LARES (LAser RElativity Satellite): Status Report

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for the LARES Collaboration

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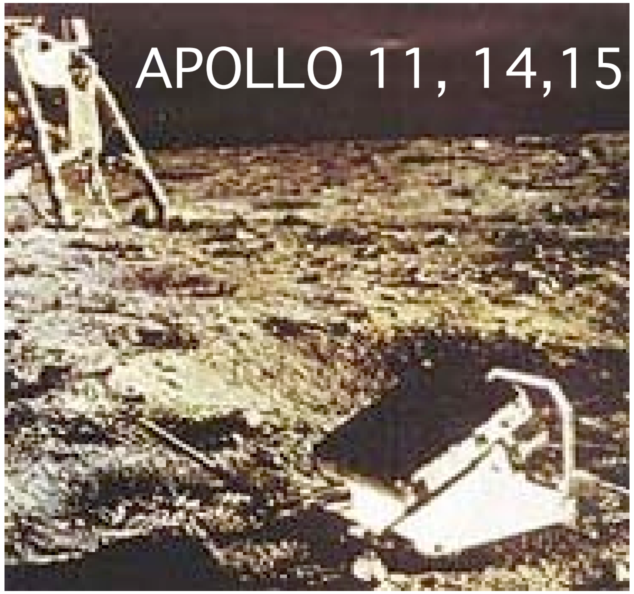
36th Meeting of the LNF Scientific Committee, May 21, 2008

Outline

- The Satellite Laser Ranging technique
- Testing General Relativity with LAGEOS and LARES
- Experimental characterization of LAGEOS and LARES at LNF
  - New industry-standard space test developed with ETRUSCO, a separate multidisciplinary experiment of INFN
- Testing new physics with LAGEOS and LARES
  - Original LNF work on Torsion theories
- Pending LNF commitments on LARES
  - Note: LNF commitments on LAGEOS with NASA complete by Sep. 2007
- Conclusions

Satellite Laser Ranging (SLR)
Lunar Laser Ranging (LLR)

Time of flight measurement



- 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)

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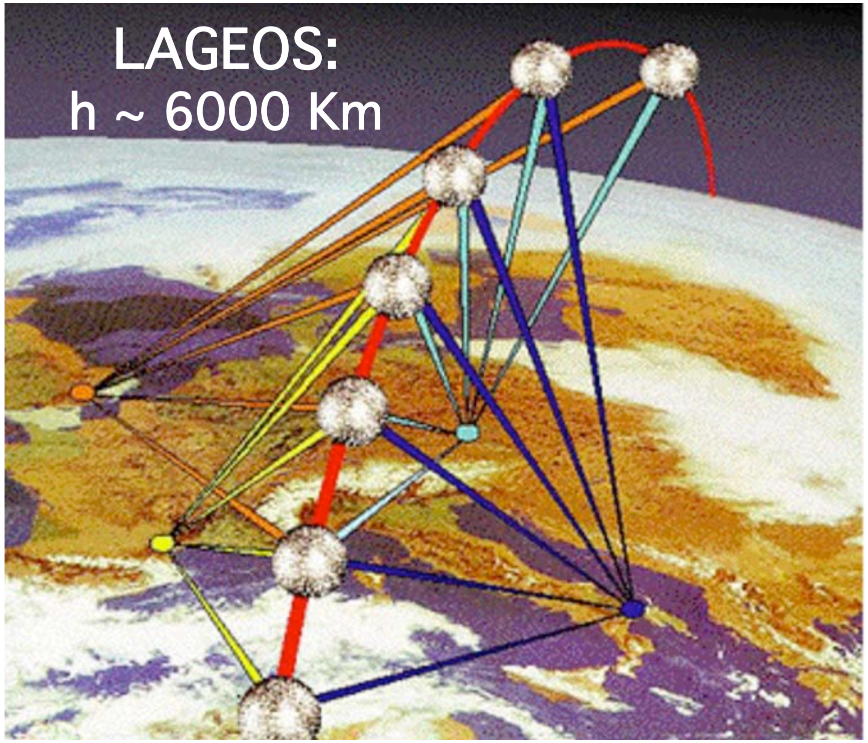
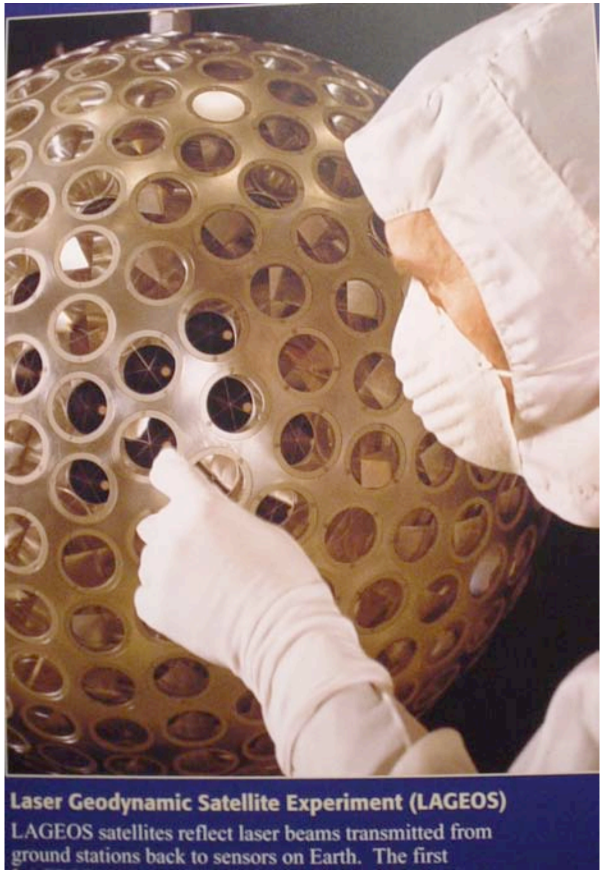
R



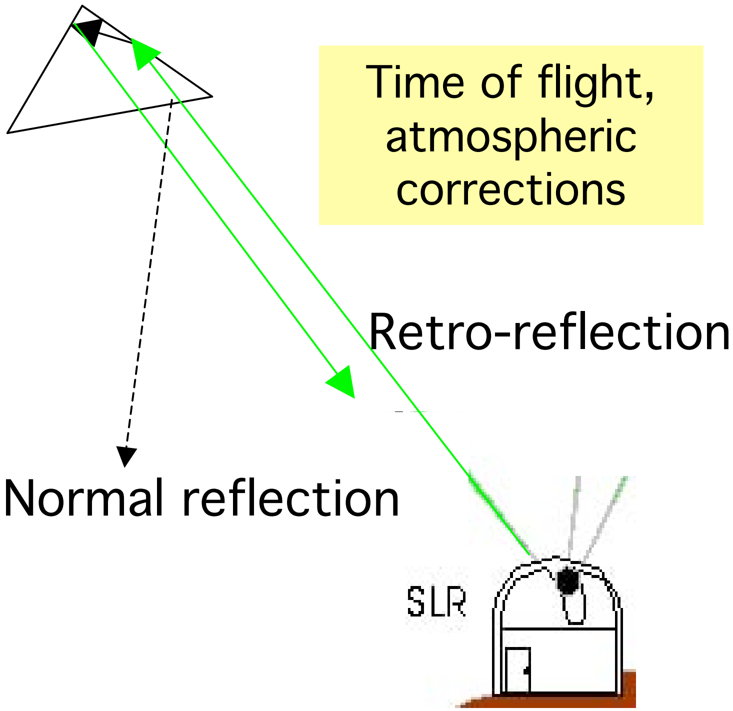
LAGEOS: the LAser GEOdynamics Satellites

LAGEOS I (1976; NASA), LAGEOS II (1992; NASA - ASI)

∅= 60 cm
400 Kg
426 CCRs



Cube corner retro-reflectors (CCRs)



SLR is the most (cost-effective).AND.(precise) orbitography

Laser interferometry in space more precise but way more expensive

SLR: Space Geodesy, Satellite Navigation

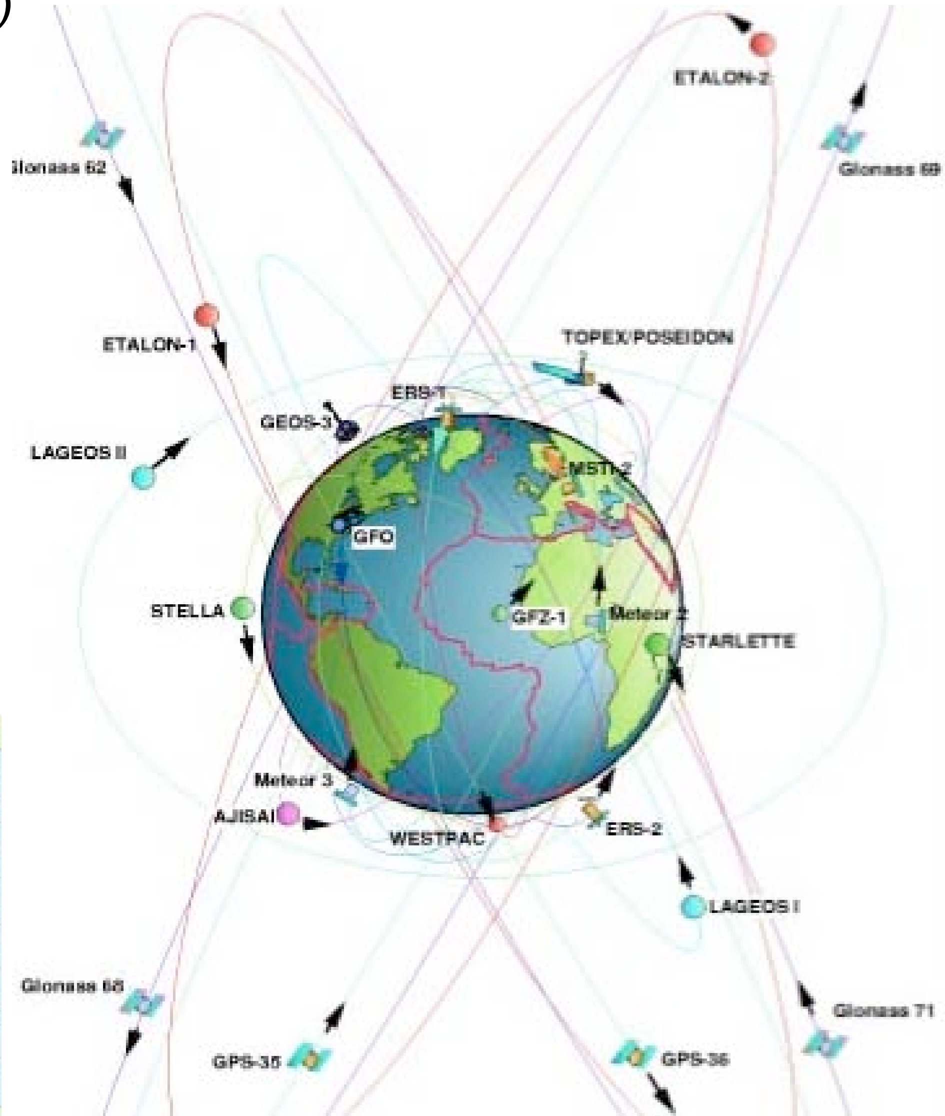
Altitudes from few hundreds km (LEOs)
to ~20K Km (GNSS), 36K Km (GEO)

Int. Terrestrial Reference Frame (ITRF)
- **Geocenter** of ITRF
- **Scale of length** of ITRF

are defined uniquely by LAGEOS I & II

International Laser Ranging Service

SLR constellation in NEO



LARES Approval

- Approved by INFN experiment - Sep. 2007
- Approved ASI space mission - End 2007
- ASI Industrial Contract approved on Feb 7, 2008, GAVAZZI is Prime Contractor
- AI Scientific Contract in progress ….
- Launch with ESA's new rocket VEGA

Luce verde per LARES

Il CdA dell'ASI approva il finanziamento industriale per il satellite che volerà con VEGA

Nella seduta dell'7 febbraio 2008, il Consiglio di Amministrazione dell'ASI ha approvato in via definitiva il finanziamento industriale di LARES, il satellite che volerà con il primo lancio del nuovo vettore europeo VEGA, previsto entro la fine del 2008. LARES, che verrà costruito da Carlo Gavazzi Space SpA, è un satellite completamente passivo, in tungsteno, che ospita retroriflettori grazie ai quali il suo spostamento sarà seguito via laser da terra. Il suo obiettivo scientifico è misurare con un'accuratezza dell'ordine dell'1% l'effetto Lense-Thirring, cioè lo spostamento dall'orbita newtoniana che, secondo la Teoria della Relatività Generale, subisce un satellite in orbita a causa della rotazione terrestre. Attualmente l'accuratezza di questa misura è dell'ordine del 10% . LARES è stato progettato in collaborazione con l'INFN e il suo principal investigator è Ignazio Ciufolini, dell'Università di Lecce.

