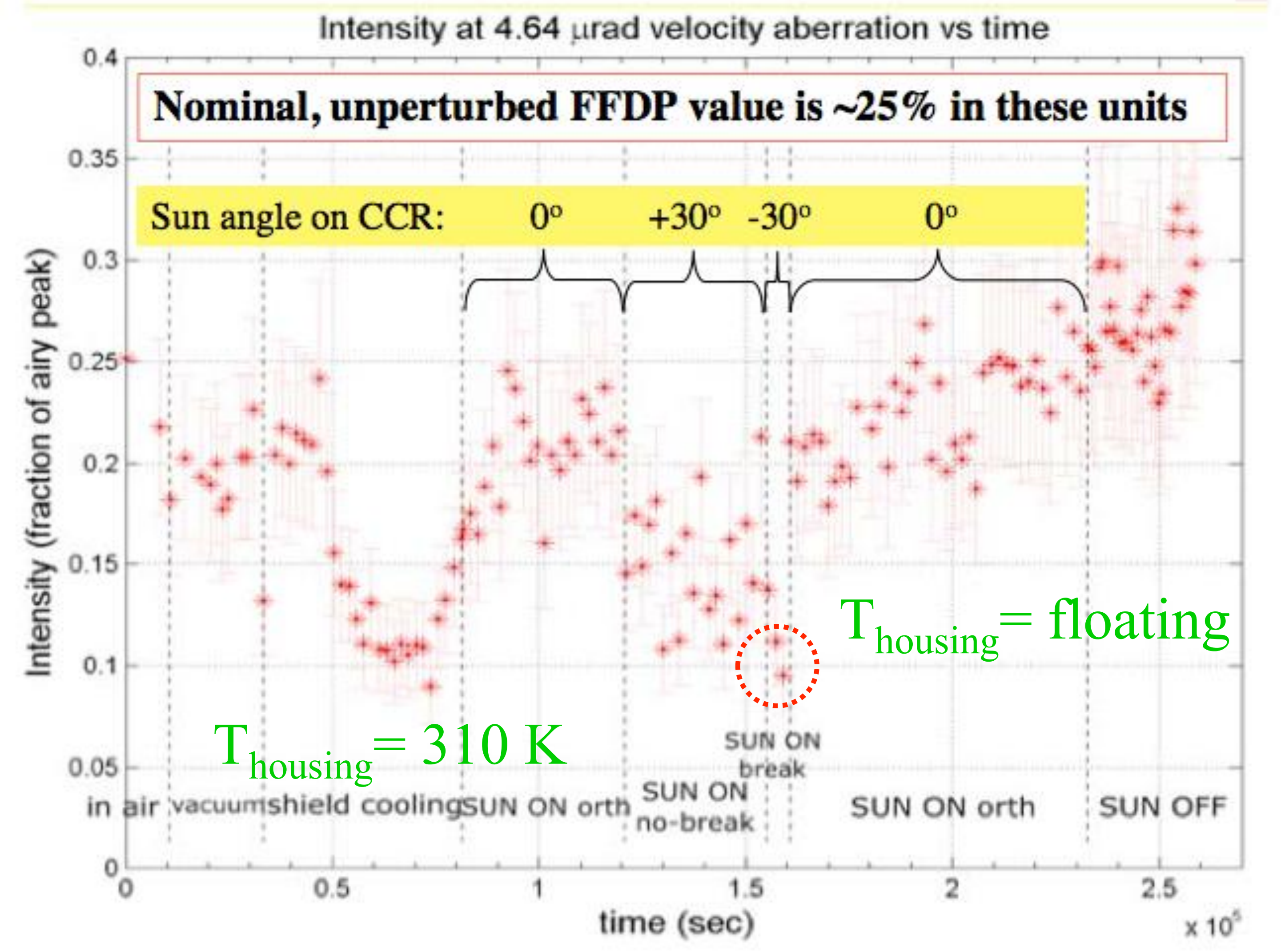
The intensity is mediated along the circumferance at velocity aberration due to relative motion of the Earth respect with the Moon

FFDPs at key points of the SCF-Test:

FFDP measurements performed with green laser (λ=532 nm), with ∅ = 38 mm



Variation of FFDP during SCF-Test



Nominal, unperturbed FFDP value is ~25% in these units

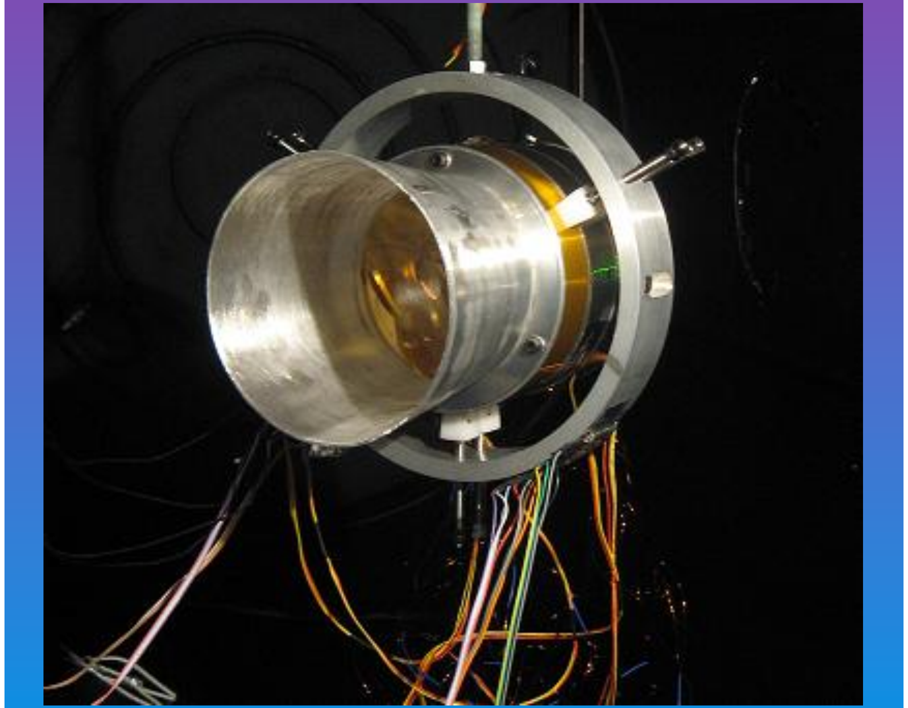
Sun angle on CCR: 0° +30° -30° 0°

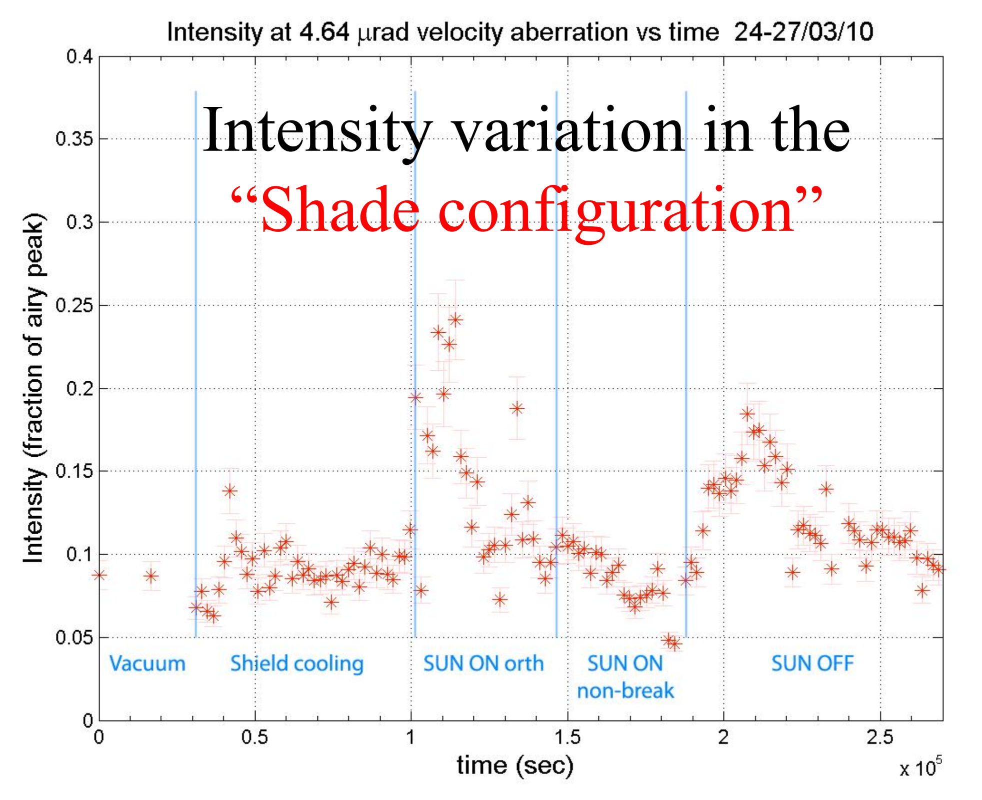
$T_{housing}$ = 310 K

$T_{housing}$ = floating

MoonLIGHT/LLRRA-21 flight CCR FFDP average intensity variation at Moon velocity aberrations (2V/c) during tests

