Probing Gravity with 2nd Generation Lunar Laser Ranging

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for the MoonLIGHT Collaboration

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APOLLO Lunar Laser-Ranging Observatory (T. Murphy et al), Los Alamos, USA

LNF Spring School, May 2008

Outline

- Science with Lunar Laser Ranging (LLR)
- MoonLIGHT: a study for 2nd generation Lunar Laser Ranging (LLR) approved in Aug 2007 by NASA
- Testing new physics
- Conclusions

Satellite Laser Ranging (SLR)
Lunar Laser Ranging (LLR)
Time of flight measurement

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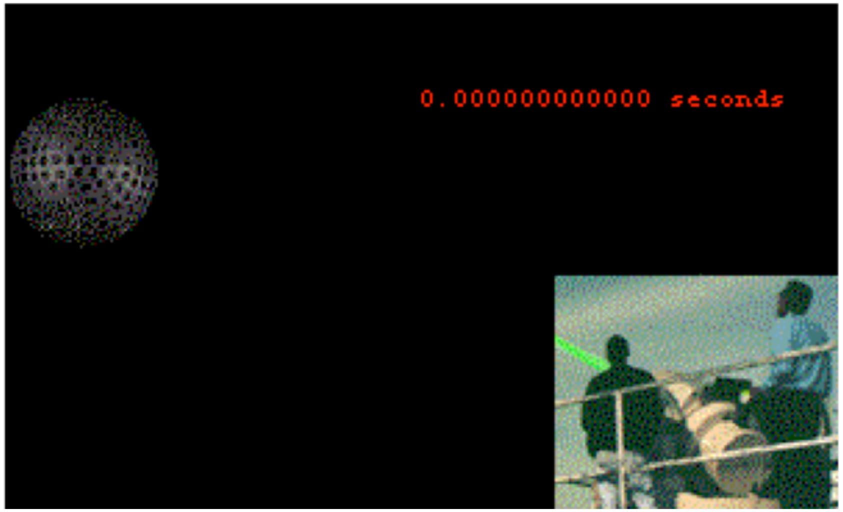
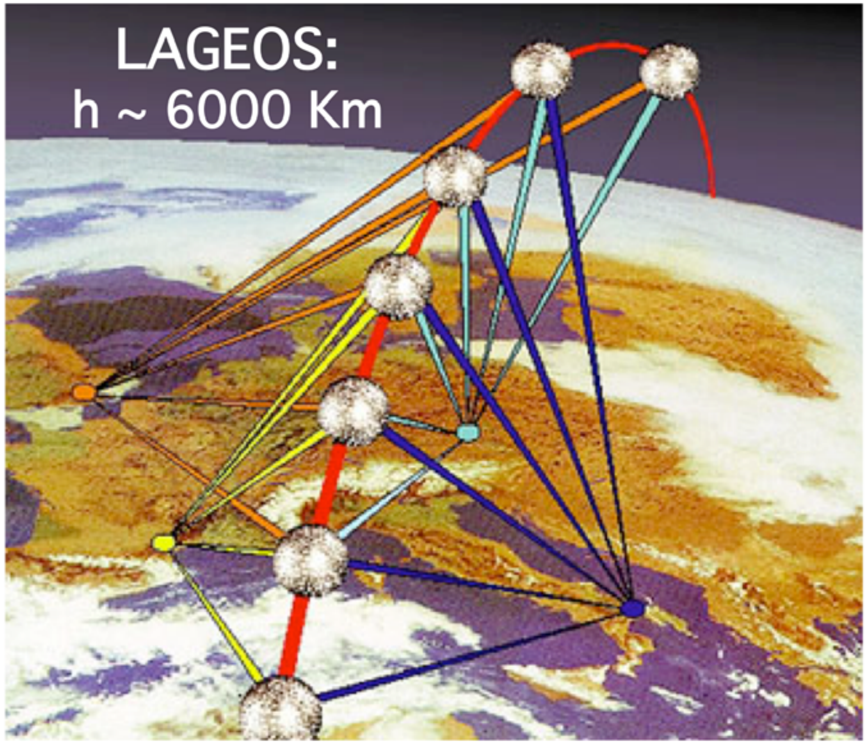
R



- The Moon as a test mass (1969+, Alley, Bender, **Currie**, Faller …)
- LAGEOS: “cannon-ball”, point-like test-masses covered with laser retro-reflectors (raw orbit accuracy < 1 cm)