High-accuracy General Relativity (GR) tests

- Direct observation of Gravitational Waves is *the most important* dynamical test of GR
- **Main theoretical goal**
  – Quantum Gravity and Unification of the 4 interactions
  – GR is a classic theory; cannot be the ultimate theory
- **Main experimental goal**
  – Where does GR fail? At what accuracy?
  – **Dragging of inertial frames (Gravitomagnetism, Lense-Thirring effect)**
    - LAGEOS: 10%
    - GP-B: 300% (April 14, 2007), now 30%, final results in June 08
    - LAGEOS+LAGEOS II+LARES aims to 1%. Is 1% enough ?
  – Space-time curvature (Cassini; PPN γ)
  – Geodetic/De Sitter precession (**Lunar Laser Ranging**; PPN β)
  – Redshift/clock dilation (GP-A, VIKINGS/Shapiro time delay; PPN γ)

Measurement of “frame-dragging” w/LAGEOS

(Einstein-Lense-Thirring, 1918)

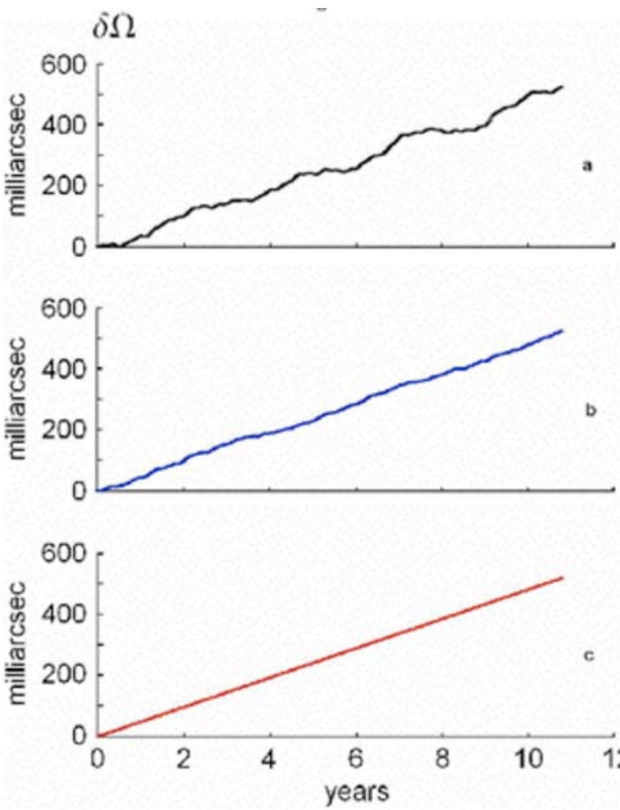
μ = 99 % GR

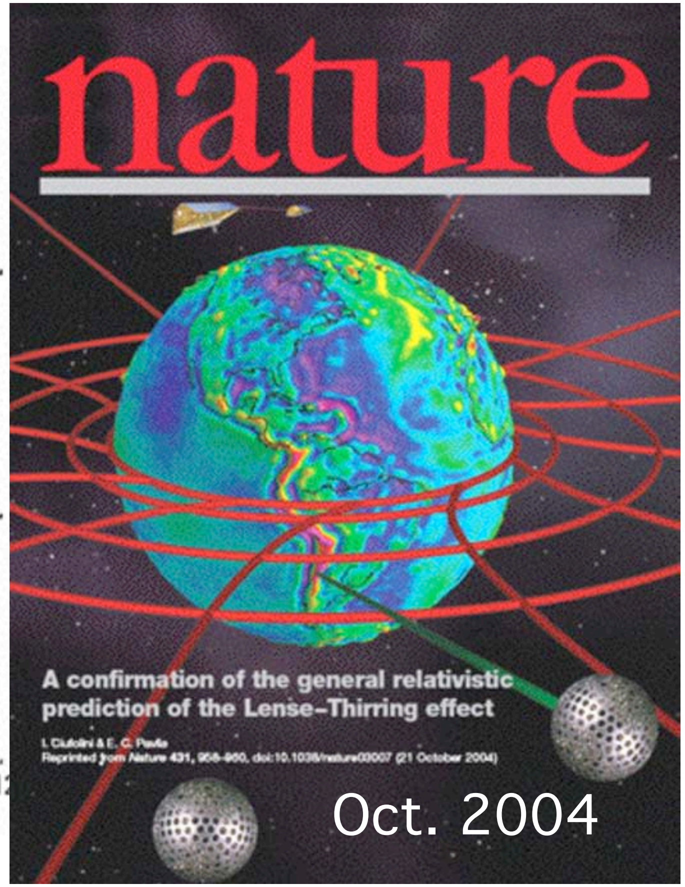
5 to 10 % error

Earth angular momentum drags space-time around it. The node of LAGEOS satellites (a~12300 Km) is dragged by ~2 m/yr

$$\boxed{\dot{\Omega}^{L-T} = \frac{2GJ}{c^2 a^3 (1-e^2)^{3/2}}}$$

- Raw observed node residuals combined
- Raw residuals with six periodic signals removed, estimated rate is 47.9 mas/yr
- GR-predicted residuals, rate: 48.2 mas/yr





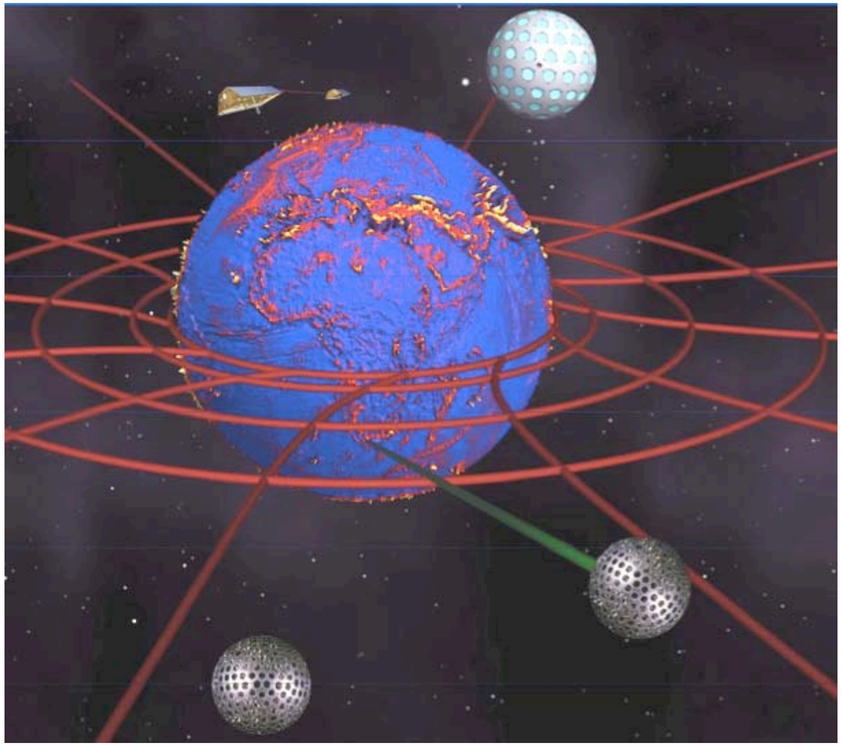
EIGEN-GRACE02S 2004 data by GFZ
1993-2003 LAGEOS I and LAGEOS II data

I.Ciufolini, E. C. Pavlis

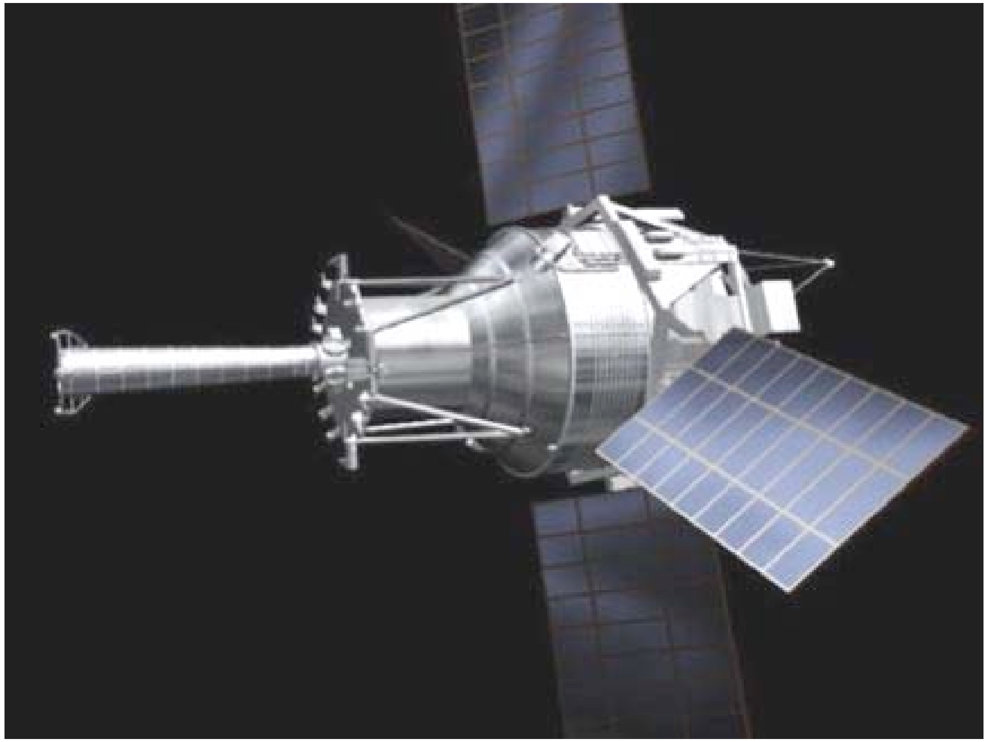
LAGEOS+LARES vs Gravity Probe B

LAGEOS, LAGEOS II & LARES:
dragging of angular momentum wrt ITRF.
Passive satellites.
Altitude ≥ 1200 Km, inclination ~ 70^o,
eccentricity ≤ 0.04

Gravity Probe B:
dragging of gyroscopes inside very high-tech spacecraft wrt distant guide star IM Pegasi.
NASA mission ended in 2006.
h = 650 Km, i = 90^o



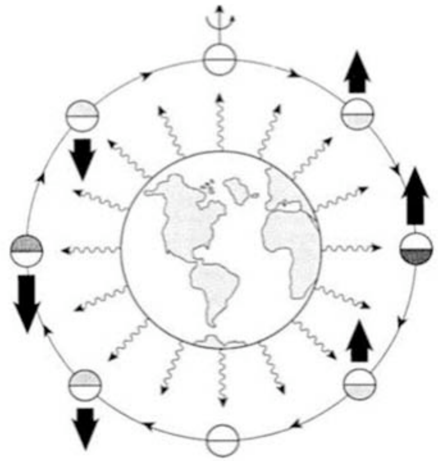
LARES cost: few M€



Official satellite cost: 760 M$

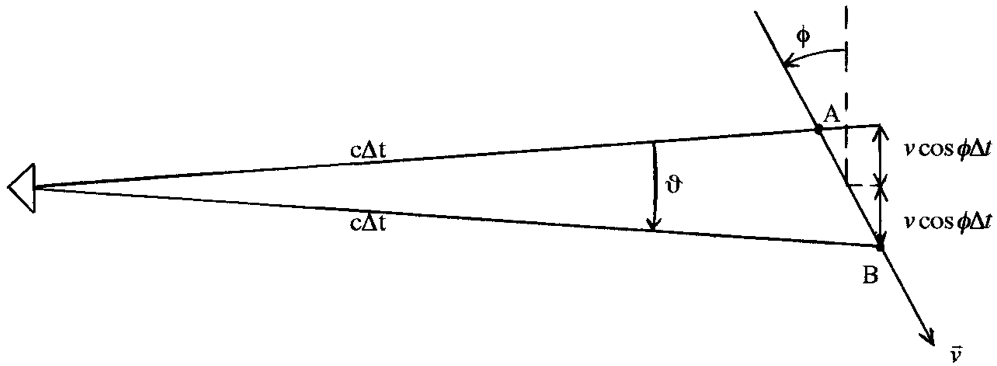
Very critical issues with laser-ranged test masses

- **Non Gravitational Perturbations** (NGP): asymmetric thermal thrusts due to Solar constant and Earth IR
  - 2-3% of error on frame dragging



- **Velocity aberration**. Relative station-satellite velocity requires non-zero expensive CCR dihedral angle offsets w/0.5 arcsec accuracy

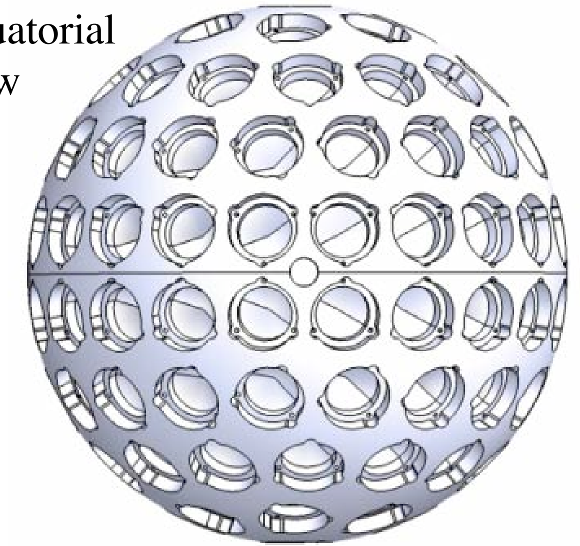
For LARES: θ ~ 2 v/c cosϕ ~ 40 mrad ⇒ ~50 m



- Design to control thermal NGPs
- Characterize/validate thermal and optical performance
  - **INFN-LNF built from scratch a dedicated facility**

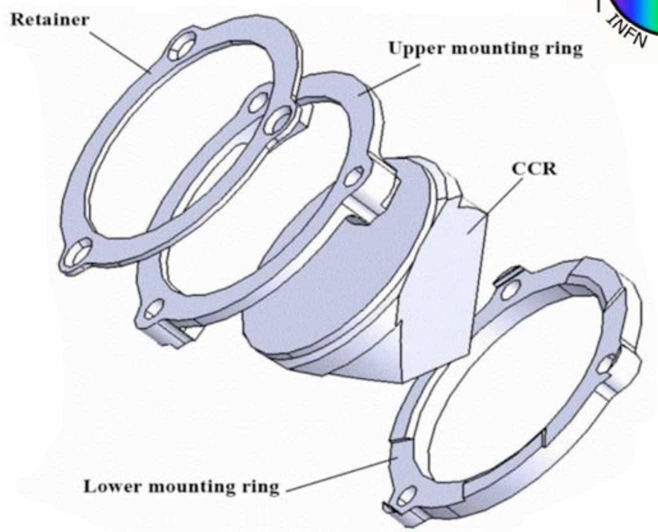
LARES design

Equatorial view

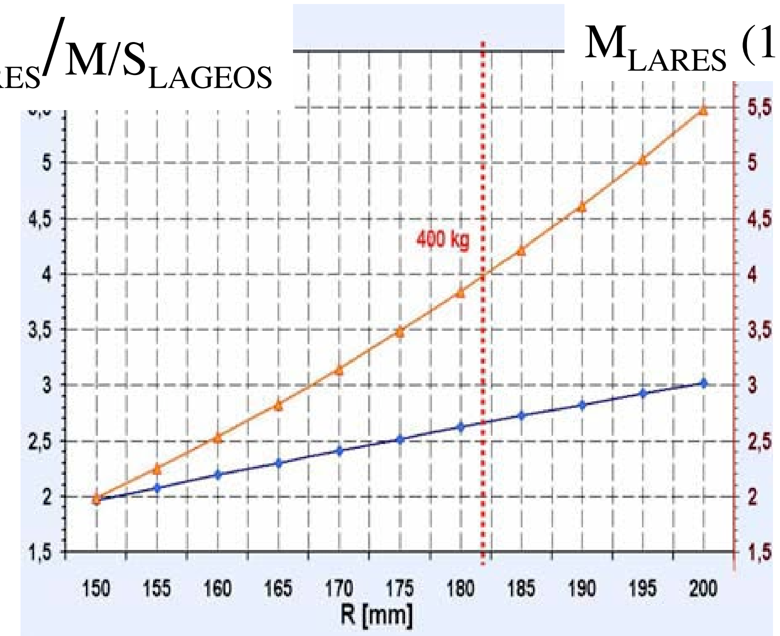


Work by Univ. Rome "Sapienza"

Single piece of W-alloy
Ø = 38 cm
92 CCRs



$M/S_{LARES}/M/S_{LAGEOS}$ $\qquad$ M_{LARES} (10^2 Kg)