Further payload developments

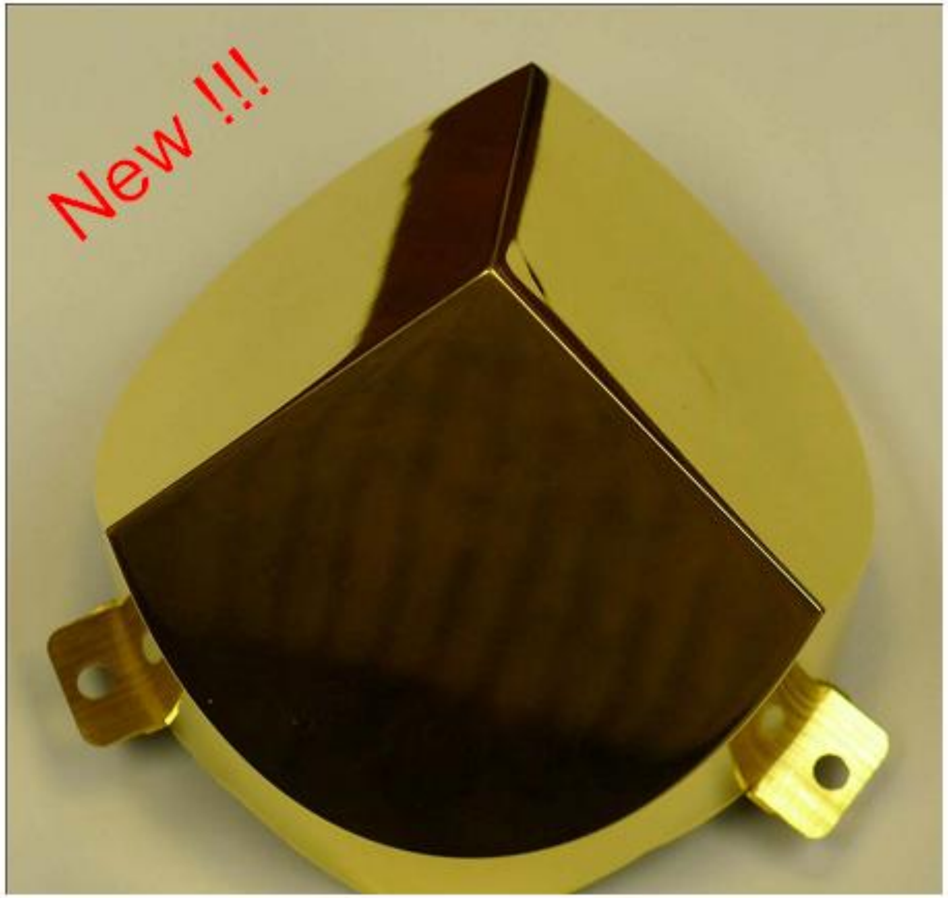




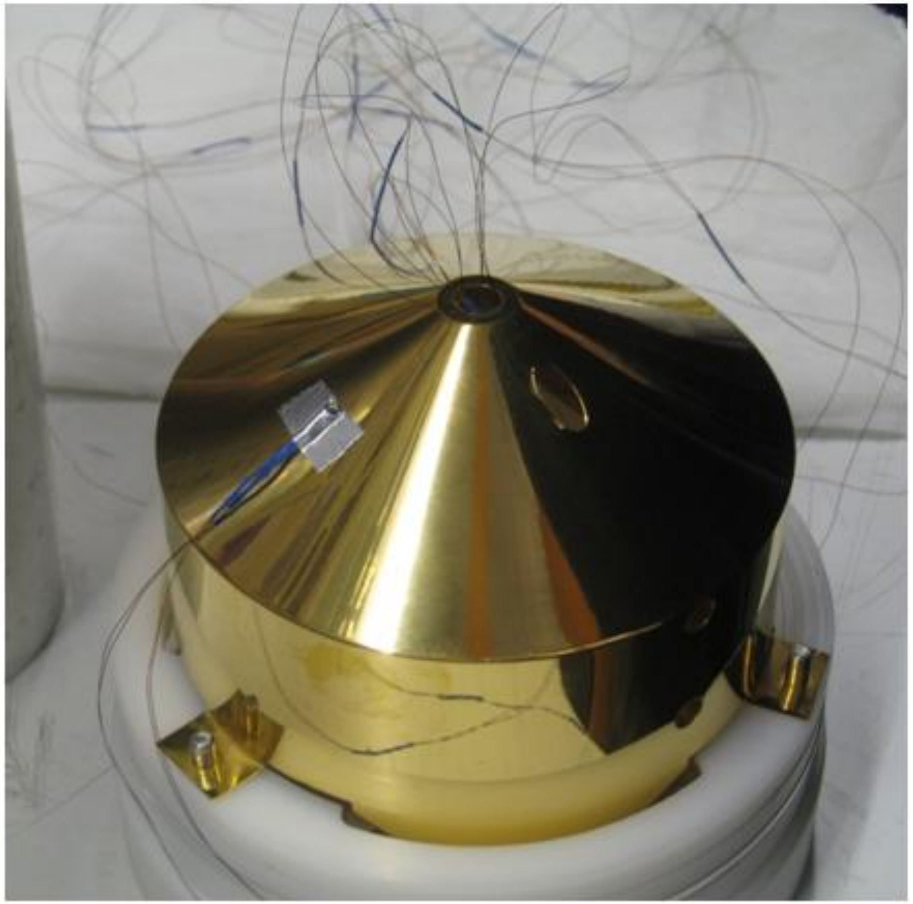
Intensity variation in the
“Shade configuration”

The break-through phase is gone, but the CCR has retained the previous performance, ensuring its operativity also during a non orthogonal solar illumination

“Conformal Can”



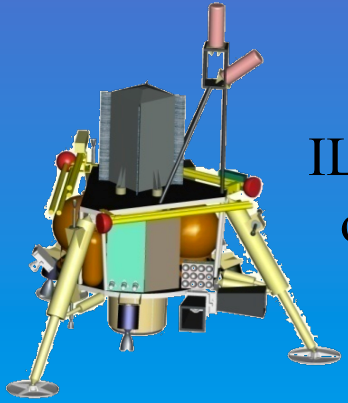
Inner conformal shield



Outer conical shield

Geopolitically-free Network of 4 multi-site simultaneously operating instruments

Core Instrument WG Results



ILN Lander Node
or ESA Lander

- Core Science/Instruments List
  - Seismology
  - Heat Flow
  - E&M Sounding
  - **Laser Ranging** for Lunar Geodesy and Test for General Relativity
- Note that all landing site activities will require geologic context

Conclusions…

Investigating the Earth-Moon system is one of the ways to verify the laws of gravity and providing a new connection between high-energy physics, astrophysics and cosmology

The LLR still remains one of the most powerful and competitive of all methods and technologies for this kind of investigations

This is an all round contribution to the progress of LLR, developing and integrating:

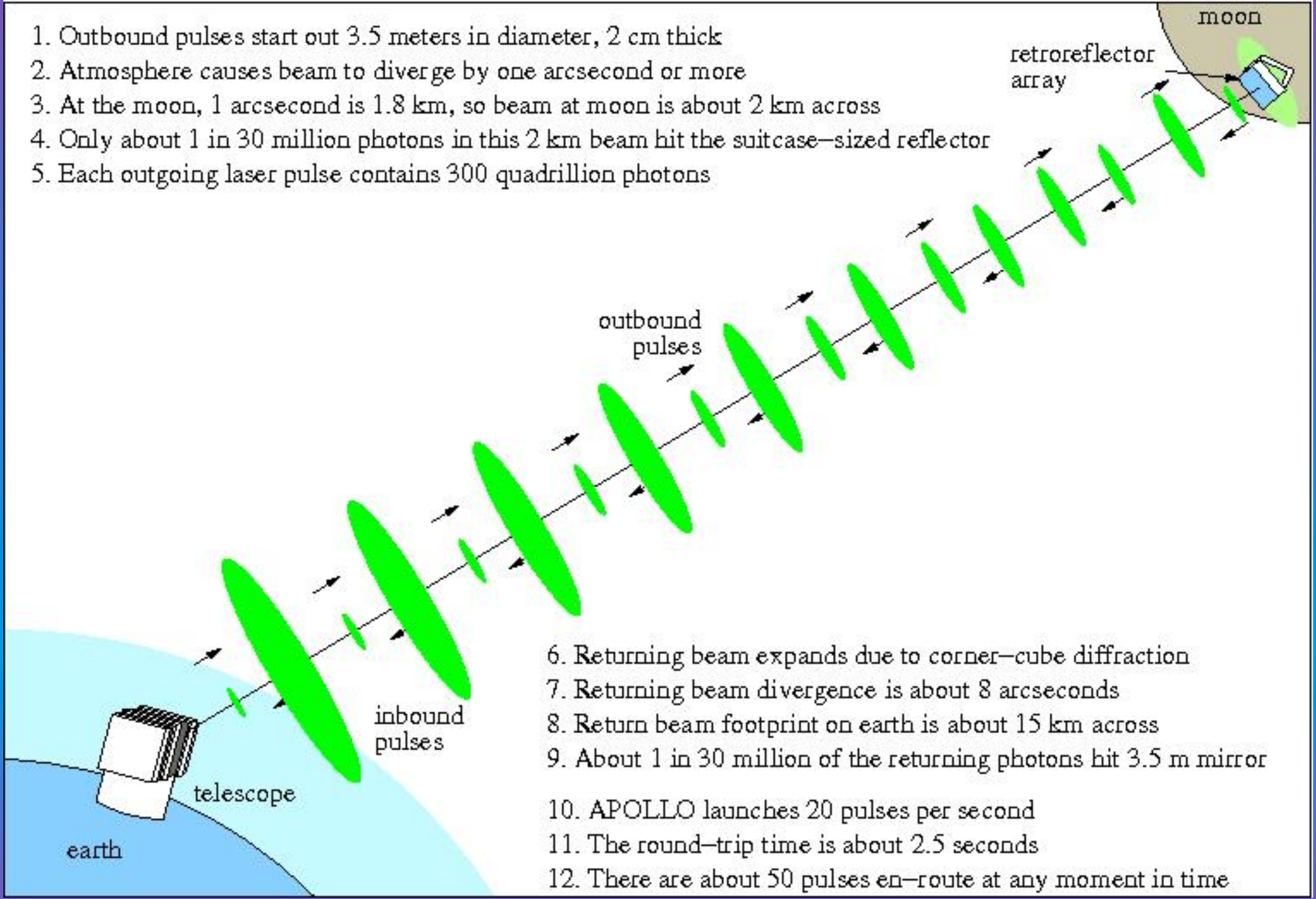
1) New LLR payload	(MoonLIGHT/LLRA-21st)
2) New characterization facility	(SCF)
3) New test procedure	(SCF-Test)
4) New station	(APOLLO Station)

THANKS

For your attention…

SPARES

Scheme of the APOLLO Laser Ranging Operation



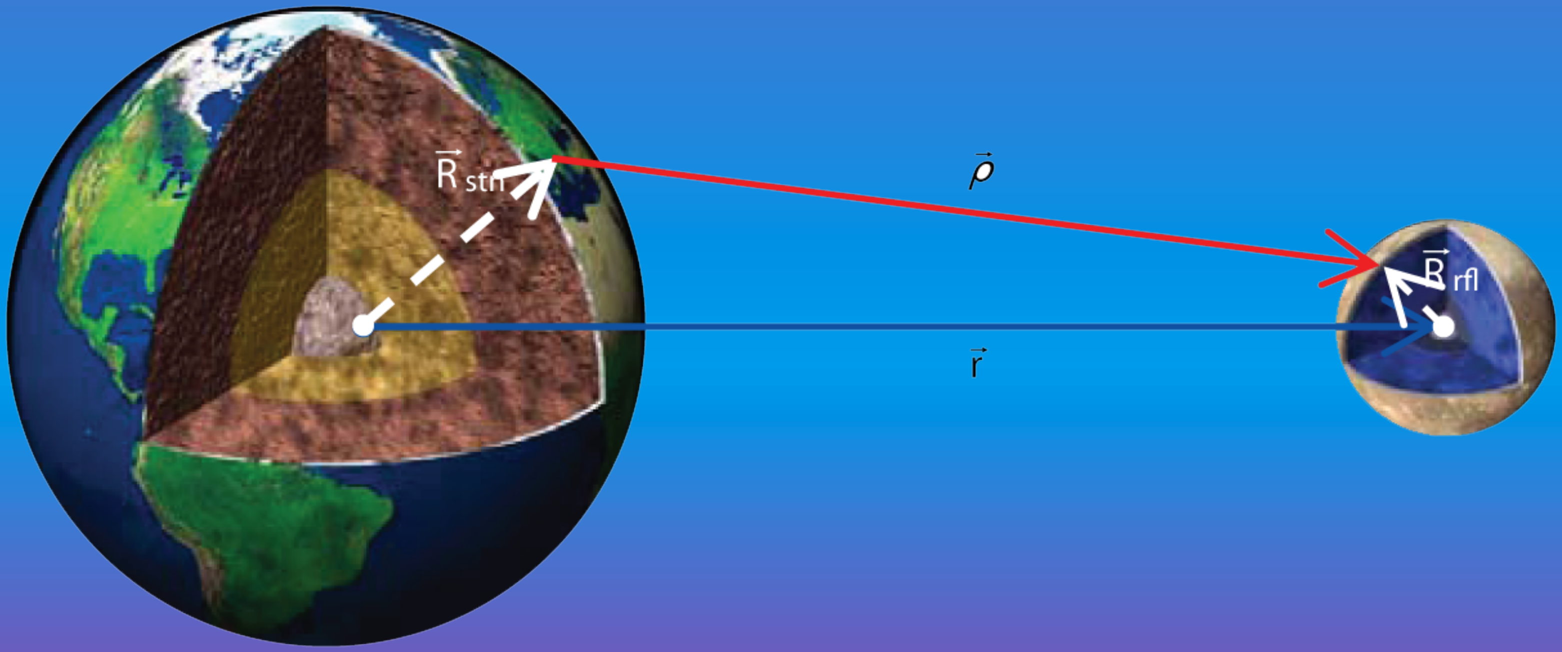
1. Outbound pulses start out 3.5 meters in diameter, 2 cm thick
2. Atmosphere causes beam to diverge by one arcsecond or more
3. At the moon, 1 arcsecond is 1.8 km, so beam at moon is about 2 km across
4. Only about 1 in 30 million photons in this 2 km beam hit the suitcase–sized reflector
5. Each outgoing laser pulse contains 300 quadrillion photons

6. Returning beam expands due to corner–cube diffraction
7. Returning beam divergence is about 8 arcseconds
8. Return beam footprint on earth is about 15 km across
9. About 1 in 30 million of the returning photons hit 3.5 m mirror

10. APOLLO launches 20 pulses per second
11. The round–trip time is about 2.5 seconds
12. There are about 50 pulses en–route at any moment in time

LLR physics data analysis

- General Relativity (GR) equations of motion
  - LLR provides not just one, but a suite of physics measurements, which have given a deep and thorough, weak-field, slow-motion test of GR
- PPN parameters
- Other new physics beyond GR ($1/r^2$ deviations, braneworlds …)
- Description of Earth & Moon as rigid bodies
- Earth & Moon geophysics (tides, librations, interiors, tectonic plate motion …)



Selenodesy and lunar interior

- Q = is the lunar tidal dissipation parameter
- K_2 = the elastic response to lunar solid body tides parameter

- $\dot{G}/G = (4 \pm 9) \times 10^{-13}/\mathrm{yr}$ (Williams et al. 2004) has a strong correlation (0,74) with Q
- $K_{GP} = -0.0019 \pm 0.0064$ (Williams et al. 2004) is strongly correlated (0,88) with K_2 and the lunar core oblateness parameter

- A better estimation of K_2 (to 1%) will come from GRAIL (The Gravity Recovery and Interior Laboratory) mission
- The ILN (International Lunar Network) project will provide a better estimation of Q

Post Newtonian Parameters

Schwarzschild metric:

$$ds^2 = c^2dt^2\left(1-\frac{2GM}{rc^2}\right)-\frac{dr^2}{1-\frac{2GM}{rc^2}}-r^2(sen^2\theta d\psi^2+d\theta^2)$$