High-accuracy General Relativity (GR) tests

- Of course direct observation of Gravitational Waves is “the” most important dynamical test of GR
- **Main theoretical goal: quantum theory of Gravity and Unification of the 4 interactions**. GR is a classic theory
- **Main experimental goal: where does GR fail ?**
  - Parametrized Post Newtonian (PPN) approach: expansion of metric field in powers of (v/c) and as a function of PPN parameters β, γ, δ
  - Space-time curvature (Cassini, PPN γ)
  - Geodetic/De Sitter precession (Lunar Laser Ranging, PPN β)

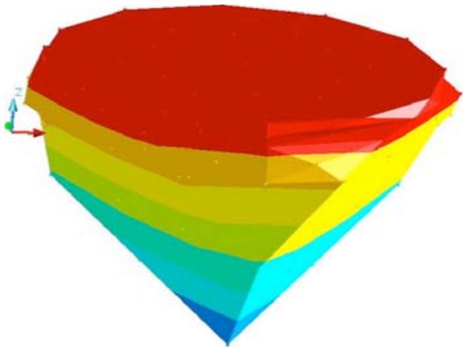
    ⇒ See table at slide 7
  - Frame dragging (LAGEOS, GP-B, LAGEOS+LARES)
  - Redshift/clock dilation (GP-A, VIKINGS/Shapiro time delay, PPN δ)

- **New theories?** ⇒ See slide 9

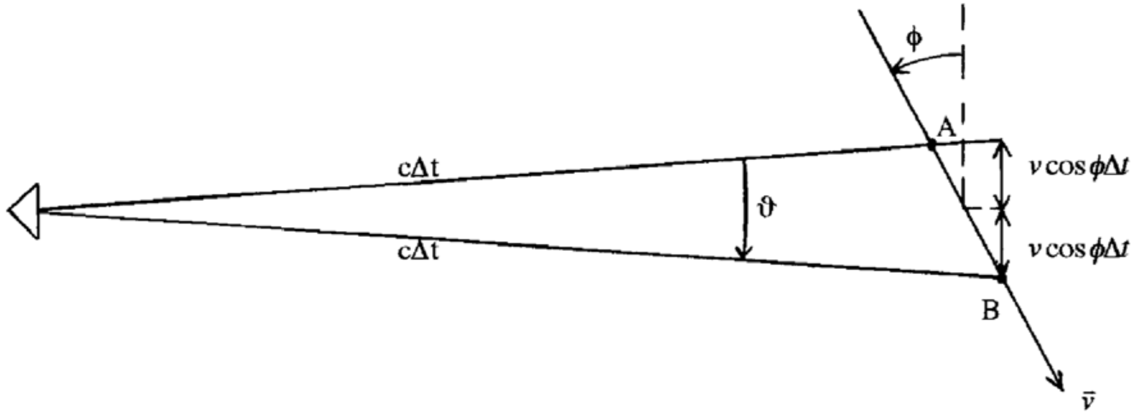
Very critical experimental issues

- **Velocity aberration**. Relative station-satellite velocity requires non-zero expensive CCR dihedral angle offsets w/ 0.5 arcsec accuracy
- Design to control **thermal perturbations** on optical performance
- Characterize “as-built” thermal and optical performance of the INFN dedicated facility