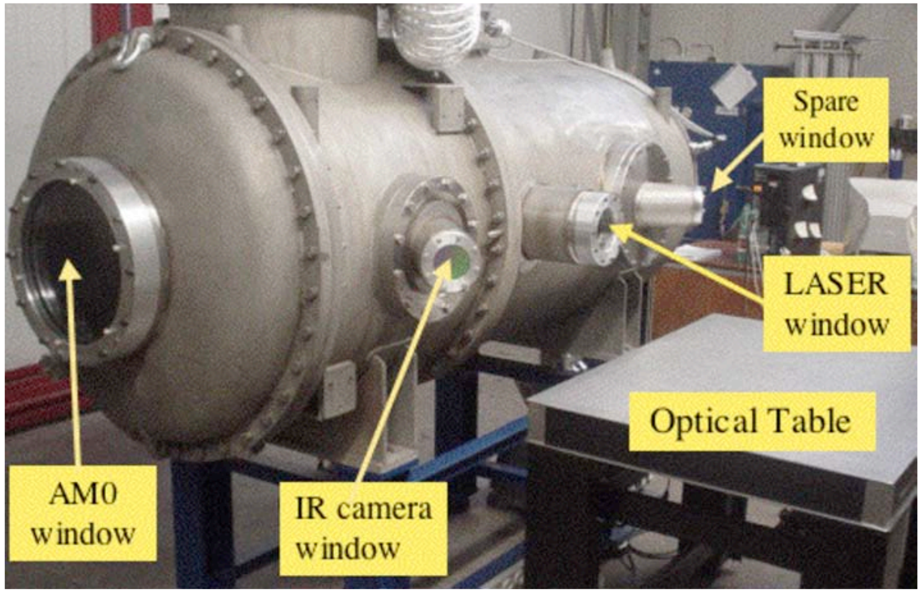
Thermal NGPs proportional to satellite Area/Mass

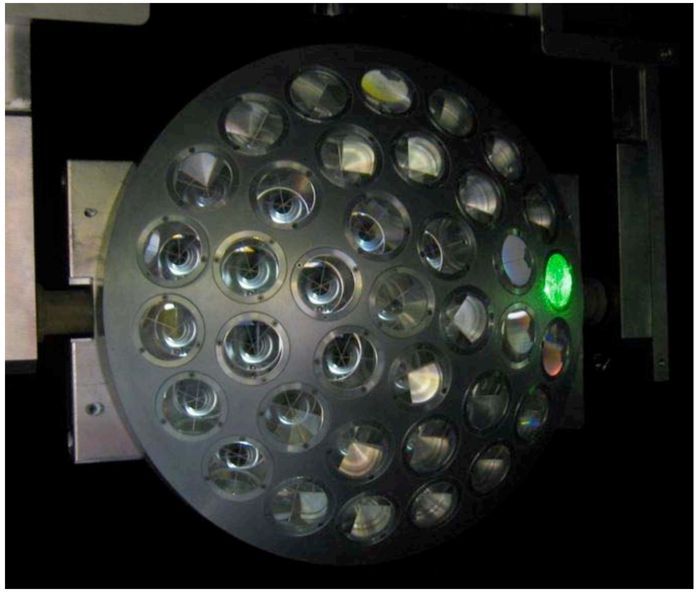
$M_{LARES} \sim M_{LAGEOS} \sim 400$ Kg

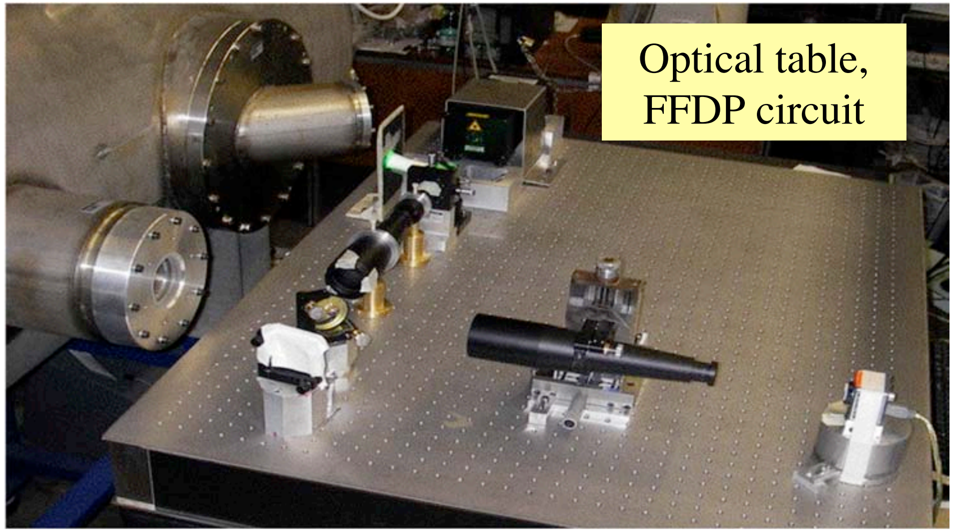
$M/S_{LARES}/M/S_{LAGEOS} \sim 2.7$

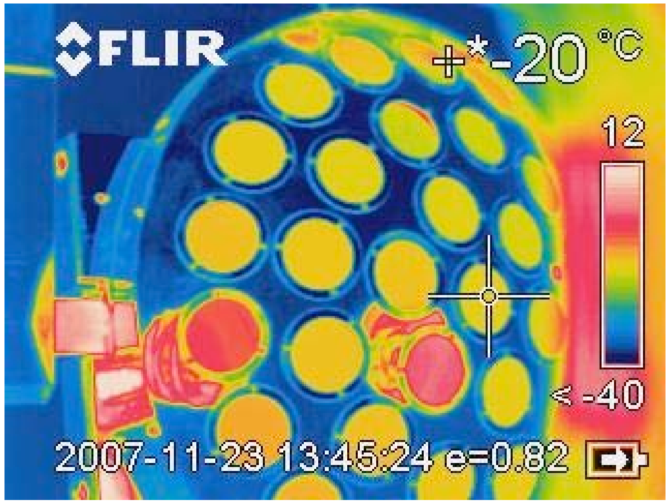
SLR Characterization Facility (SCF) - LAGEOS proto from NASA

Thermal and laser tests never performed before in space conditions









New space test developed at LNF: the "SCF-Test"

- Measurement in space conditions of:
  - IR emissivity, Solar absorptivity of CCR and metal
  - $T_{surface}$ of CCR and metal
  - Thermal relaxation time of CCR (τ_{CCR}), plastic and metal
  - T difference of outer face and inner tip of CCR

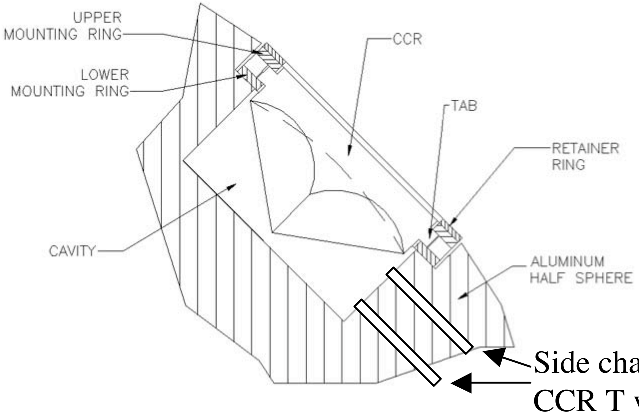
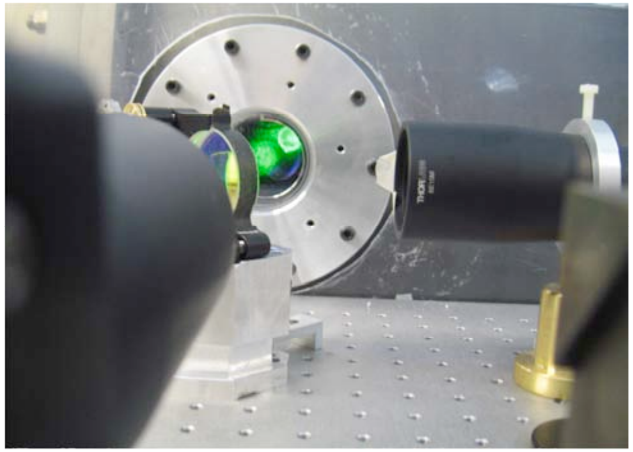


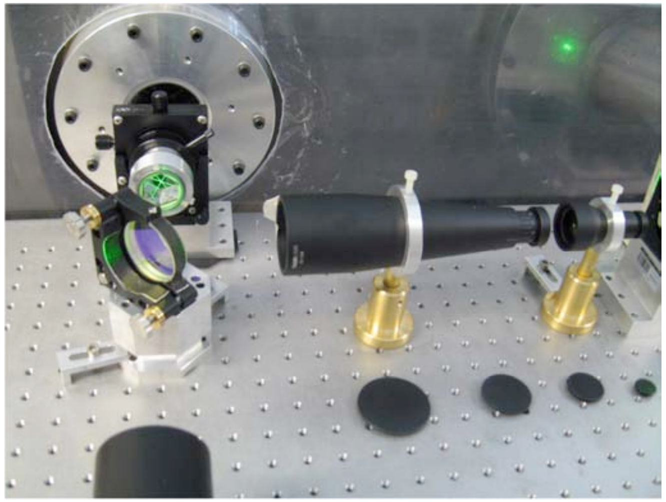
Figure 3. LAGEOS CCR assembly

  - Far field diffraction patters (FFDP) of each CCR in the SCF
- FFDPs also at STP to measure that velocity aberration is correct
- Thermal and optical model of SCF data
- Thermal and optical model of SPACE behavior