Post Newtonian theory:

$$ds^2 = cdt^2A(r)+dr^2B(r)+Angularpart$$

$$A(r)=1-\frac{2GM}{rc^2}+2(\beta-\gamma)\left(\frac{GM}{rc^2}\right)^2+..........$$

$$B(r)=1+2\gamma\frac{GM}{rc^2}+.........$$

In General Relativity

$\beta = \gamma = 1$

- γ space-time curvature → $\gamma - 1 < 2.3 \text{ x}10^{-5}$ Cassini
- β non linearity of gravity → $\beta - 1 < 1.4 \text{ x}10^{-4}$ Lunar Laser Ranging

LLR test of the Weak Equivalence Principle

Williams et al, arXiv: gr-qc/0507083v2, 2 Jan 2009

- Compare free fall acceleration of Earth and Moon towards the sun using JPL sw by Williams et al; solve for their M_G/M_I
- If WEP violated, lunar orbit displaced (*polarized*) along Earth-Sun line with range variation

  $\Delta r \propto \cos D$ (D corresponds to 29.53 day = new-full-new mean period)

- Fit to LLR data corrected for solar radiation perturbations, SRP:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,LLR} = (-1.0 \pm 1.4) \times 10^{-13}$$

  - This corresponds to $\Delta r = (2.8 \pm 4.1)$ mm × cos D $= \Delta r_{LLR} - \Delta r_{SRP}$
  - SRP is accounted for a posteriori by subtracting from Δr_{LLR}

    $\Delta r_{SRP} = (-3.65 \pm 0.08)$ mm × cos D (Vokrouhlicky 1997)

    - SRP error << LLR fit error
  - For example: one particular LLR fit returns -0.6 +/- 4.2 mm (no solar rad pressure), but SRP-corrected results is 3.1 +/- 4.2 mm

LLR test of the Strong Equivalence Principle

Williams et al, arXiv: gr-qc/0507083v2, 2 Jan 2009

- LLR test of EP sensitive to both composition-dependent (CD) and self-energy violations

UW: Baessler et al, PRL **83**, 3585 (1999);
Adelberger et al Cl. Q. Gravity **12**, 2397 (2001)

- University of Washington (UW) laboratory EP experiment with “miniature” Earth and Moon, measures only CD contribution:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,UW} = (1.0 \pm 1.4) \times 10^{-13}$$

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,LLR} = (-1.0 \pm 1.4) \times 10^{-13}$$

- Subtracting UW from LLR results one gets the SEP test:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{SEP} = (-2.0 \pm 2.0) \times 10^{-13}$$

SEP can only be tested by LLR

LLR SEP test: implications on PPN β

Williams et al, arXiv: gr-qc/0507083v2, 2 Jan 2009

- SEP violation is due to self-energy contribution only; it can be expressed as

$[(M_G/M_I)]_{SEP} = 1 + \eta\,(U/Mc^2)$ U = gravitational self-energy

Note: $U/M \propto M$ => to test SEP need astronomical bodies => only LLR

- Theory prediction

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{SEP} = [U_e/Mc^2 - U_m/Mc^2] \times \eta = -4.45 \times 10^{-10} \times \eta$$

- Considering only PPN β and γ

$$\eta = 4\beta - \gamma - 3 = (4.4 \pm 4.5) \times 10^{-4}$$

- β described the degree of non. Using Cassini's value of linearity of gravity associated to a SEP violation γ

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

Best measurement to date

LLR measurement of geodetic precession

Williams et al, arXiv: gr-qc/0507083v2, 2 Jan 2009

- 3-body effect (Sun, Earth, Moon) predicted by GR (de Sitter)

~ 3m/moon-orbit ~ 2”/cy

- Relative deviation of geodetic precession from GR value

K_{gp} = -0.0019 ±0.0064

- Highly correlated (0.88) with lunar potential Love number and with a parameter for lunar oblateness
- Adding the latter parameter, not present in earlier solutions increases the uncertainty of the geodetic precession

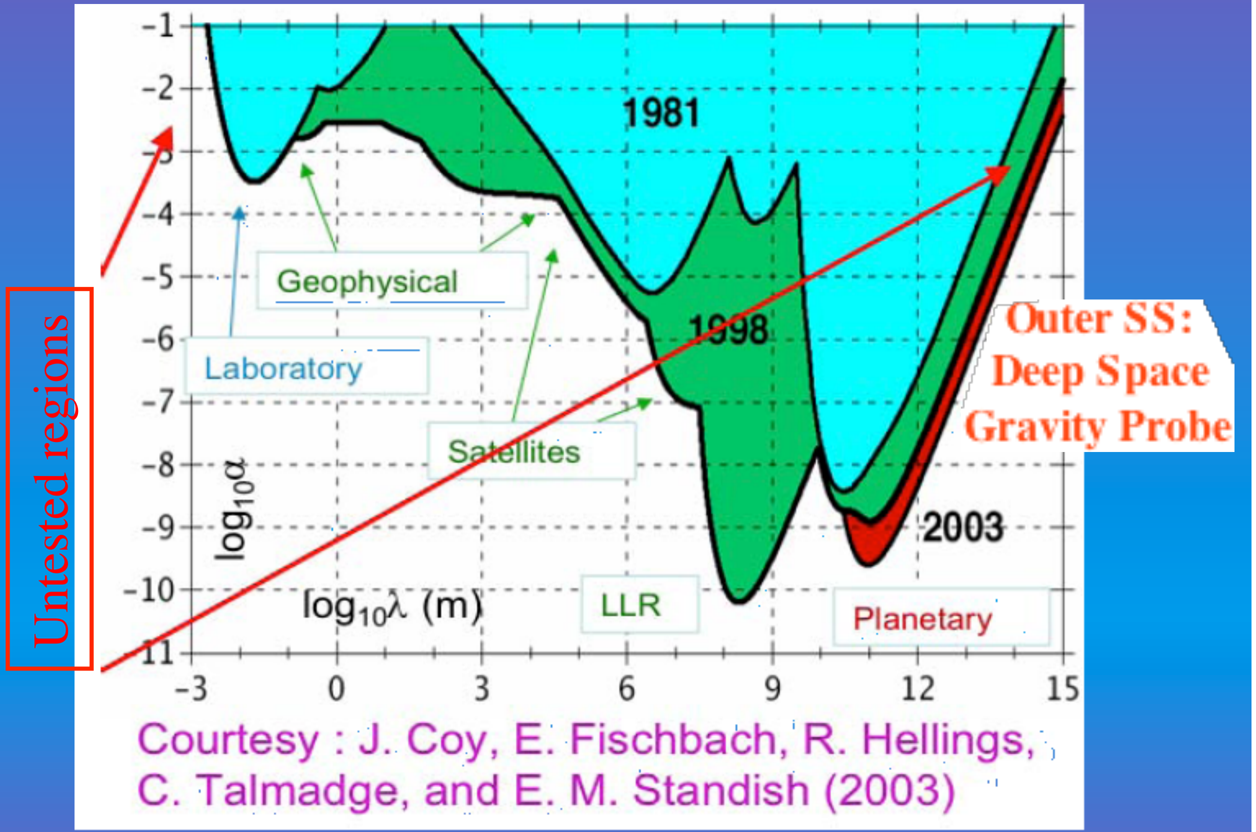
- LLR data give unique science products both in relativistic gravity and in lunar geophysics. LLR addresses both cannot do our beloved fundamental physics without modeling geophysics effects like the above, and, especially, the … LIBRATIONS

Limits on $1/r^2$ deviations in the Solar System

Current limits on additional Yukawa potential: $\alpha \times (\text{Newtonian-gravity}) \times e^{-r/\lambda}$

