MoonLIGHT

Moon Laser Instrumentation for General relativity High-accuracy Tests

D. G. Currie (PI) — *University of Maryland at College Park, MD, USA*

R. Vittori — *Aeronautica Militare Italiana, Rome, ITALY*

A. Boni, G. Bellettini, C. Cantone, S. Dell'Agnello (Co-PI), G. O. Delle Monache,
M. Garattini, N. Intaglietta, M. Martini, R. Tauraso — *INFN-LNF, Frascati (Rome), ITALY*

ASI-MLRO, Matera Laser-Ranging Observatory (G. Bianco et al), Matera, ITALY

T. Murphy — *University of California at San Diego, CA, USA*

D. Carrier — *Lunar GeoTechnical Institute, Lakeland, Florida, USA*

D. Rubincam — *NASA-GSFC, Greenbelt, MD, USA*

A. Hajian — *U. S. Naval Observatory, Washington DC, USA*

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

Outline

- Physics goals
- New array design and next challenges
- Optimal payload preparation at INFN-LNF
  - Thermal simulations
  - Space Climatic Facility
  - Optical Laboratory
- Conclusions and prospects

MoonLIGHT basics

ITALY-US proposal for improving by a factor up to 1000 the accuracy of the current Lunar Laser Ranging (LLR) done with cube corner retro-reflector (CCR) arrays deployed by the Apollo 11, 14 and 15 landings.

ITALY works on two of the main mission requirements:

- new design of the CCR array and thermal simulation
- thermal and laser tests at the LNF Space Climatic Facility

Rich program of accurate tests of General Relativity already with current laser ranging systems, like **ASI-MLRO** (Matera) and **APOLLO** (Los Alamos).

This accuracy will get better and better as laser performance improves over the next few decades, like it did since the ‘60s.

Mechanics, installation, “suitcase”: opportunity for industries.

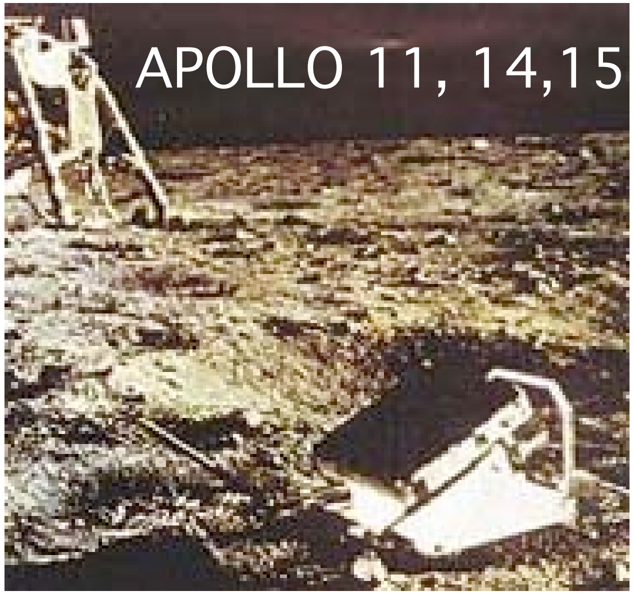
Why high-accuracy GR tests ?

- Observation of Gravitational Waves is “the” (dynamical) test
  - For INFN this is the Amaldi legacy
- **Main theoretical goal: quantum theory of Gravity and Unification of the 4 interactions**. GR is a classic theory !
  - Study of fundamental interactions is one of the basic goals of INFN
- **Main experimental goal: where does GR fail ?**
  - Space-time curvature (Cassini) ?
  - Frame dragging (LAGEOS, GP-B, LARES) ?
  - Redshift/clock dilation (GP-A) ?
  - At what accuracy ? For example, for frame-dragging:
    - LAGEOS: 10%
    - GP-B: 100-200% now, 13% final (press release on April 14, 2007)
    - LARES: new mission, aims to 1%. Is 1% enough ?
- **New theories ?**
  - Brane world: “The accelerated Universe and the Moon” (Dvali et al)
  - Torsion: signature similar to frame dragging (e.g. Guth at al)