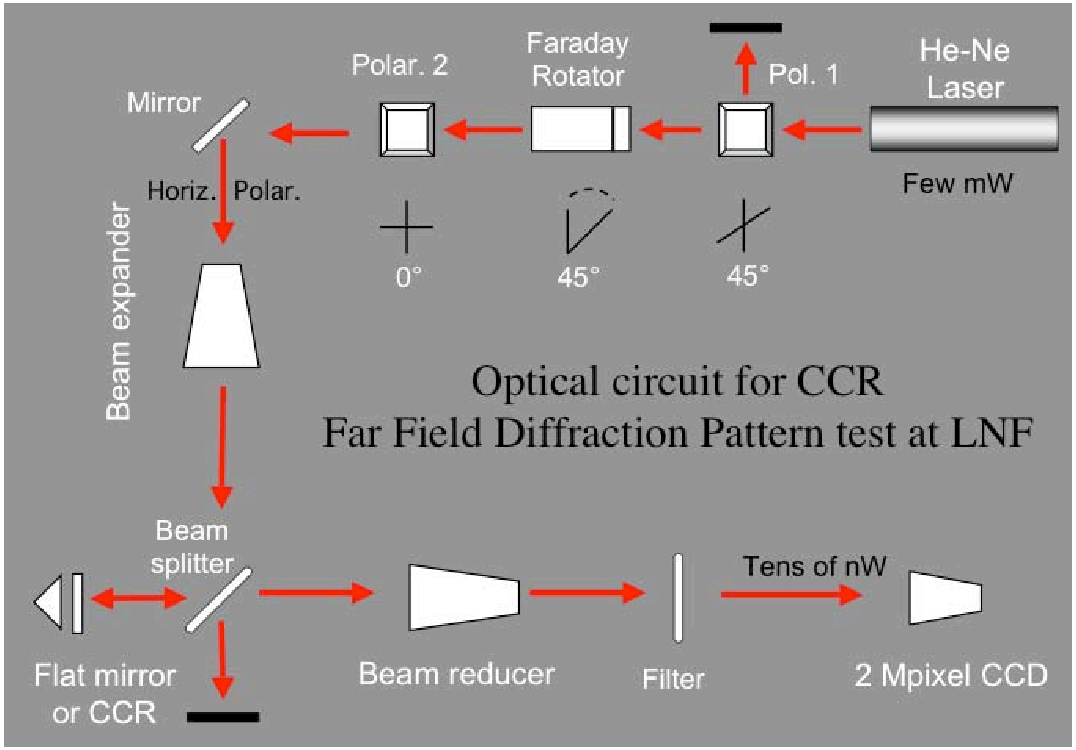
CCR "in space", inside SCF

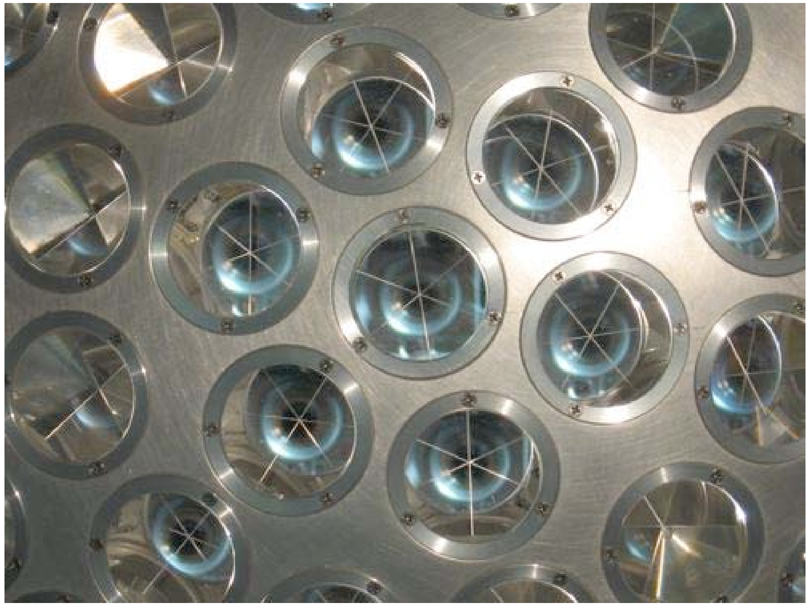


CCR at STP, outside SCF



Measured & simulated Far Field Diffraction Pattern

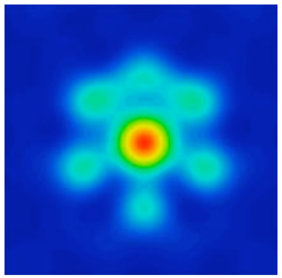




Simulated with CodeV

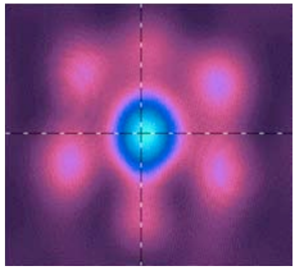
Measured @ LNF

NASA-GSFC proto has dihedral angle offset = 0.0 ± 0.5 arcsec



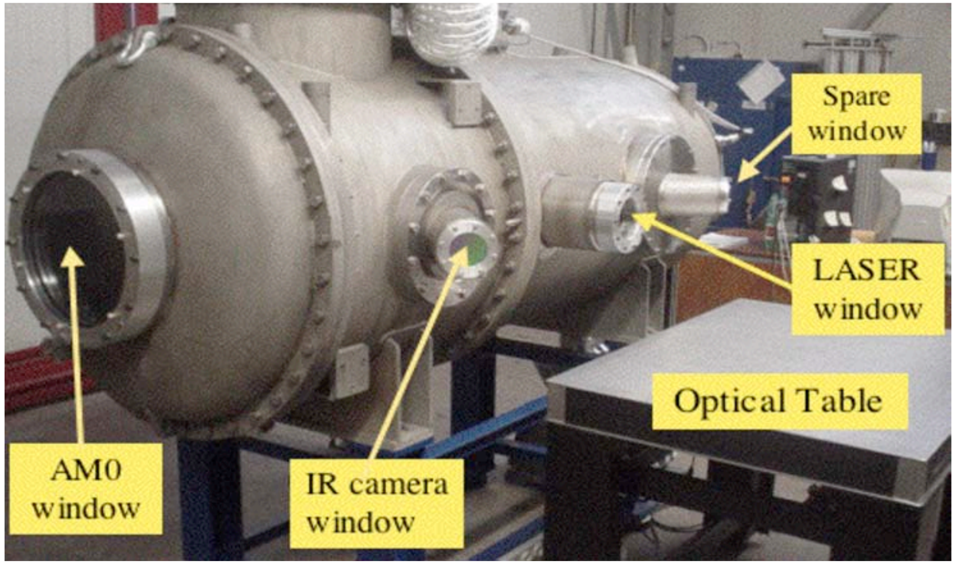
Good agreement

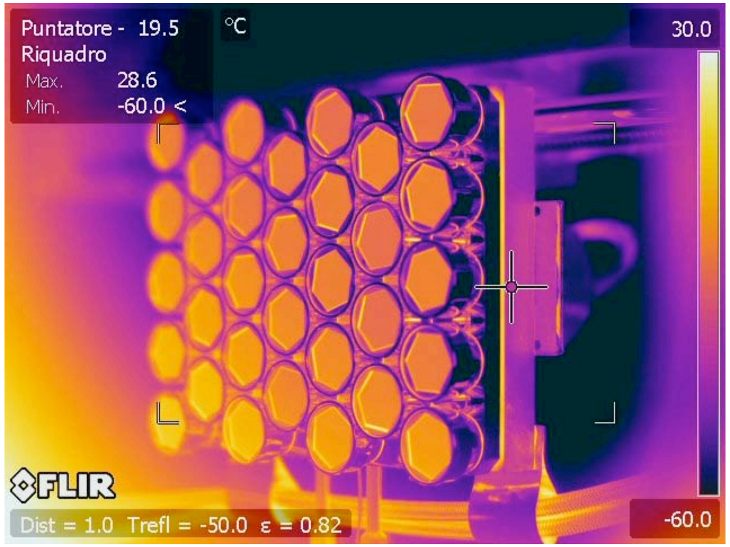
Scale is ± 50 μrad

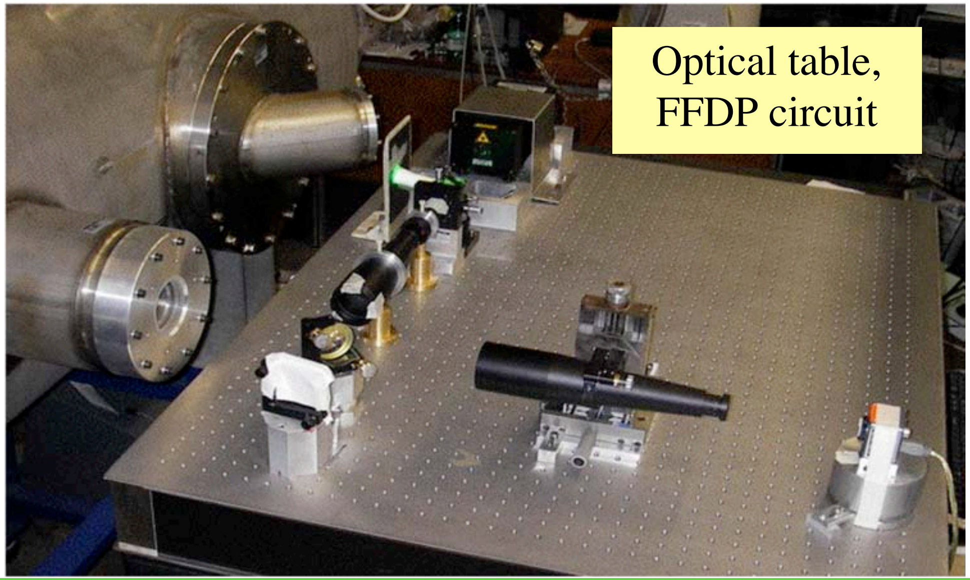


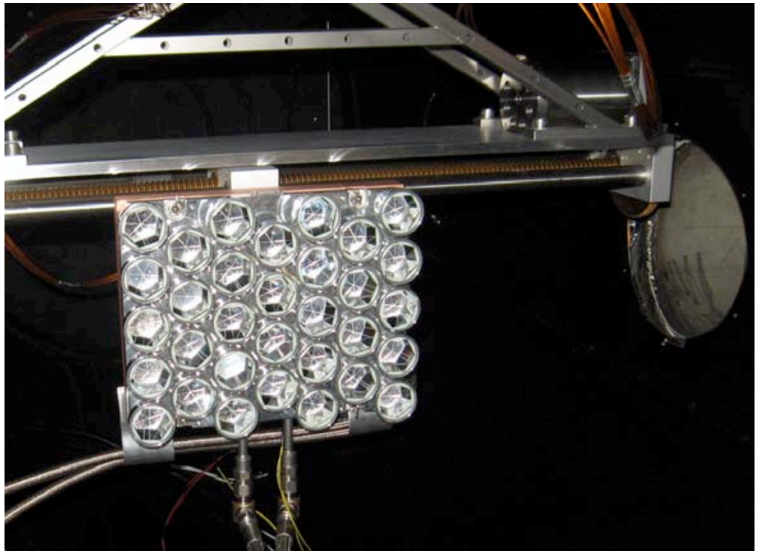
SCF-Test of GPS-2 *flight model* from Univ. of Maryland

Industry-standard space test developed with INFN experiment ETRUSCO





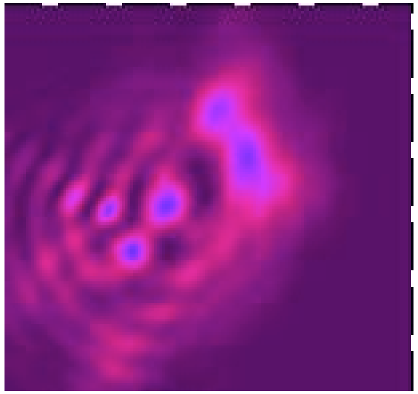




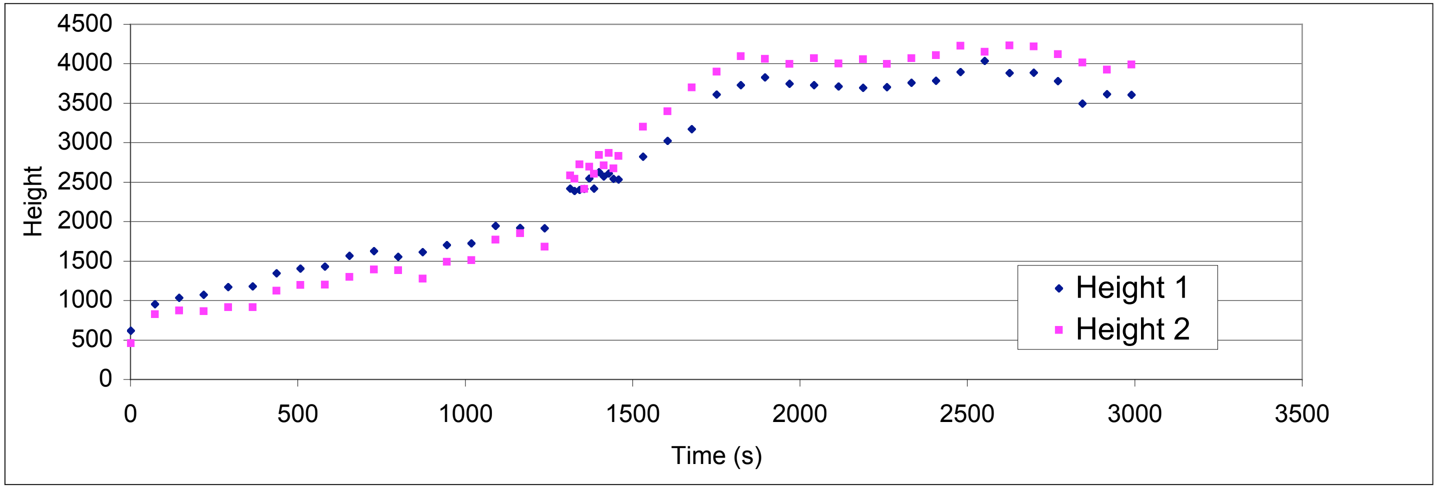
GPS-2 SCF-Test: FFDP spoiled by Sun thermal perturbation

Thermal effect: reduction of signal, retro-reflected to the wrong place!!

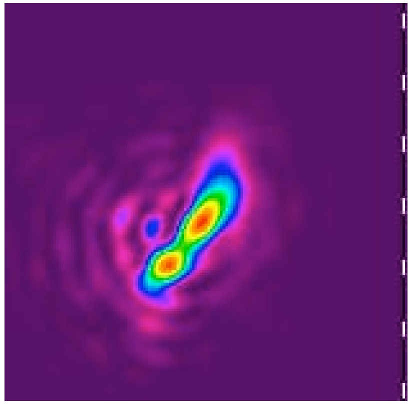
FFDP with Sun ON
@t = 0 sec



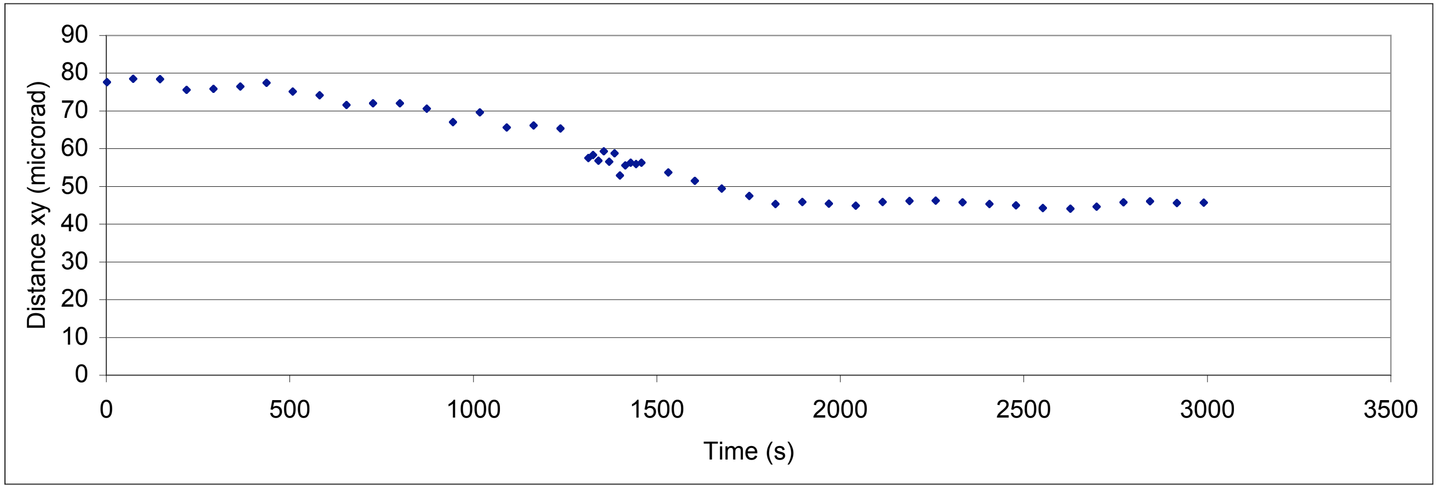
FFDP height (CCD counts) vs time (s) after exposure to Sun



FFDP with Sun OFF
@ t= 3000 sec



FFDP peak-to-peak distance (μrad) vs time (s) after exposure to Sun



Experimental explanation of long-standing issue. To be corrected for GALILEO

LAGEOS: Thermal SCF-Test and simulation (tough job)

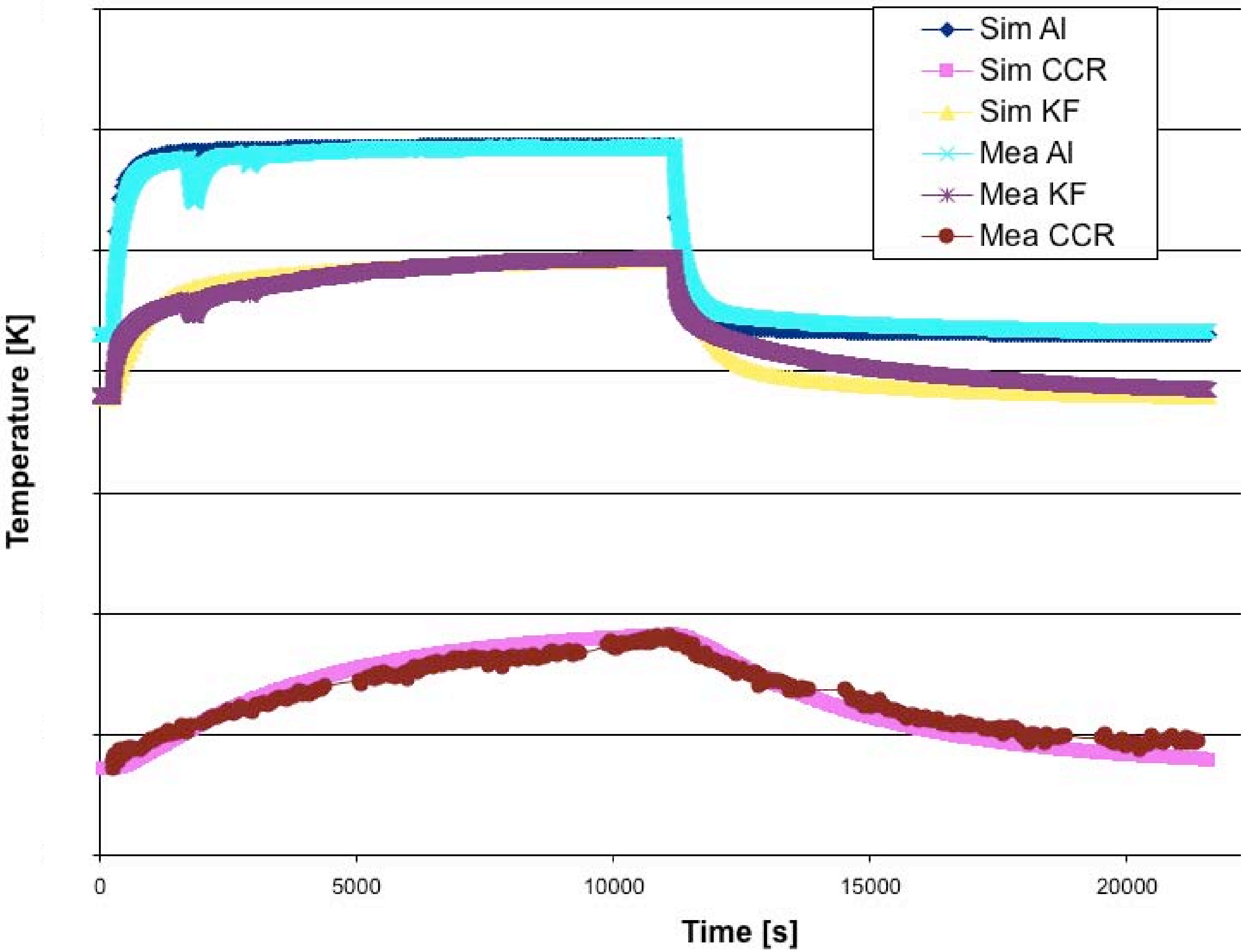
SCF work led by G. O. Delle Monache

Temp. from IR camera
τ_{CCR} drives NGPs

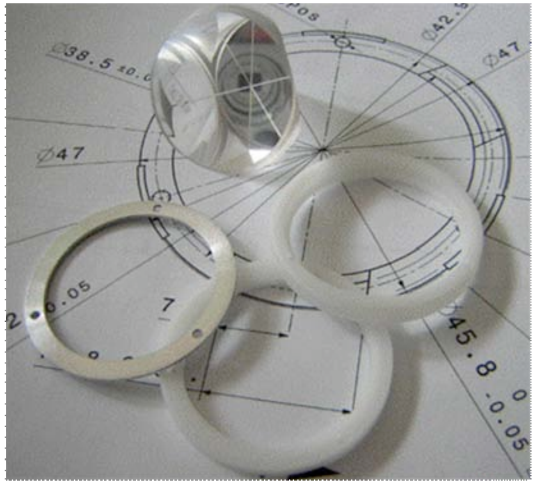
τ_{CCR} **never measured**

τ_{CCR} predictions vary by 350% (2000 - 7000 sec)