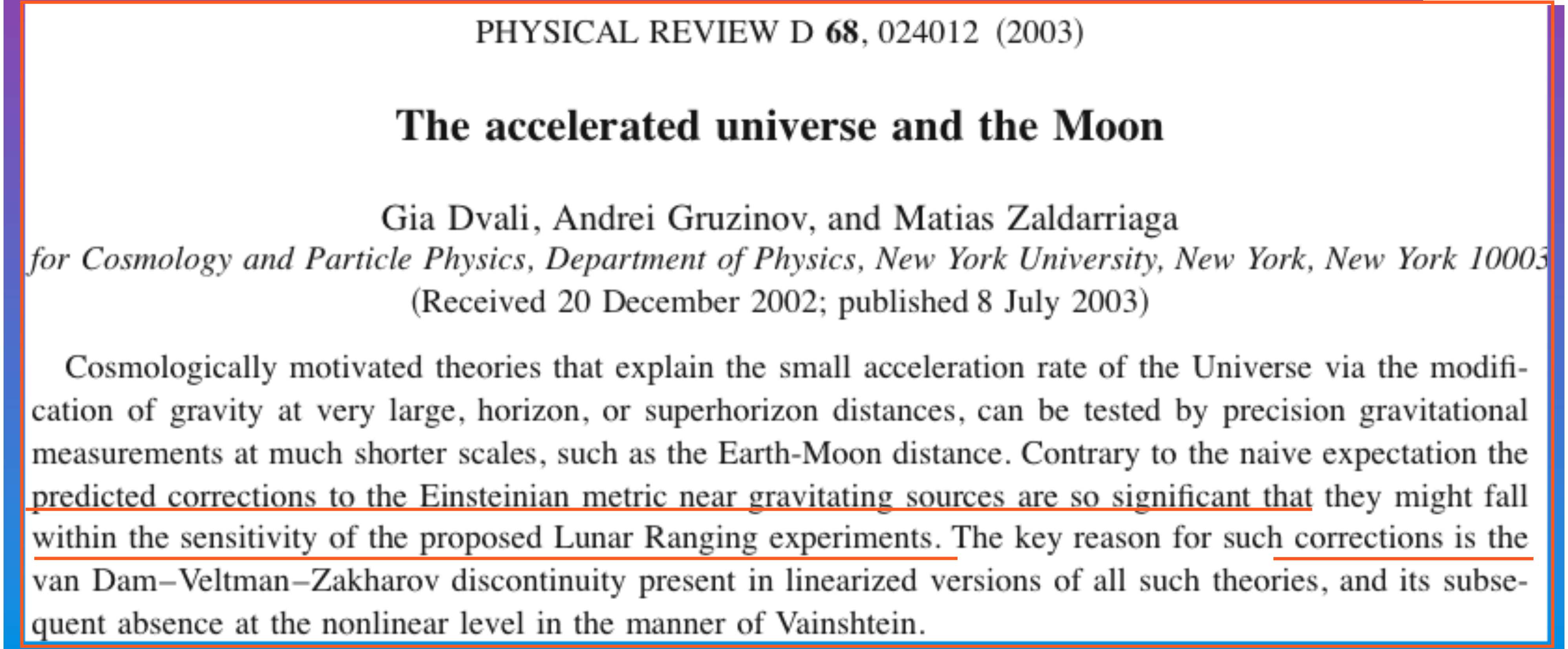
MoonLIGHT designed to provide accuracy of 100 mm on the space segment (the CCR).

If the other error sources on LLR will improve with time at the same level then a MoonLIGHT CCR array will improve limits from ~10^{-10} to 10^{-12} at scales of 10^6 meters



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

"Brane new world" without Dark Energy



PHYSICAL REVIEW D **68**, 024012 (2003)

The accelerated universe and the Moon

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Cosmologically motivated theories that explain the small acceleration rate of the Universe via the modification of gravity at very large, horizon, or superhorizon distances, can be tested by precision gravitational measurements at much shorter scales, such as the Earth-Moon distance. Contrary to the naive expectation the predicted corrections to the Einsteinian metric near gravitating sources are so significant that they might fall within the sensitivity of the proposed Lunar Ranging experiments. The key reason for such corrections is the van Dam–Veltman–Zakharov discontinuity present in linearized versions of all such theories, and its subsequent absence at the nonlinear level in the manner of Vainshtein.

- **Weak gravity explains apparent universe acceleration without Dark Energy**
- Gives anomalous precession of the Moon of ~ **0.7 mm/orbit**, in addition to geodetic precession of GR, which is ~ **3 m/orbit**
- LLR accuracy now ~ **cm**. New laser station APOLLO is achieving **millimeter level**
- Ultimate goal of 2nd Gen. LLR: confirm or deny braneworld with **100 mm** LLR

Einstein-Infeld-Hoffman equations of motion

Given N bodies, labelled by indices $A = 1 \ldots N$, with positions $\vec{x}_A$ and masses m_A, the E.I.H. equation gives the acceleration of each body as :

$$\begin{aligned}\frac{d^2\vec{x}_A}{dt^2} = -\sum_{B\neq A}\frac{Gm_B\vec{n}_{AB}}{r_{AB}^2} + \frac{1}{c^2}\sum_{B\neq A}\Bigg\{-\frac{Gm_B\vec{n}_{AB}}{r_{AB}^2}\Bigg[v_A^2 + 2v_B^2 - 4(\vec{v}_A\cdot\vec{v}_B) - \frac{3}{2}(\vec{n}_{AB}\cdot\vec{v}_B)^2 \\ -4\sum_{C\neq A}\frac{Gm_C}{r_{AC}} - \sum_{C\neq B}\frac{Gm_C}{r_{BC}}\left(1 + \frac{r_{AB}}{2r_{CB}}(\vec{n}_{AB}\cdot\vec{n}_{CB})\right)\Bigg] \\ -\frac{7}{2}\sum_{C\neq B}\frac{G^2m_Bm_C\vec{n}_{BC}}{r_{AB}r_{BC}^2} + \frac{Gm_B}{r_{AB}^2}\left[\vec{n}_{AB}\cdot(4\vec{v}_A - 3\vec{v}_B)\right](v_A^i - v_B^i)\Bigg\}\end{aligned}$$

Photon propagation

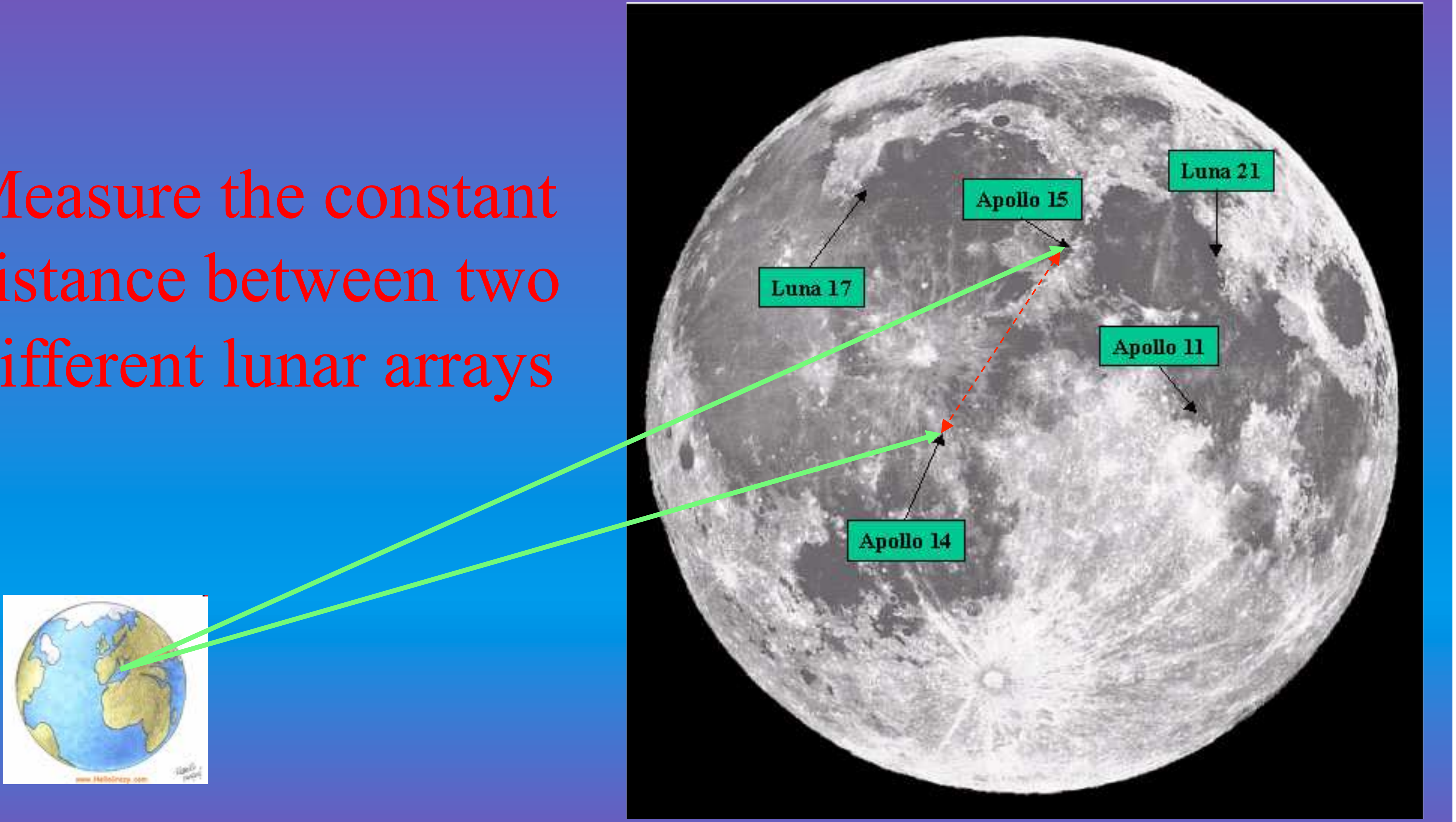
PEP calculate the photon propagation time

- **Earth Atmosphere:** Air n ›1, atmosphere introduces an excess path length in to LLR observation, considering air pressure, temperature and relative humidity at the site.