T(center) = 139.2 K



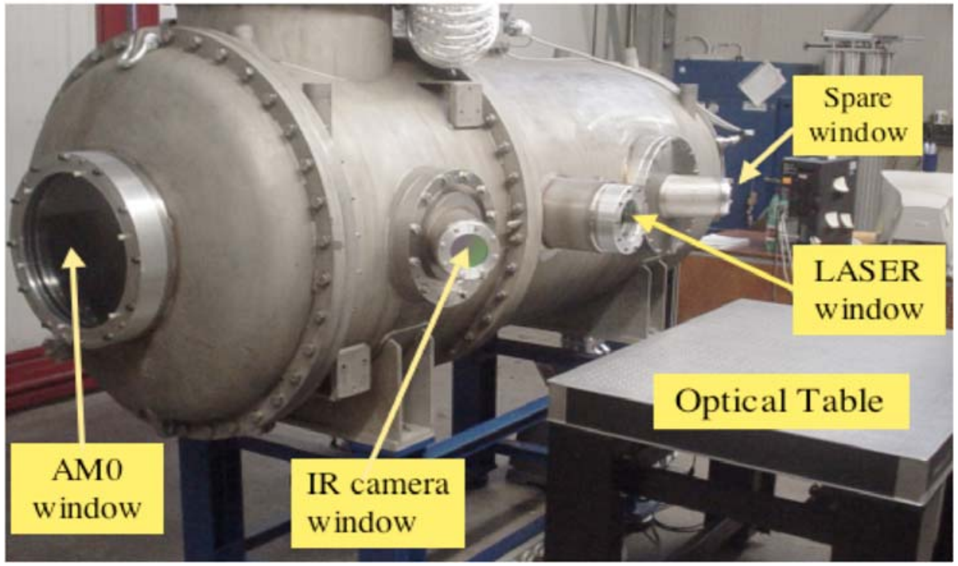
T(tip) = 137.4 K

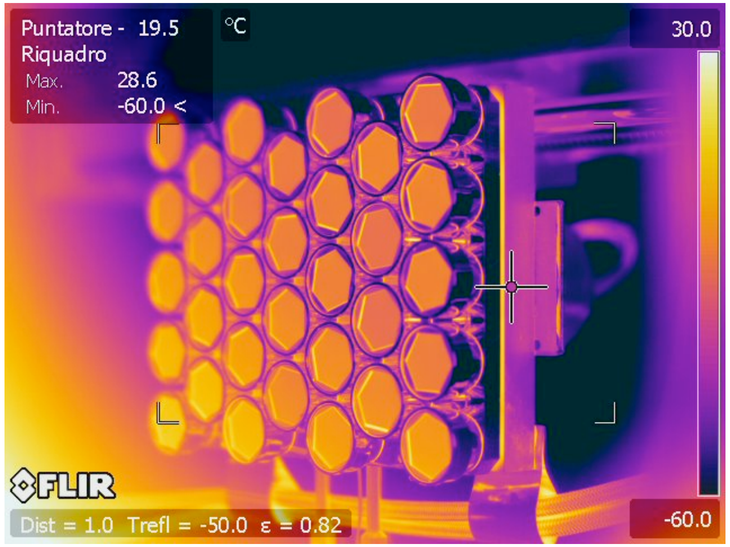


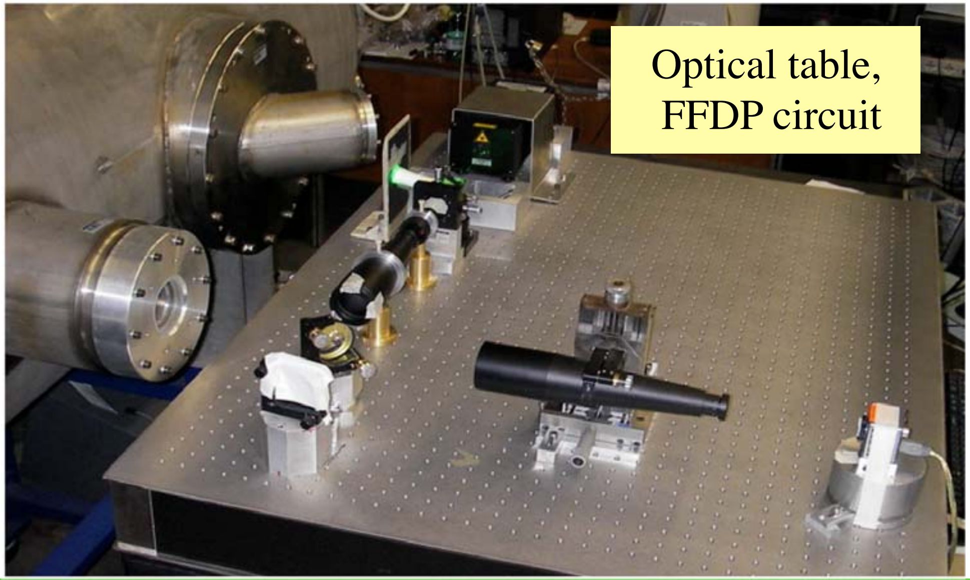
SCF-Test of GPS-2 flight model from USA

The INFN-LNF Satellite Laser Ranging Characterization Facility

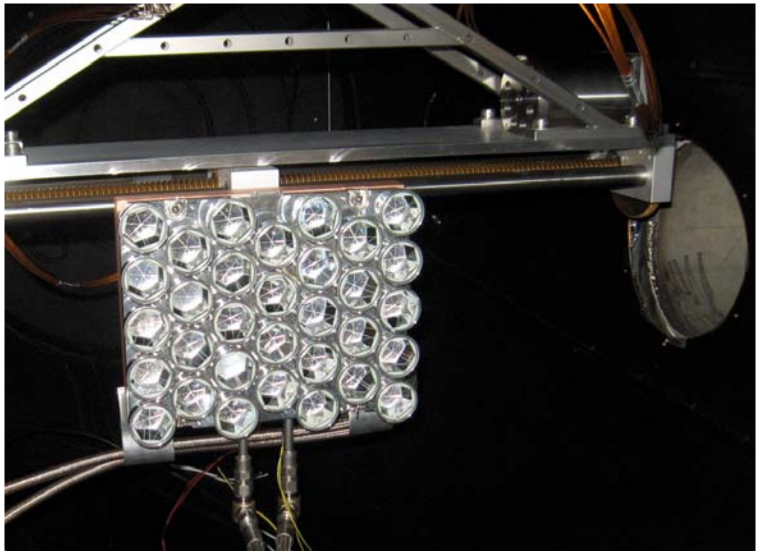
Thermal and laser tests never performed before in space conditions