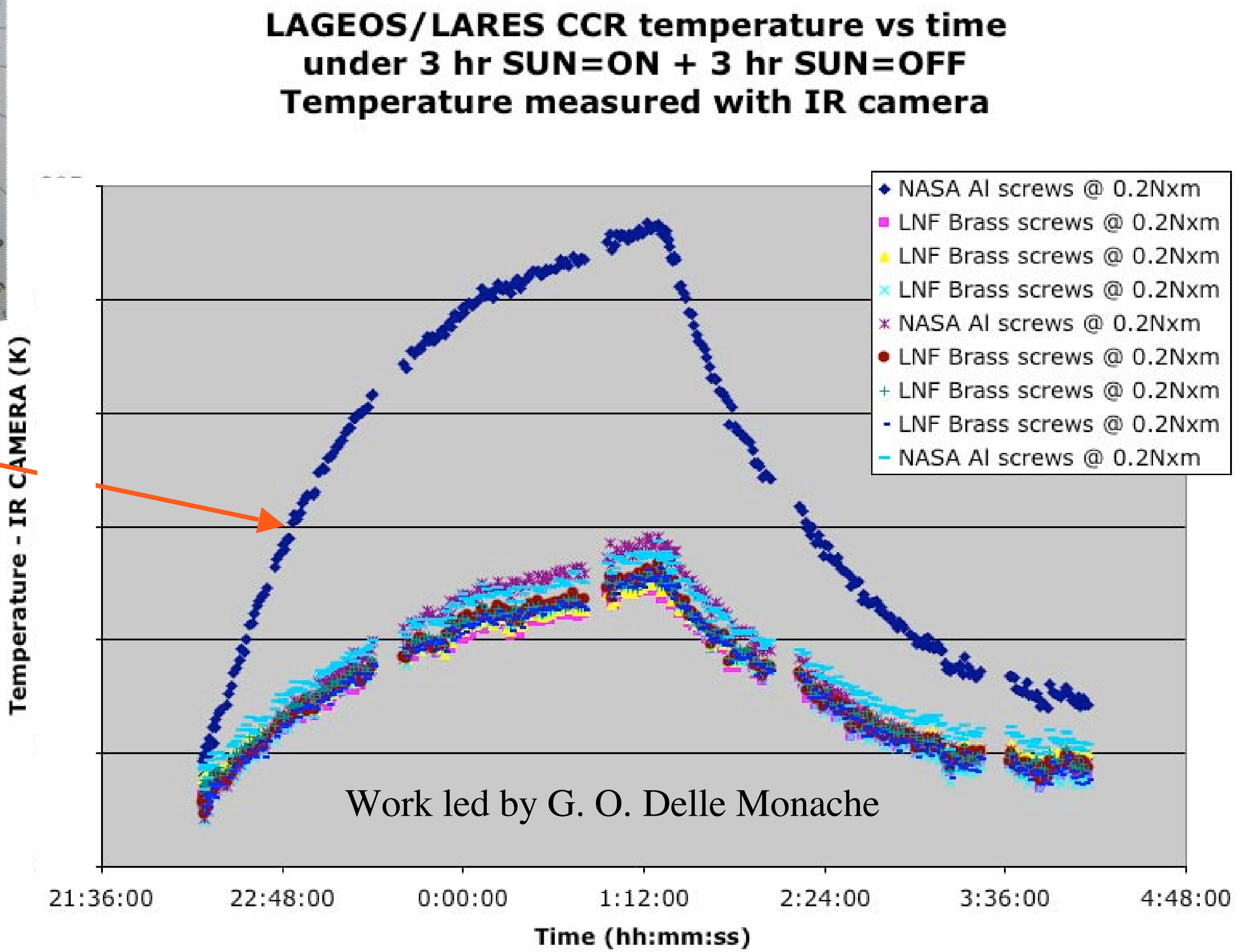
Our measurement:
$\sigma(\tau_{CCR}) \sim 10\%$,
which makes thermal NGPs negligible for LAGEOS & LARES



Full-blown thermal SCF-test performed (I)



Suprasil LAGEOS/LARES retro-reflectors



CCR perturbed (as expected) by PT100 probe attached close to its outer surface.

<u>The other 8 CCRs are unperturbed because measured with IR camera</u>

Our 1st published paper: SCF & thermal NGPs

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PROBING GRAVITY IN NEO'S WITH HIGH-ACCURACY LASER-RANGED TEST MASSES

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Thermal thrusts give ~2% error on the Measurement of the Lense-Thirring effect

Let us now consider the uncertainty on the prediction for $\tau_{\rm CCR}$ and let us take, for example, $\sigma(\tau_{\rm CCR})/\tau_{\rm CCR} \sim 250\%$. First of all, the orbital effects of the thermal drag are periodical and are, thus, averaged out or fitted for[2] over very long periods at the level of 90% and only a residual factor, $R_{\rm TD} = 10\%$, remains. Second, the long period nodal perturbations of the thermal drag during the eclipse season are linearly proportional to $\tau_{\rm CCR}$. Therefore

$$\frac{\sigma(\dot{\Omega}_{\rm TD})}{\dot{\Omega}_{\rm TD}} = \frac{\sigma(\tau_{\rm CCR})}{\tau_{\rm CCR}} \times R_{\rm TD} = 250\% \times 10\% = 25\%. \quad (1)$$

For $\dot{\Omega}_{\rm TD} = 1\text{–}2\,\rm mas/yr$ (see above), one then gets

$$\sigma(\dot{\Omega}_{\rm TD}) = 1\text{–}2\,\rm mas/yr \times 25\% = 0.25\text{–}0.5\,\rm mas/yr. \quad (2)$$

Finally, the relative uncertainty in the measurement of the frame dragging effect from the thermal relaxation time *only* is

$$\frac{\sigma(\dot{\Omega}_{\rm TD})}{\dot{\Omega}_{\rm FD}} = \frac{0.25\text{–}0.5\,\rm mas/yr}{31\,\rm mas/yr} = 0.8\text{–}1.6\%. \quad (3)$$

Clearly, for LARES, it will be critical to have an accurate measurement of $\tau_{\rm CCR}$ to use in the NASA GEODYNE orbit determination program used for data analysis. The SCF has been designed to achieve $\sigma(\tau_{\rm CCR})/\tau_{\rm CCR} \le 10\%$ for the LARES retroreflectors, which, in the baseline design, are the same as the LAGEOS ones. Since $\tau_{\rm CCR}$ is the basic observable which governs all thermal forces, this will put the climatic NGP's well under control for the LARES goals.

Thermal NGPs: orbit, spin and Earth shadow

Comparison of thermal thrusts vs time (one orbit) between:

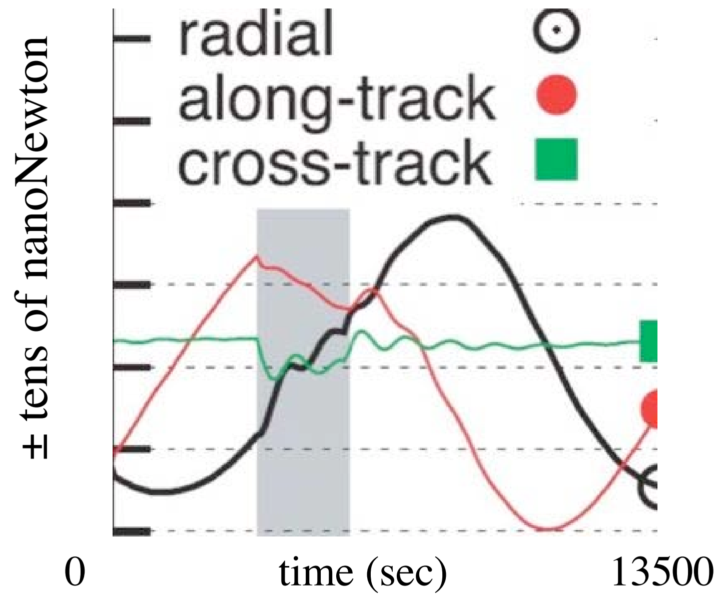
- LageOS Spin Axis Model (LOSSAM): no measured data
- LNF model: based on orbital/thermal FEM model tuned to SCF data

Models DO NOT agree quantitatively by significant factor

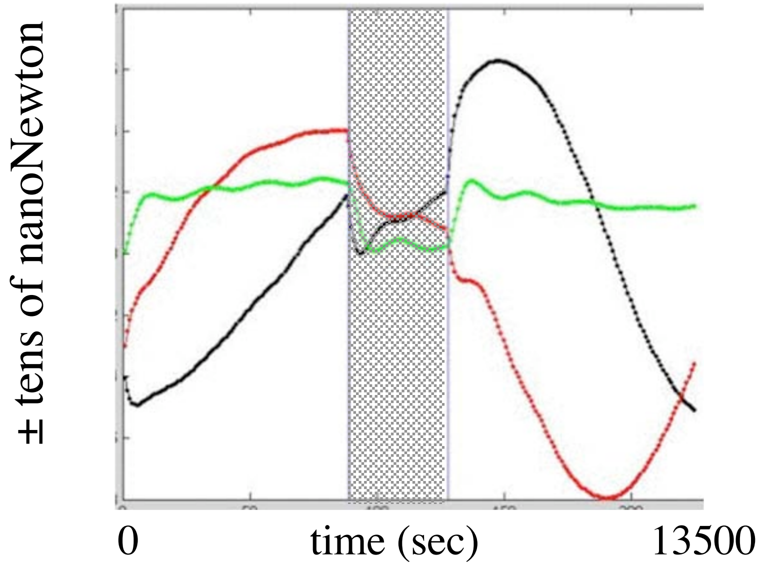
Wrong spin-orbit model can give error on Lense-Thirring up to 5%

Spin and Orbit of **1/1/2000**
(with longest Earth shadow)

LOSSAM (Nacho Andres *et al*)
Earth shadow = grey area



LNF model tuned to SCF data
Earth shadow = grey area



Limits on non-newtonian gravity using the perigee

Current limits on additional Yukawa potential:

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

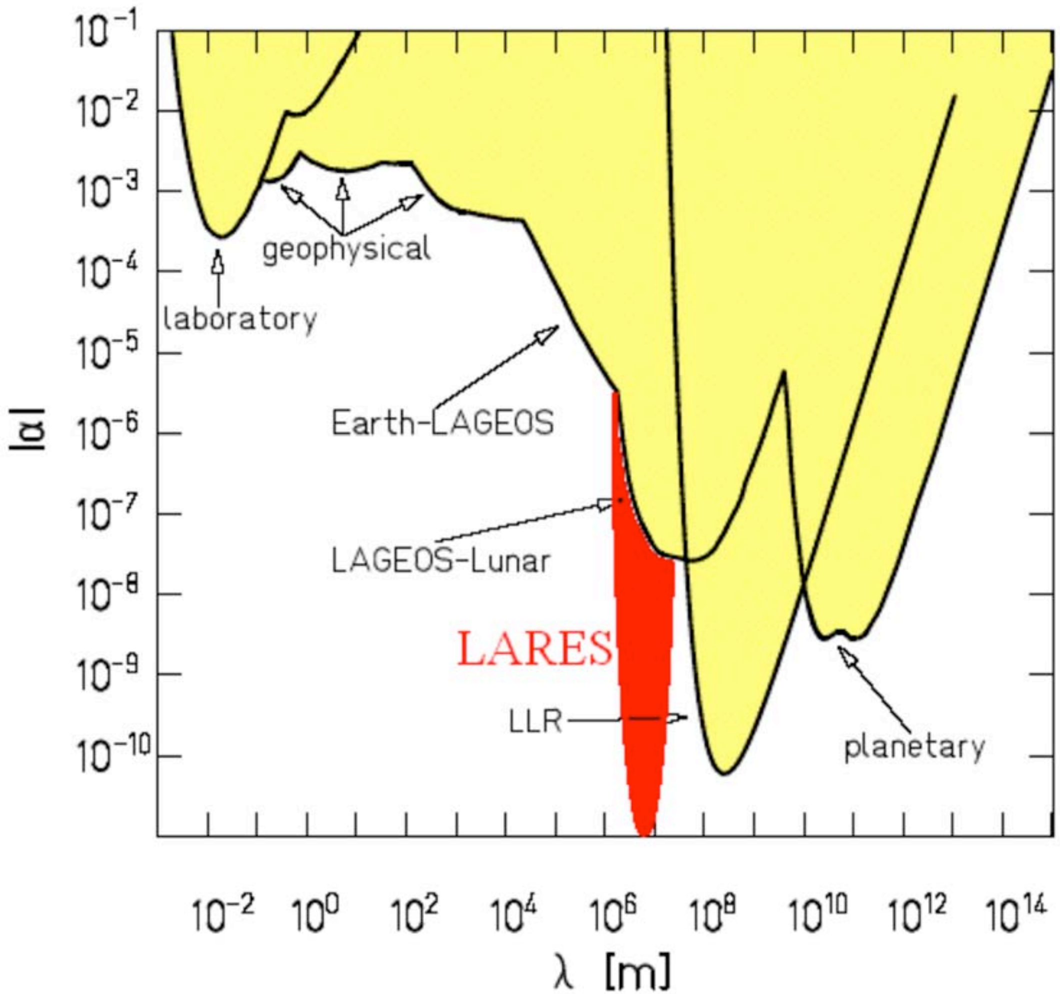
Expected limit on α set by the LARES mission at an orbit radius of about 8000 Km.