- **Shapiro Time Delay:** the gravitational field of the Earth will increase the round-trip travel time of light from Earth to the Moon and back (~ μs). PEP includes Shapiro delay introduced by the Earth and the Sun, but not by the Moon.

Test of experimental measurements

Measure the constant distance between two different lunar arrays



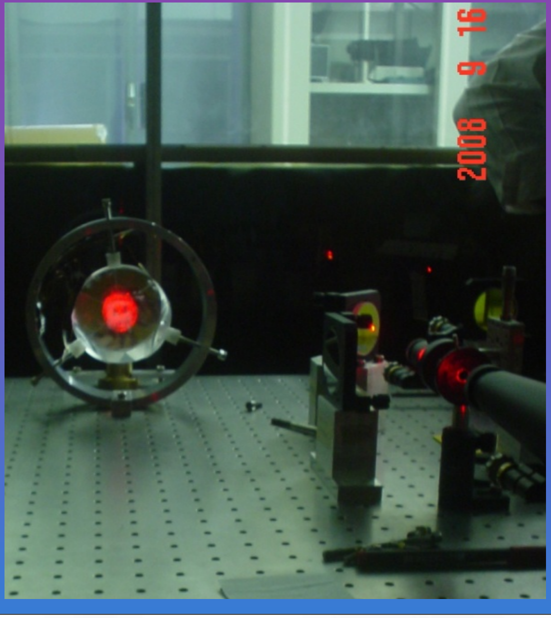
CCR FABRICATION CHALLENGE

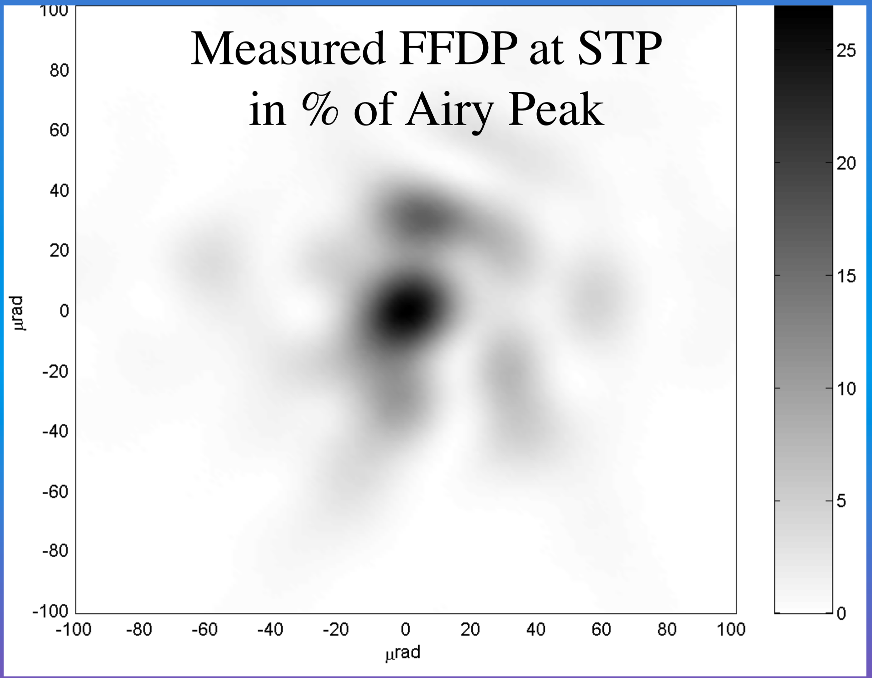
Results from Proto-CCR

- CCR Fabricated with SupraSil 1
- Geometry: expansion of old Apollo geometry

- Specifications / **Measured**
  - Clear Aperture Diameter
    - 100 mm / **100 mm**
  - Wave Front Error –
    - 0.25 waves / **0.15 waves**
  - Dihedral Angle Offsets
    - 0.00, 0.00, 0.00 +/-0.2 / **0.18, 0.15, 0.07**