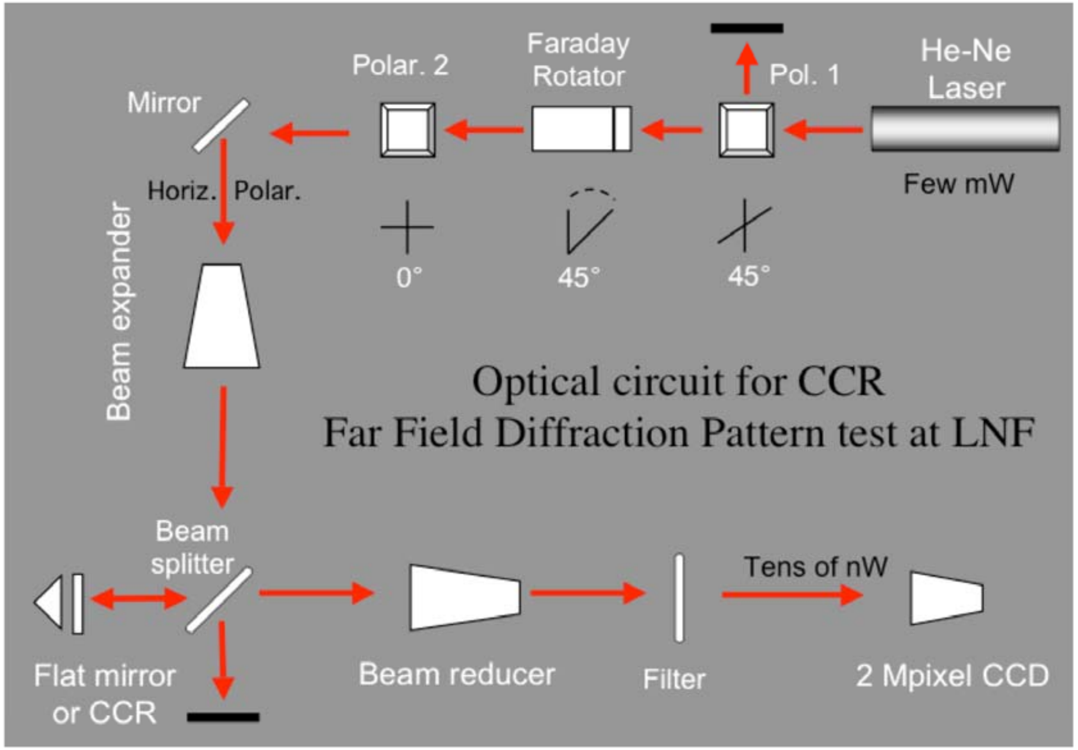




Optical table, FFDP circuit



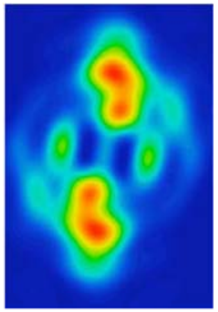
Measured & simulated Far Field Diffraction Pattern



Simulated with CodeV

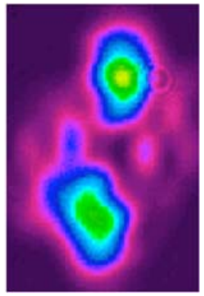
Measured @ LNF

GPS-2 proto
has dihedral angle
offset = 2 ÷ 3 arcsec



Good agreement

Peak distance is 50 μrad



General Relativity Science Objectives
(for up to factor 100 improvement over current LLR)

Table by T. Murphy (U. of California at San Diego), who operates the APOLLO LLR station at Los Alamos

The golden measurement

Phenomenon	Current limit	Limit with 1 mm ranging	Limit with 0.1 mm ranging	Measurement timescale
Weak Equivalence Principle ($\Delta a/a$)	10^{-13}	$\sim 10^{-14}$	$\sim 10^{-15}$	2 yr
Strong EP (Nordvedt param.)	4×10^{-4}	$\sim 10^{-5}$	$\sim 10^{-6}$	2 yr
Gdot/G	10^{-12}/yr	$\sim 10^{-13}$/yr	$\sim 10^{-14}$/yr	4 yr
Geodetic Precession (PPN parameter β)	$\sim 5 \times 10^{-3}$	5×10^{-4}	$\sim 5\times10^{-5}$	6-10 yr
Deviations from $1/r^2$ (Yukawa param. α)	$10^{-10}\times$ gravity	$\sim 10^{-11}$	$\sim 10^{-12}$	6-10 yr