For a clean perigee measurement

1) accurate measurement of thermal perturbations
2) high value of Mass/Area

Warning: perigee defined only if VEGA will deliver $e \neq 0$

LARES limit by I. Ciufolini



LARES vs GP-B: main goals & differences

- Both want to test the gravitomagnetic field at the 1% level

- They are based on two **DIFFERENT equations** for the effect of the gravitomagnetic field, this difference could have profound implications in some **gravitational theories** embedding GR
  - LNF work: for example Gravity with Torsion

- LARES data analysis may be **repeatable** by any laboratory. LARES measurements will **improve** with time, because of longer periods of observations
  - LNF work: better modeling of the physical orbital perturbations

General Relativity with Torsion: GP-B

Constraining Torsion with Gravity Probe B*

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(Dated: Submitted to Phys. Rev. D. 1/8-07; Revised 9/18-07; Accepted 9/27-07)

It is well-entrenched folklore that all torsion gravity theories predict observationally negligible torsion in the solar system, since torsion (if it exists) couples only to the intrinsic spin of elementary particles, not to rotational angular momentum. We argue that this assumption has a logical loophole which can and should be tested experimentally, and consider non-standard torsion theories in which torsion can be generated by macroscopic rotating objects. In the spirit of action=reaction, if a rotating mass like a planet can generate torsion, then a gyroscope would be expected to feel torsion. An experiment with a gyroscope (without nuclear spin) such as Gravity Probe B (GPB) can test theories where this is the case.

Using symmetry arguments, we show that to lowest order, any torsion field around a uniformly rotating spherical mass is determined by seven dimensionless parameters. These parameters effectively generalize the PPN formalism and provide a concrete framework for further testing GR. We construct a parametrized Lagrangian that includes both standard torsion-free GR and Hayashi-Shirafuji maximal torsion gravity as special cases. We demonstrate that classic solar system tests rule out the latter and constrain two observable parameters. We show that Gravity Probe B is an ideal experiment for further constraining non-standard torsion theories, and work out the most general torsion-induced precession of its gyroscope in terms of our torsion parameters.

Missing in this paper is the effect of Torsion on the "obital" frame dragging on LAGEOS & LARES …

General Relativity with Torsion: GP-B

Rebuttal paper: problem found with use of (more predictive) EHS model. After some time and updates both papers published on PRD. EHS models in Mao et al demoted to *toy model* after Flanagan/Rosenthal criticism

Can Gravity Probe B usefully constrain torsion gravity theories?

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Center for Radiophysics and Space Research, Cornell University, Ithaca, New York, 14853

(Dated: draft of May 8, 2007; printed February 1, 2008 at 2:33)

In most theories of gravity involving torsion, the source for torsion is the intrinsic spin of matter. Since the spins of fermions are normally randomly oriented in macroscopic bodies, the amount of torsion generated by macroscopic bodies is normally negligible. However, in a recent paper, Mao et al. (gr-qc/0608121) point out that there is a class of theories, including the Hayashi-Shirafuji (1979) theory, in which the angular momentum of macroscopic spinning bodies generates a significant amount of torsion. They further argue that, by the principle of action equals reaction, one would expect the angular momentum of test bodies to couple to a background torsion field, and therefore the precession of the Gravity Probe B gyroscopes should be a ected in these theories by the torsion generated by the Earth.

We show that in fact the principle of action equals reaction does not apply to these theories, essentially because the torsion is not an independent dynamical degree of freedom. We examine in detail a generalization of the Hayashi-Shirafuji theory suggested by Mao et al. called Einstein-Hayashi-Shirafuji theory. There are a variety of di erent versions of this theory, depending on the precise form of the coupling to matter chosen for the torsion. We show that for any coupling to matter that is compatible with the spin transport equation postulated by Mao et al., the theory has either ghosts or an ill-posed initial value formulation. These theoretical problems can be avoided by specializing the parameters of the theory and in addition choosing the standard minimal coupling to matter of the torsion tensor. This yields a consistent theory, but one in which the action equals reaction principle is violated, and in which the angular momentum of the gyroscopes does not couple to the Earth's torsion field. Thus, the Einstein-Hayashi-Shirafuji theory does not predict a detectable torsion signal for Gravity Probe B. There may be other torsion theories which do.

General Relativity with Torsion: LAGEOS+LARES

G. Bellettini, R. March, R. Tauraso, S. Dell'Agnello, ….

Using the Lagrange planetary equations of perturbation theory, and denoting by Ω the longitude of the node, we find

$$\dot{\Omega} = \frac{2J}{a^3(1-e^2)^{3/2}} \times (1 - \frac{\mathcal{G}+2}{2} - \frac{w_2 - w_4}{4}), \qquad (1)$$

$$\dot{\Omega} = \dot{\Omega}_{LT} \times (1 + PERT), \quad PERT = -\frac{\mathcal{G}+2}{2} - \frac{w_2 - w_4}{4}$$

a and e being the (unperturbed) semimajor axis and eccentricity, and $\dot{\Omega}_{LT} = \frac{2J}{a^3(1-e^2)^{3/2}}$ is the unperturbed Lense-Thirring rate.

- **When there is no torsion** $w_2 = w_4 = 0$. When in addition $\mathcal{G} = -2$, the metric is the weak field approximation of the Kerr metric, $PERT = 0$ and (1) becomes the classical Lense-Thirring equation.
- **Measuring $\dot{\Omega}$ at 1% relative accuracy with LARES and the two LAGEOS will allow for setting a limit on the combination of torsion parameters $PERT$ of the order of 1%.**

Limits on spacetime Torsion with frame dragging

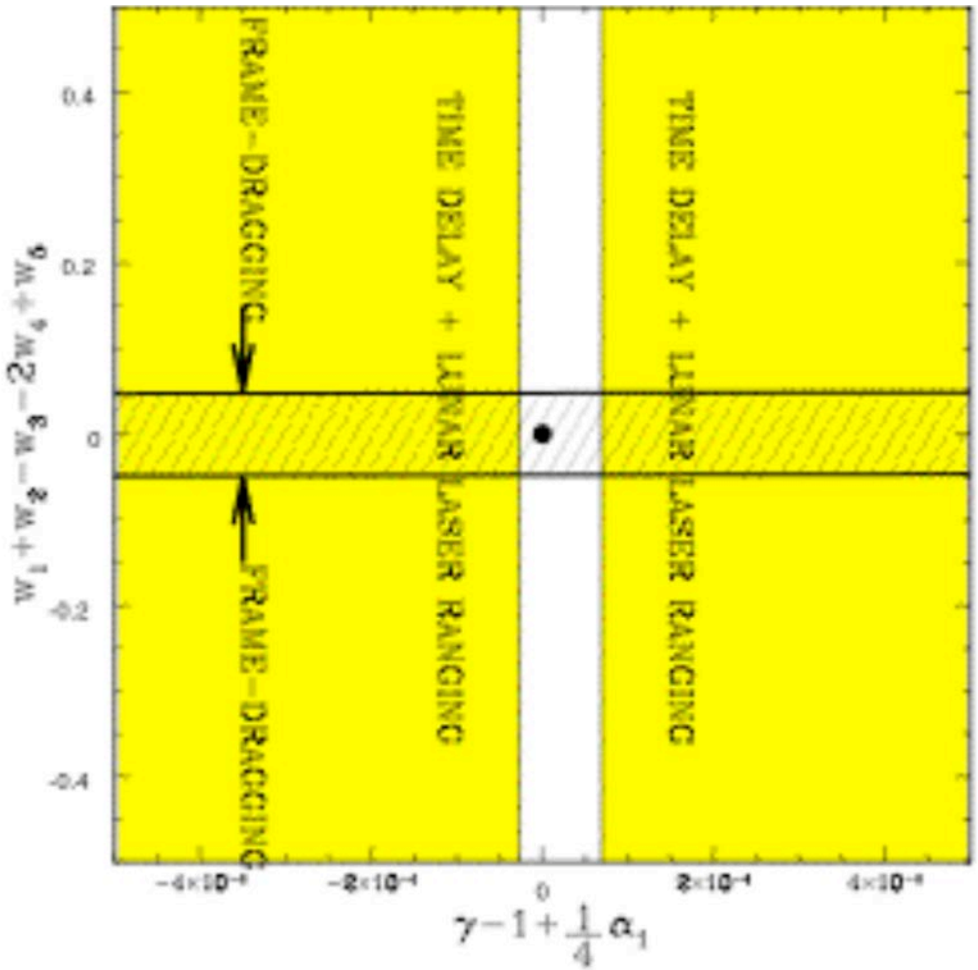
LAGEOS+LARES sensitive to combo of parameters ==> $w_2 - w_4 + \ldots$
GP-B sensitive to **different** combo ==> $w_1 + w_2 - w_3 - w_3 - 2\,w_3 + w_5$

Limit by Guth et al for GP-B in figure assumes a relative error on Lense-Thirring of ~ 1%

With April 07 GP-B error (~300%) the allowed band (hatched) is way off-scale.

With LAGEOS only the w_2-w_4 allowed band is of order of 10%

Torsion parameters



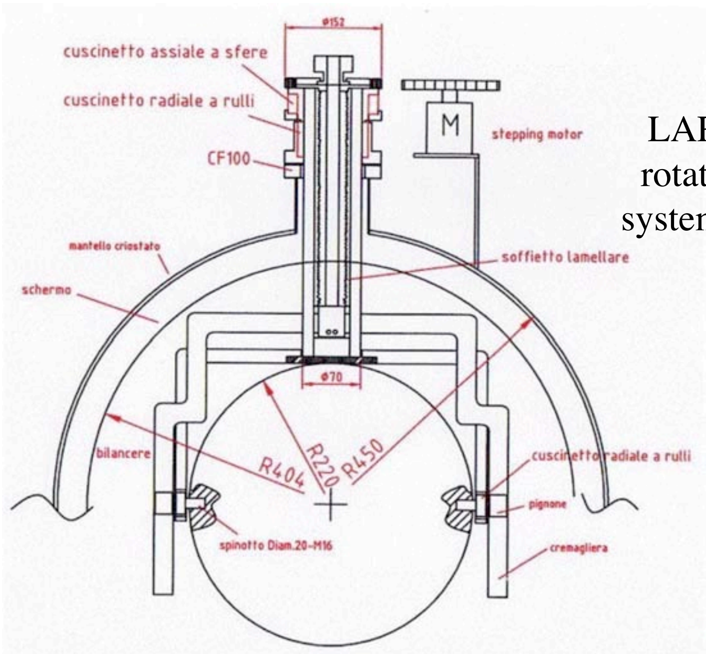
PPN parameters

Pending LNF commitments on LARES

- Subject to the approval of an INFN-ASI Memorandum of Understanding
- Thermal & optical characterization of 116 CCRs, of W-alloy samples, of “3x3 matrix” proto and of flight model
  - SCF-Tests not done on LAGEOS
  - 5 proto CCR in house, under test
  - 25 flight CCRs coming
- SCF-Test of 3x3 matrix
- SCF-Test of LARES *flight model*
  - Static and w/spin
- SCF-validated thermal and optical model of matrix
- Sw thermal and optical model of LARES in space
  - Spin-orbit model
- Original analysis work on GR with Torsion
- Analysis on Frame Dragging

“3x3 matrix”

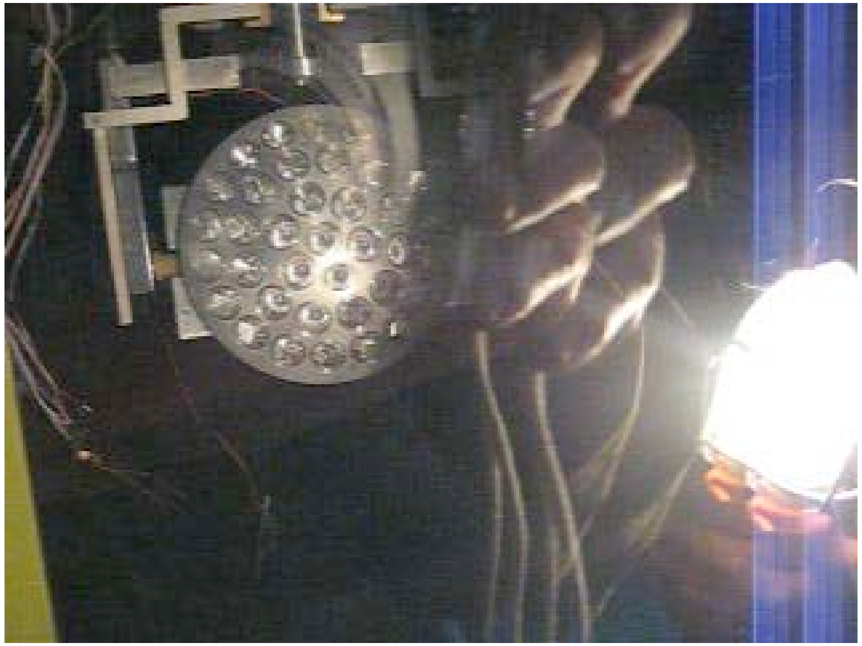
Side channels for IR camera

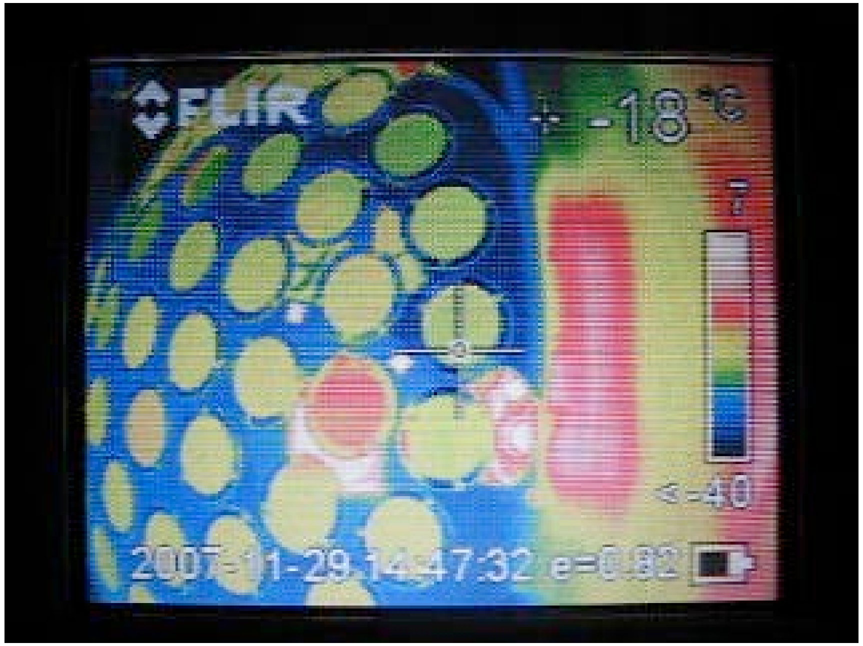


LARES on rotation+tilt system in SCF

SCF-Test of spinning LARES (never done for LAGEOS)