- Flight Qualified
  - with Certification



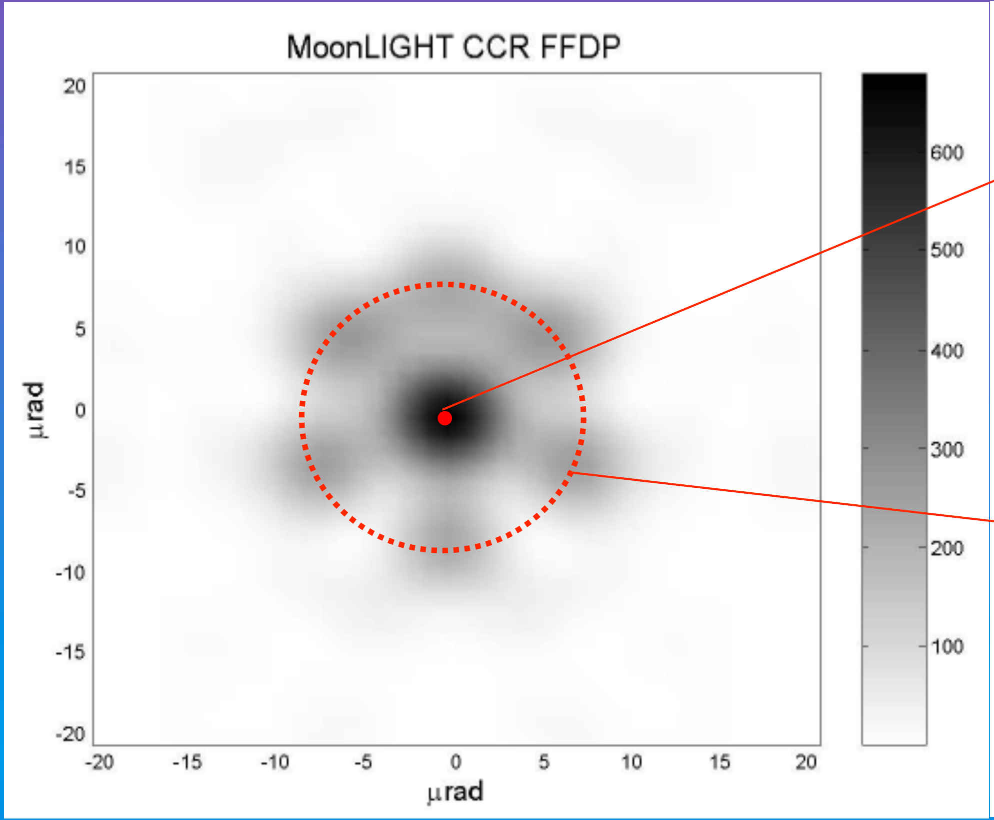


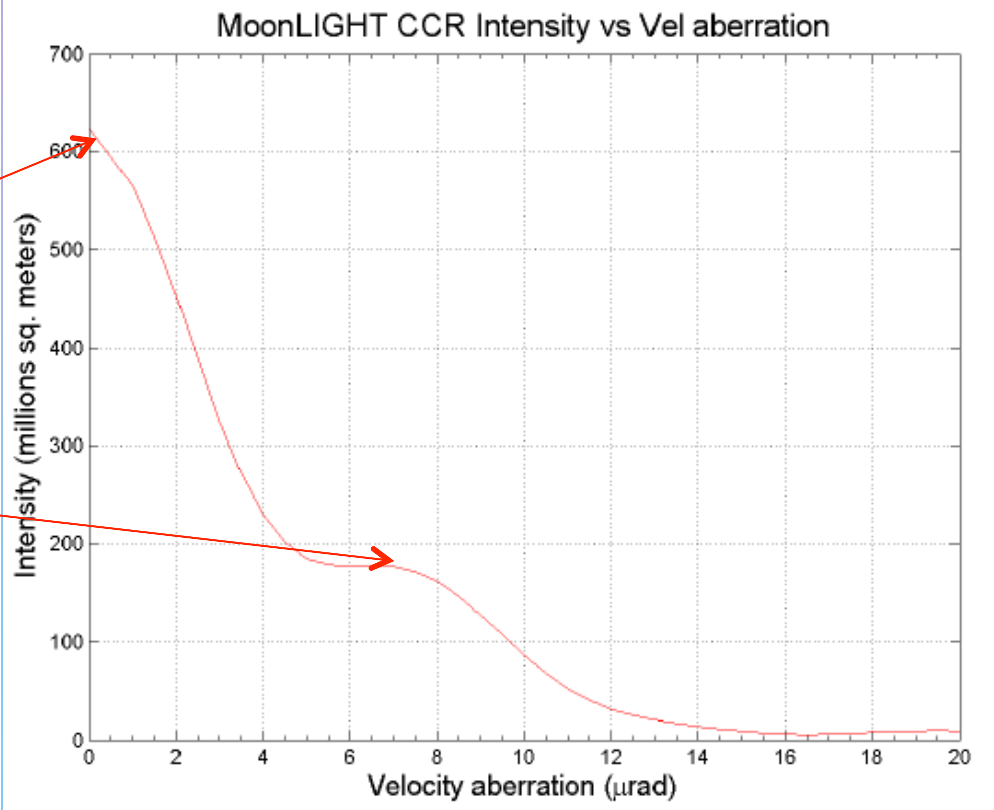
Solid, uncoated CCR. Largest, most accurate ever:

TECHNICAL CHALLENGES

- **Fabrication of the CCR to Required Tolerances (0.2”)**
- **Sufficient Return for Reasonable Operation (single CCR)**
  - Ideal Case for Link Equation
- **Thermal Distortion of Optical Performance (10 cm)**
  - Absorption of Solar Radiation within the CCR
  - Mount Conductance - Between Housing and CCR
  - Pocket Radiation - Heat Exchange with Housing
  - Solar Break-through - Due to Failure of TIR
- **Stability of Lunar Surface Emplacement (100 to 1 micron)**
  - Problem of Regolith Heating and Expansion
  - Drilling to Stable Layer for CCR Support
  - Thermal Blanket to Isolate Support
  - Housing Design to Minimize Thermal Expansion

Far Field Diffraction Pattern (FFDP)





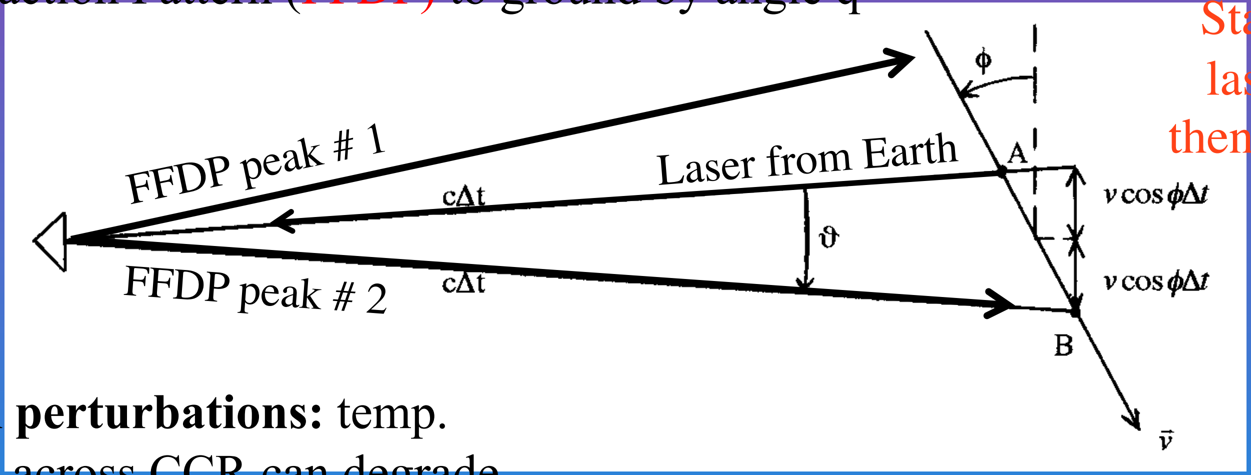
FFDP of MoonLIGHT CCR
Offset angles (0,0” 0.0” 0,0”)

Average intensity over velocity aberration of MoonLIGHT CCR

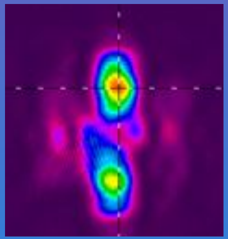
CCRs in space: optical & thermal issues

- **Velocity aberration**. Relative station-satellite velocity requires expensive non-zero dihedral angle offsets w/0.5 arcsec accuracy to widen laser return, the optical Far Field Diffraction Pattern (FFDP) to ground by angle q

CCR
in space



Station emits
laser from A
then moves to B



FFDP peaks back to ground

- **Thermal perturbations:** temp. gradients across CCR can degrade laser performance
  - A CCR could work at STP, BUT not in space for thermal reasons
- **Design** CCR array to control thermal and optical properties
- **SCF-Test**: characterize performance at the dedicated INFN-LNF facility

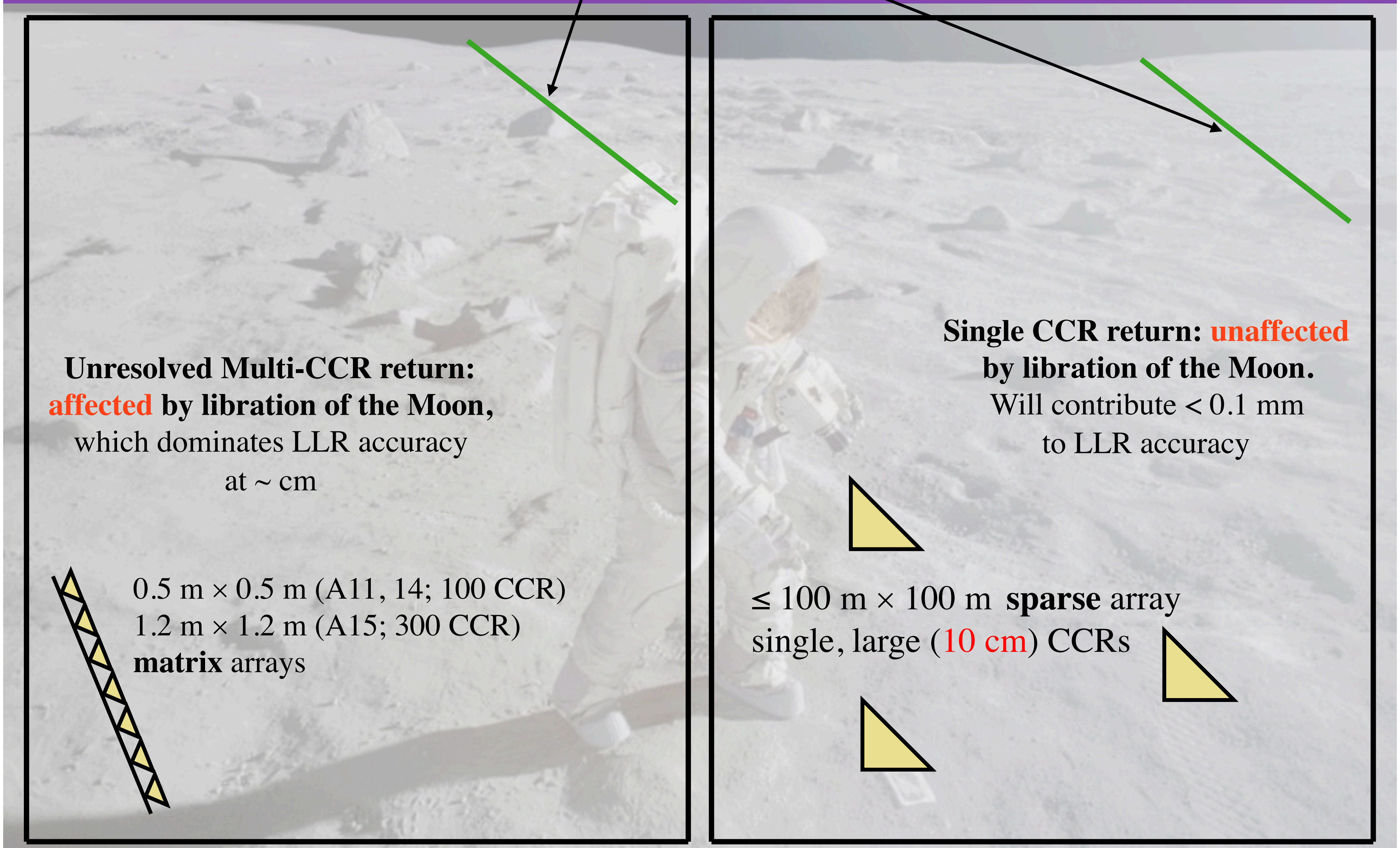
GPS/GLONASS/GALILEO
θ ~ 2 v/c cosf ~ 25 mrad
(~ 500 m on the ground)
Achievable with dihedral angle offsets ~ 2”-3”