Limits on non-newtonian gravity

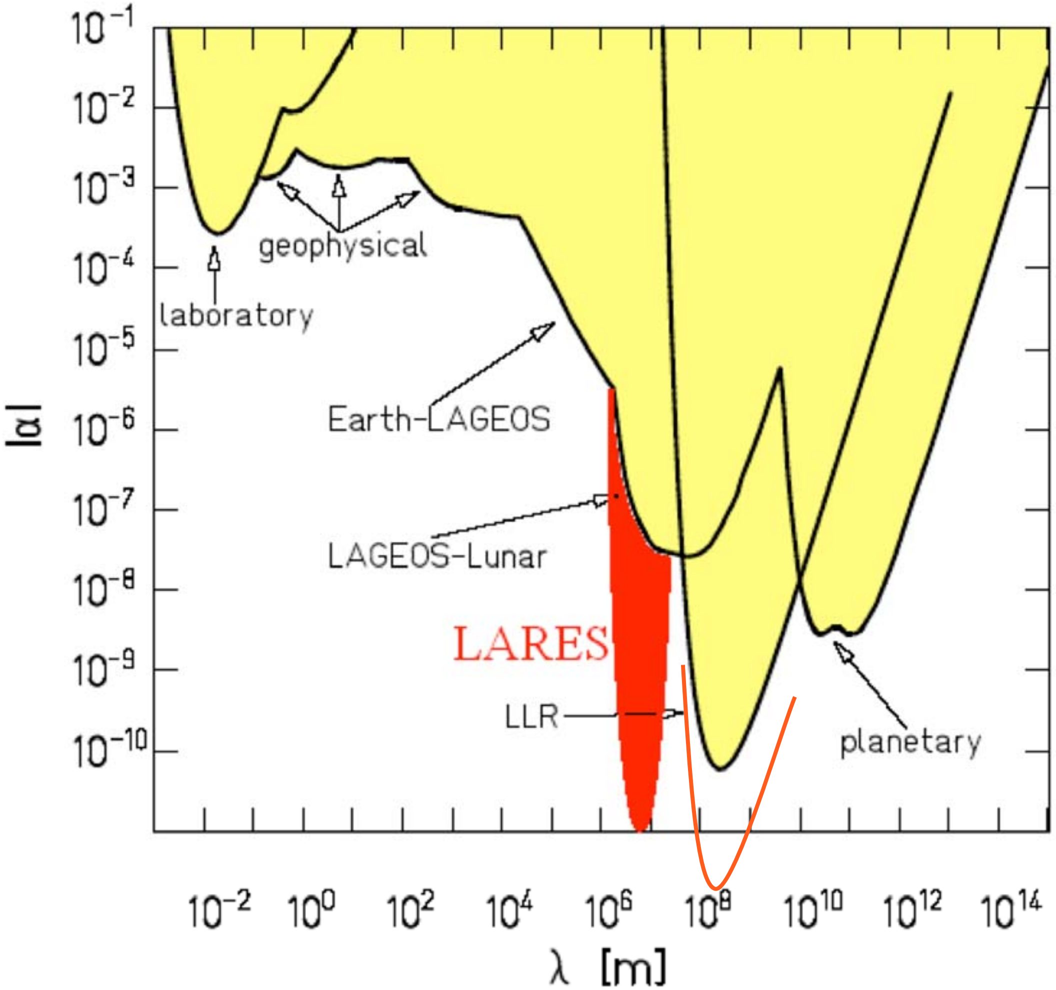
Current limits on additional Yukawa potential:

$\alpha \times$ (Newt-gravity) $\times e^{-r/\lambda}$

Expected limit on α for the MoonLIGHT proposal for a ranging accuracy of 100 μm

Expected limit on α set by the LARES mission at an orbit radius of about 8000 Km

LARES limit by I. Ciufolini
MoonLIGHT limit: current LLR limit x 10^{-2}



"BraNe new world": a model beyond General Relativity

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

The accelerated universe and the Moon

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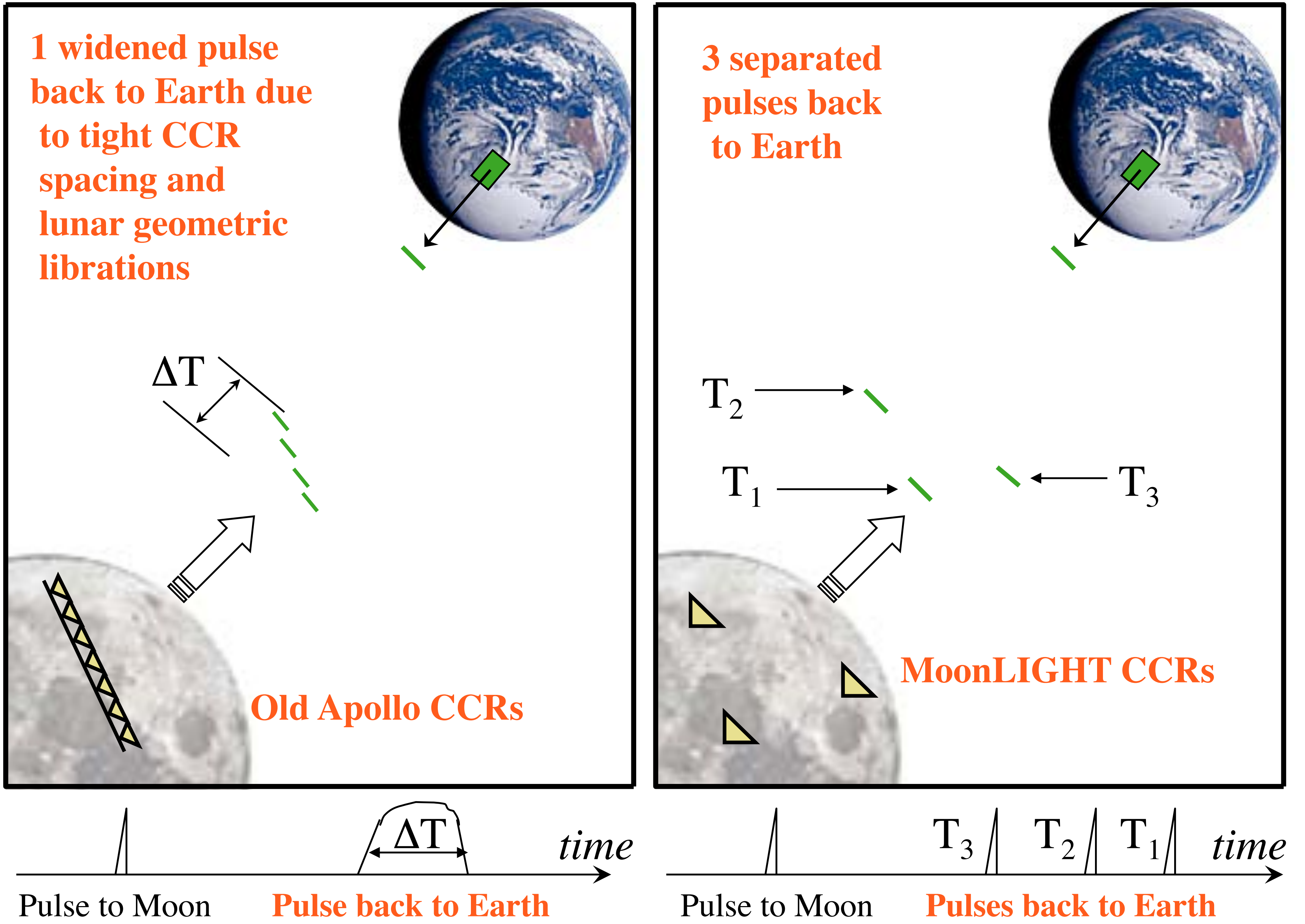
(Received 20 December 2002; published 8 July 2003)

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.

- This (mem)Brane world theory gives anomalous precession of the Moon of ~ **1 mm/orbit**, in addition to standard GR geodetic precession
- LLR accuracy now **~ 1 cm**. New laser station APOLLO is reaching **few mm**
- This model can be fully tested by MoonLIGHT with **100 µm** (or less) accuracy, i.e. w/factor 100 (or more) improvement over current LLR