Shown is the rotation in vacuum of the NASA-GSFC LAGEOS *sector* with cables and thermo-coolers attached on the back plate for thermal control.
LARES, the full test mass, will be suspended with a high insulating support by the equator or the pole and left thermally floating in equilibrium with the solar simulator AM0.
We will then perform non-invasive SCF-Testing with:
Spin = 0 rpm, 5 rpm (initial VEGA spin), 4, 3, 2, 1, <1 rpm.
Spin dumped with time by Earth B field. LAGEOS spin: 60 rpm in 1976, ~ 10^{-2} rpm now



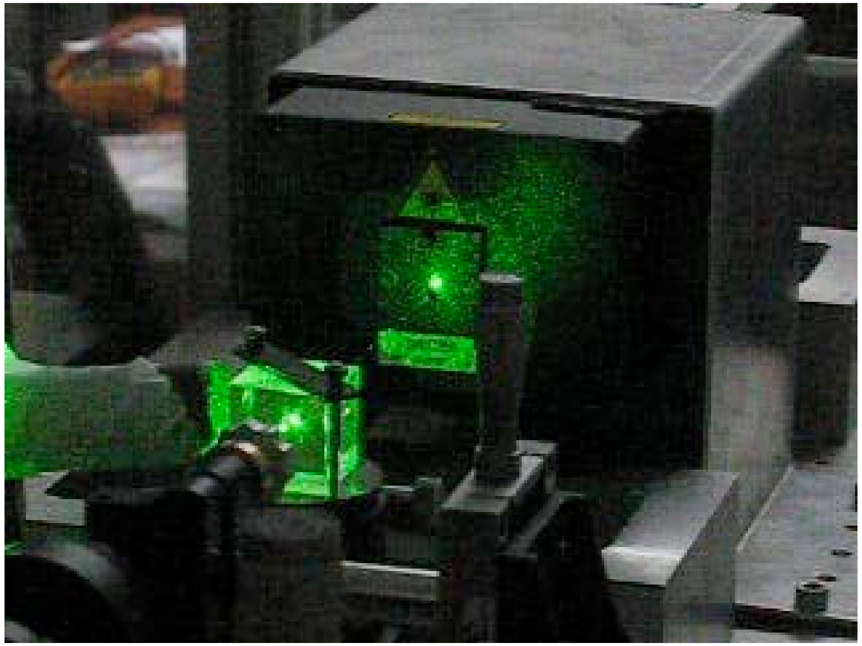


We need badly a clean room …

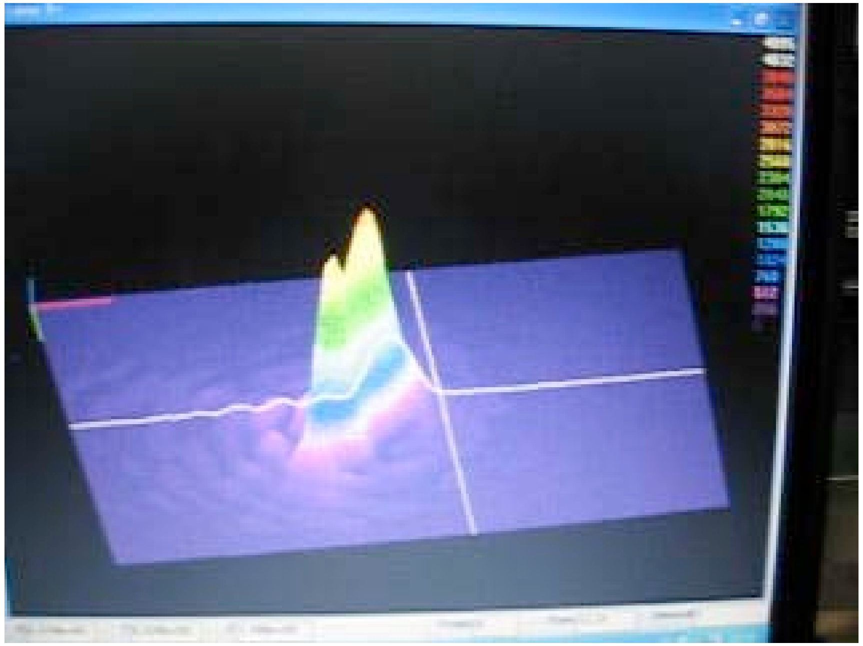
The SCF is not in a clean room. We work in open air space, with no T-conditioning. In the summer, with T = 35º C and with the Solar Simulator turned on emitting 18KW, it is an interesting environment ….

The optical circuit is enclosed in plexiglas to avoid effect of air convection. However, this doesn't solve the problem of the dust …. FROM GPS-2 SCF-Test:

1) laser beam hitting dust particles



2) Effect of dust on FFDP measurements



Conclusions

- SLR/LLR is the most precise .AND. cost-effective way to probe gravity in our home laboratory, the Solar System

  (Millimeters) .AND. (0.1 M€ to M€)

- At LNF LARES is a joint project of the Research and Accelerator Division
- Jointly, within the ETRUSCO INFN experiment we developed a new industry-standard space test: **the space characterization of SLR payloads**

- The SCF-Test is an important new tool for
  - Gravitation
  - Space Geodesy
  - Global Navigation Satellite System ===> GALILEO has CCRs on all satellites

- With Satellite and Lunar Laser Ranging we love to test:
  - **General Relativity**
  - **GR with Torsion, Yukawa deviations from $1/r^2$, BraNe New Words ….**

The SCF group

ETRUSCO

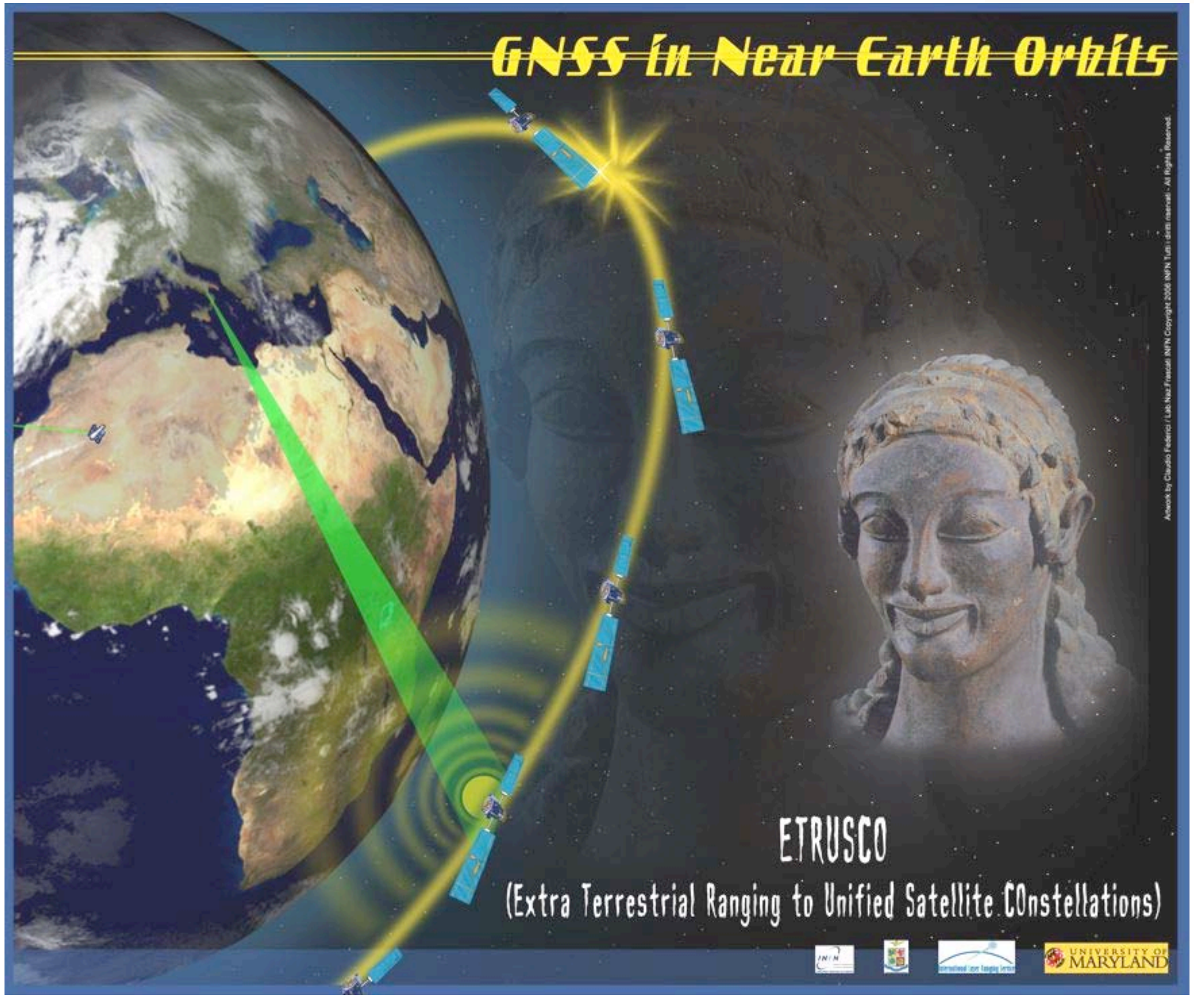
Development of new industry-standard space characterization of GRA, targeted to the 30 GALILEO satellites

Improved laser positioning by one order of magnitude
Better Gravitational Redshift

GPS-3
- R&D with NASA-GSFC
- innovative hollow CCRs

FP7-GALILEO
- Call for Tender Apr. 08

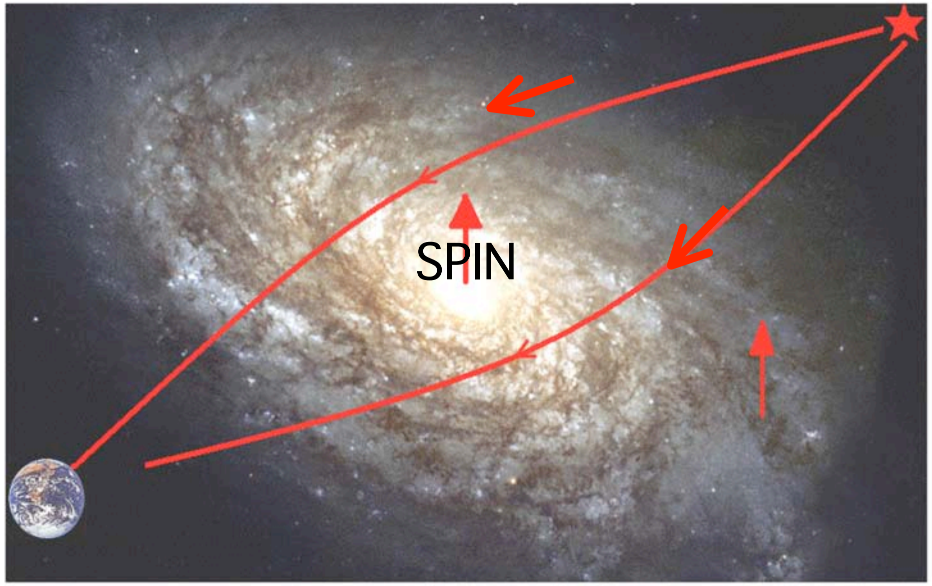
Proposal to ASI
- R&D “ETRUSCO-2” targeted to GALILEO



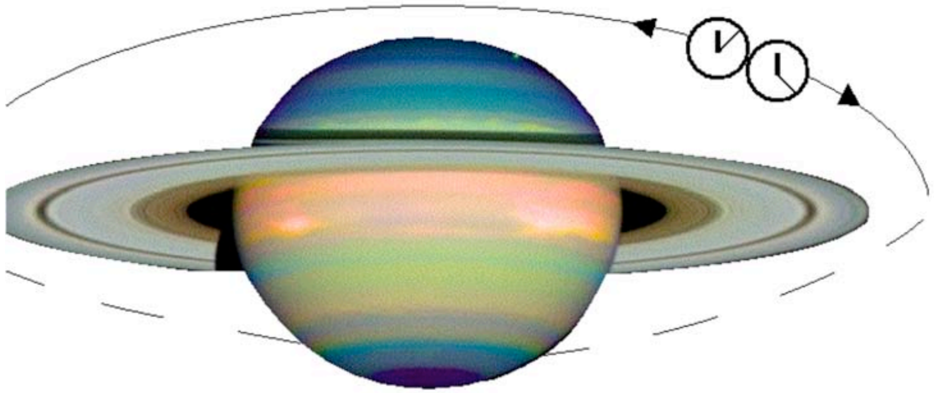
Endorsed by ILRS

Other manifestations of frame dragging

Spin-time delay and gravitational lensing: can be observable on large scale structures (I. Ciufolini)



Gravitomagnetic clock effects near spinning astrophysical objects



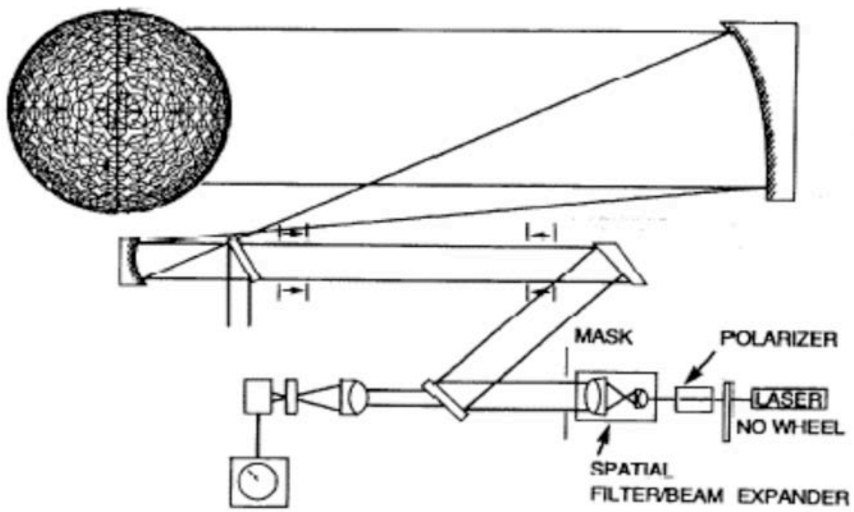
Center-of-Mass calibrations (with ASI-Matera)

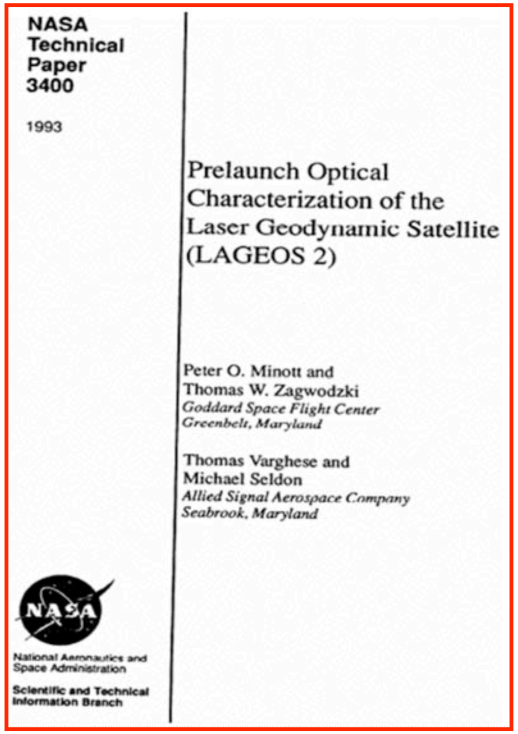
- What correction to go from the CCRs on the surface to the satellite center of mass ?
- This is not, trivially, the radius
- Pulsed laser - Matera
- Streak camera - Matera
- Mirror, large SCF window - LNF
- Electronics for start time, stop time, TDC - LNF

  This has been evaluated with Felici, Ciambrone, Corradi (including a visit to Matera).