Nominal distance between FFDP peaks is
2 x q = 50 mrad=> 1 Km

Apollo
LLRRA_20th

532 nm laser
wavefront from Earth

MoonLIGHT
LLRRA_21st Century



Unresolved Multi-CCR return:
affected by libration of the Moon,
which dominates LLR accuracy
at ~ cm

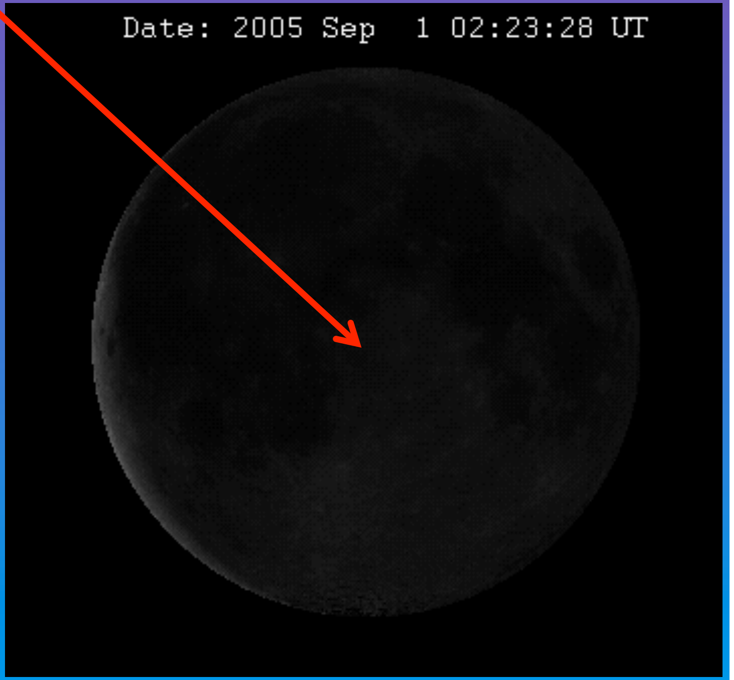
0.5 m × 0.5 m (A11, 14; 100 CCR)
1.2 m × 1.2 m (A15; 300 CCR)
matrix arrays

Single CCR return: unaffected
by libration of the Moon.
Will contribute < 0.1 mm
to LLR accuracy

≤ 100 m × 100 m **sparse** array
single, large (10 cm) CCRs

LLRRA-21/MoonLIGHT innovations

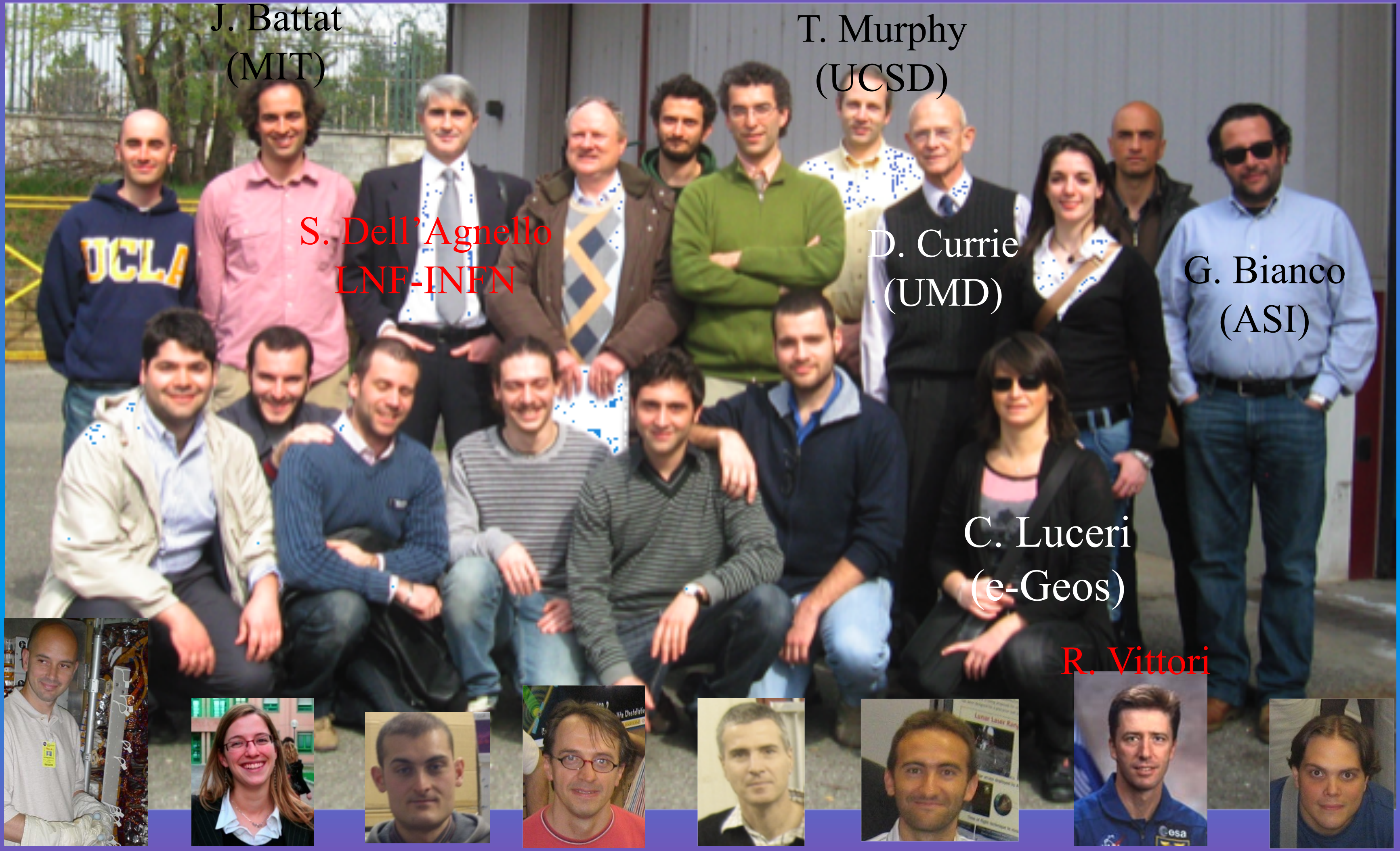
- **Escape from Lunar Libration Problem**
- Better control of velocity aberration effect
- Control of emplacement problems due to lunar cycle heating
- New housing concepts for thermal control
- Addressing solar absorption within SiO_2 of CCR
- Much more detailed thermal and optical simulation, analysis and **SCF-Tests**



Frascati 2nd Generation LLR workshop photo

March 25, 2010, outside the SCF lab, during 24x7 shifts for the SCF-Test of our 2nd Generation “MoonLIGHT/LLRRA21” CCR

Small photos: people absent, on SCF night shifts or training for a Space Shuttle flight…



Publications

1. ***“Fundamental Physics and Absolute Positioning Metrology with the MAGIA Lunar Orbiter”,*** S.Dell’Agnello et al., “*Experimental Astronomy*“, 29 July 2010, DOI 10.1007/s10686-010-9195-0.

2. ***“Creation o the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS”,*** S.Dell’Agnello et al., *“Galileo Issue in Journal of Advances in Space Research, Scientific* application of Galileo Navigation Satellite System”, 47 (2011) 822-842.

3. ***“A Lunar Laser Ranging Retroreflector Array for the 21st Century”,*** D.Currie et al., “Acta Astronautica” 68 (2011) 667-680

4. ***“The moon as a test body for General Relativity and new gravitational theories”,*** M. Garattini, proceeding about the talk at the conference: *“Frontier Objects in Astrophysics and Particle Physics”*, Vulcano Workshop 2010.

5. ***“Probing Gravity with the Proposed MAGIA and ILN Lunar Missions”,*** M.Garattini et al., submitted to “Memorie della Società Astrofisica Italaina”, 2011.