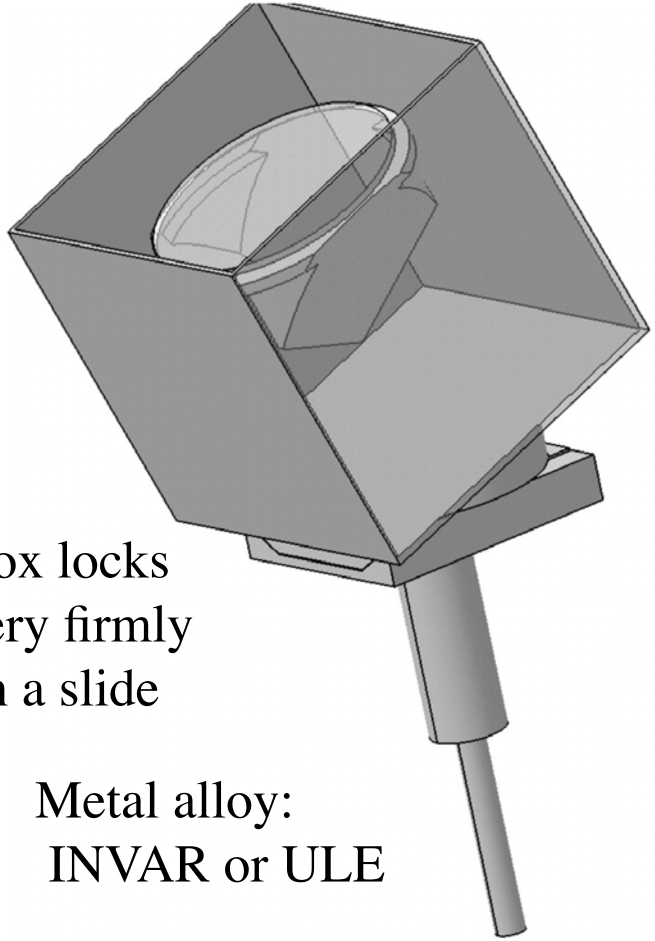


1 widened pulse back to Earth due to tight CCR spacing and lunar geometric librations
ΔT
Old Apollo CCRs
ΔT
time
Pulse to Moon
Pulse back to Earth
3 separated pulses back to Earth
T2
T1
T3
MoonLIGHT CCRs
T3
T2
T1
time
Pulse to Moon
Pulses back to Earth

NASA call: "Suitcase" science to the Moon

Concept by Astronaut Roberto Vittori. Manned missions on 2015-18

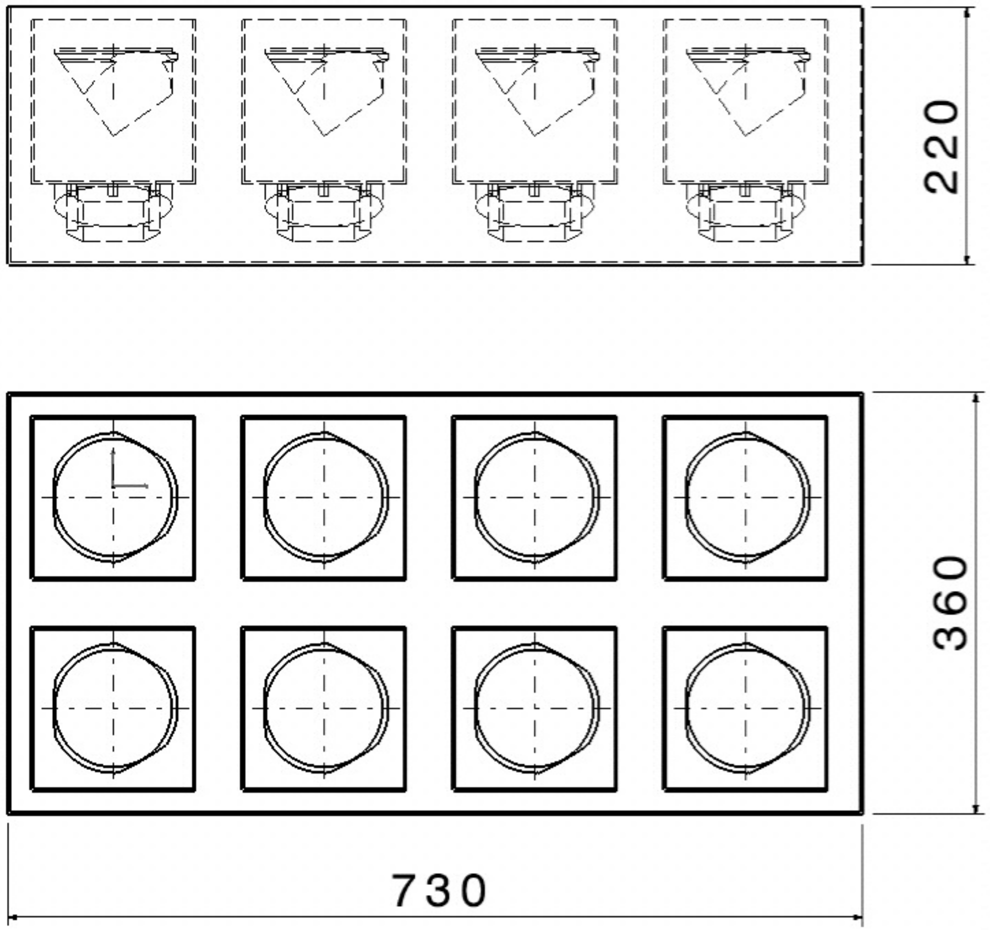
Retro-reflector: 10 cm diam.
Box: 14 cm side