Repeat test with LARES inside the SCF (never done for LAGEOS)

Methods to define the stop time of the retro-reflected signal with the electronics:
Peak, Centroid, Half max, Constant fraction.
The correction depends on the satellite, the space climatic conditions and on what detection methods the ground stations use (single vs multi-photon detection)




NASA Technical Paper 3400

1993

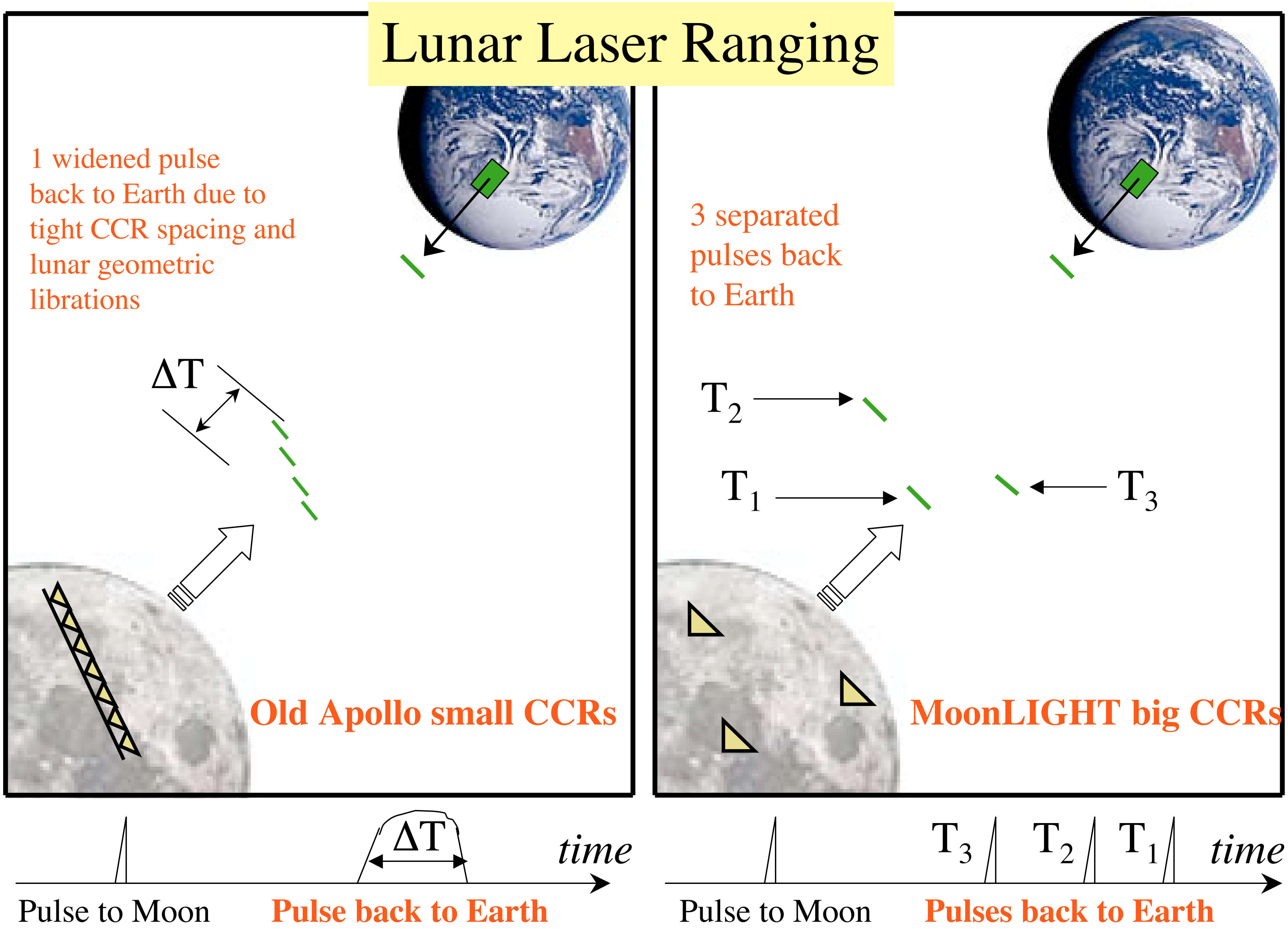
Prelaunch Optical Characterization of the Laser Geodynamic Satellite (LAGEOS 2)

Peter O. Minott and Thomas W. Zagwodzki
Goddard Space Flight Center Greenbelt, Maryland

Thomas Varghese and Michael Seldon
Allied Signal Aerospace Company Seabrook, Maryland

National Aeronautics and Space Administration

Scientific and Technical Information Branch



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

MoonLIGHT: 2nd Generation Lunar Laser Ranging

Ongoing approved NASA project

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}	$\sim 5 \times 10^{-5}$	6-10 yr
Deviations from $1/r^2$ (Yukawa param. α)	$10^{-10} \times$ gravity	$\sim 10^{-11}$	$\sim 10^{-12}$	6-10 yr

“BraNe new world”: a quantum theory beyond General Relativity

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

The accelerated universe and the Moon

Gia Dvali, Andrei Gruzinov, and Matias Zaldarriaga
for Cosmology and Particle Physics, Department of Physics, New York University, New York, New York 10003

(Received 20 December 2002; published 8 July 2003)

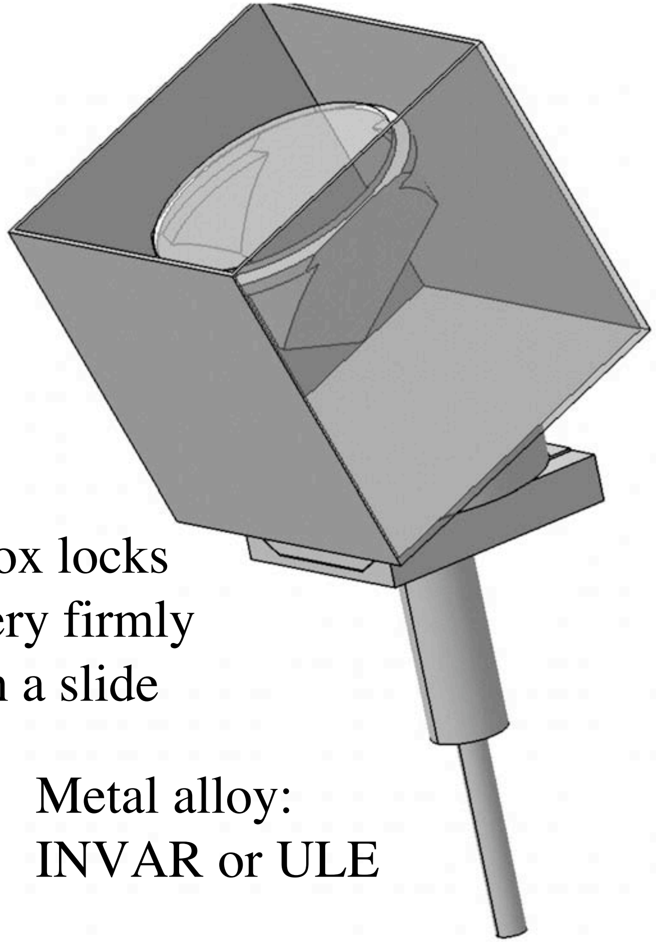
Cosmologically motivated theories that explain the small acceleration rate of the Universe via the modification of gravity at very large, horizon, or superhorizon distances, can be tested by precision gravitational measurements at much shorter scales, such as the Earth-Moon distance. Contrary to the 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

NASA call: "Suitcase" science to the Moon

Concept by Astronaut Roberto Vittori. Manned NASA missions, 2015-18

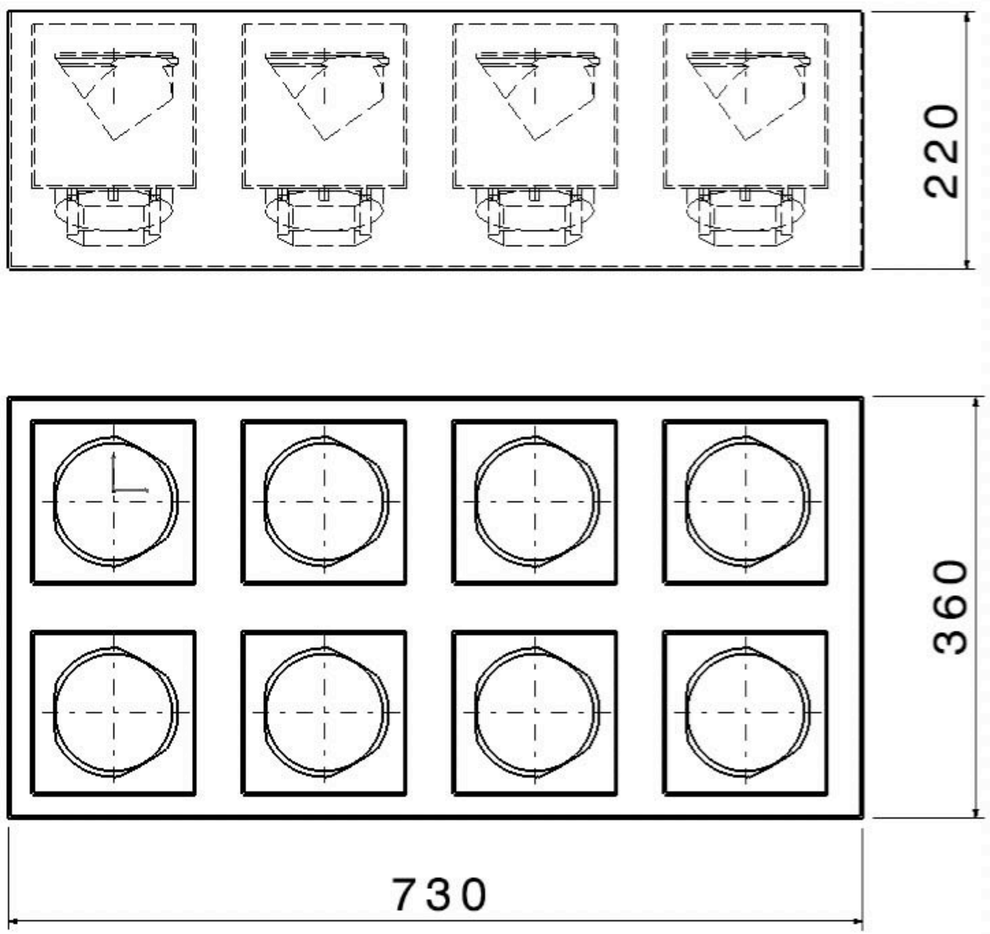
Retro-reflector: 10 cm diam.
Box: 14 cm side



Box locks very firmly on a slide

Metal alloy: INVAR or ULE

Suitcase for the CCR boxes (mm)



Next laser ranging frontier: MARS

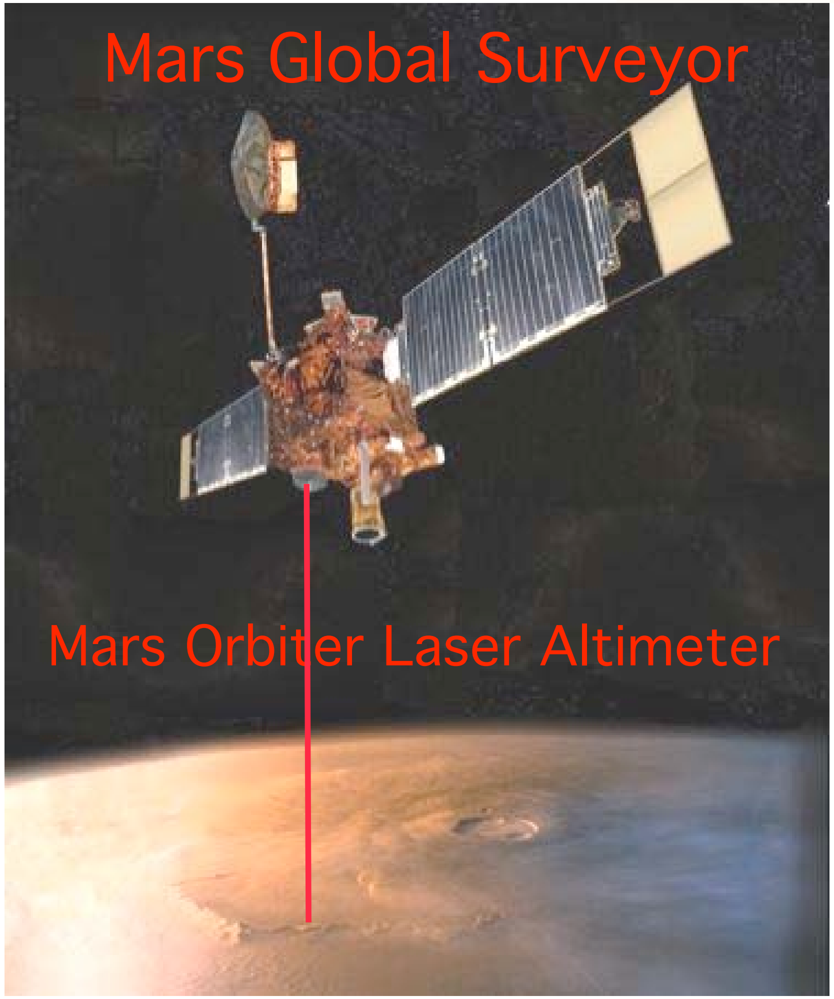
- What physics?
  1) similar to the Moon (see Dvali *et al*)
  2) Shapiro time delay w/VIKINGS (70s)
- Technically feasible: NASA-GSFC laser transponder experiment done with MGS 100 milions of Km way
- Dust storms a problem? Rovers Spirit & Opportunity say no!
- Next lander should have CCRs !!

MOLA-Earthlink Experiment
at NASA's 1.2 meter telescope

J. Abshire, X. Sun, G. Neumann, J. McGarry,
T. Zagwodzki, P. Jester, + many others

Experiment Objectives - Demonstrate:

- Laser pulse detection at Mars distances
  Assess Earth laser to Mars orbit detection probabilities
- Laser communications at ~ 100 Mkm distance



Courtesy of Jan MacGarry
ILRS05 workshop

Satellite Laser Ranging in deep space:
the proposed Deep Space Gravity Probe mission