Box locks very firmly on a slide

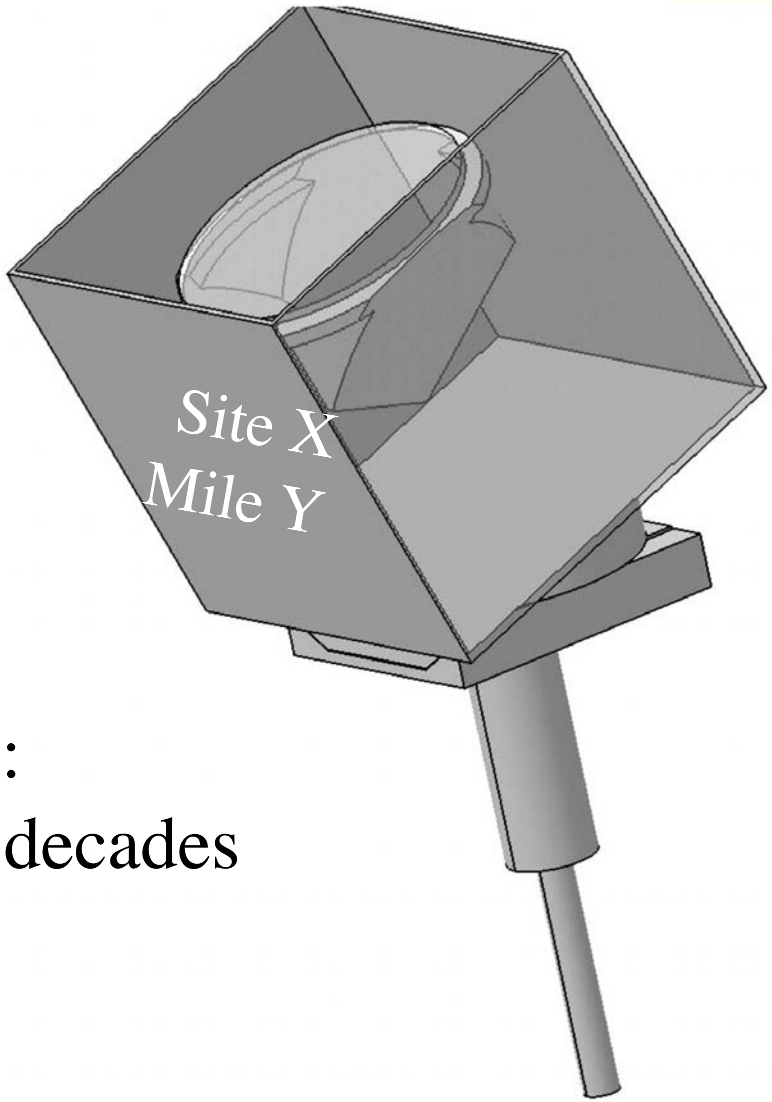
Metal alloy:
INVAR or ULE

Suitcase for the CCR boxes (mm)



Moon land-marks

- MoonLIGHT units can also be used to land-mark sites and pathways of the new lunar exploration, like the Roman "milestones"
- Can be the used to build the IMRF
  - Intern. Moon Reference Frame



MoonLIGHT landmarks:
light, passive and last for many decades

Conclusions

- SLR: precise and cost-effective way to probe gravity with the Earth-Moon system

  (Millimeter) .AND. (0.1 M€ to M€)

- Not just physics
  - Space geodesy
  - GALILEO has SLR on all satellites
- Three main contributions to science error budget
  - SLR measurements, Earth grav. models, thermal perturbations
  - The INFN SCF fills the void of non-existent of **space characterization of SLR**
- With SLR/LLR we love to test:
  - General Relativity
  - Yukawa deviations from $1/r^2$, Brane Worlds

THE LNF SCF GROUP

Preliminary thermal analysis: CCR

Thermal CCR conditions look good for integrity of laser signal: cold CCRs work well and T gradient through CCR body is small (< 2 K: variations of the refraction index variations is quite acceptable)