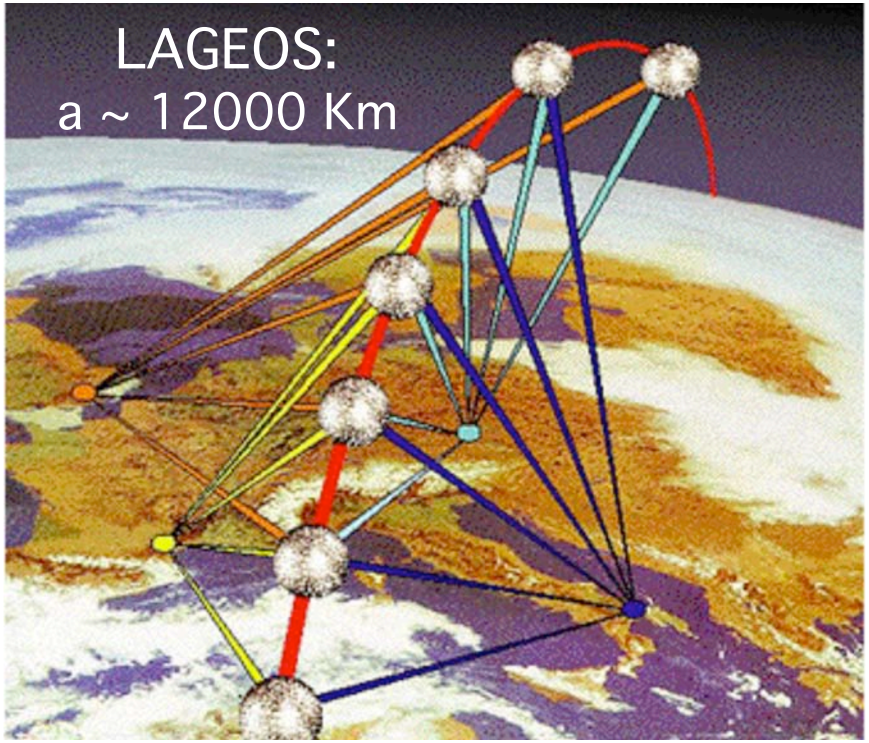
NASA RTD proposal vs. ASI concept study

- NASA call Suitcase science to the Moon: submitted **manned** version, "MoonLIGHT-M" (Oct. 2006)
  - Passive experiment only
  - Italian work at zero cost to NASA
  - **Work on manned deployment by R. Vittori**
  - US hardware to be tested at LNF
  - NASA decision expected by spring 2007
- ASI study: **robotic** version, "MoonLIGHT-R"
  - MoonLIGHT-R is one of highest priority and lightest P/L
  - Can be combined w/Optical clock (G. Tino et al, this ASI study) to measure the Gravitational Redshift
    - accuracy 4000 times better than GP-A and 400 times better than expected results of ACES on ISS !!
- LNF will do thermal and laser ranging tests on NASA CCRs and has already performed P/L design + climatic simulations

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



S
L
R



- Started in 1969 by Currie et al
- Currie is the MoonLIGHT PI
- LAGEOS II (NASA-ASI), 1992, has an orbit accuracy < 1 cm

Current General Relativity measurements with LLR

LLR currently provides the best constraints on:

* The Weak Equivalence Principle (WEP) at a level of 10^{-13}
* The Strong Equivalence Principle (SEP) at a level of 4×10^{-4}
* Time-rate-of-change of Newton's gravitational constant, G, to a part in 10^{-12}/yr
* Geodetic precession at a level of 0.35% $\Rightarrow$ PPN parameter β
* Deviations from $1/r^2$ gravity at 10^{-10} times the strength of gravity

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

Table by T. Murphy

Phenomenon	current limit	1 mm ranging	100 μm ranging	meas. timescale
Weak EP ($\Delta a/a$)	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
$\dot{G}/G$	10^{-12} per year	$\sim 10^{-13}$/yr	$\sim 10^{-14}$/yr	4 yr
Geodetic Precession	$\sim 5 \times 10^{-3}$	5×10^{-4}	$\sim 5 \times 10^{-5}$	6–10 yr
$1/r^2$ deviations	$10^{-10} \times$ gravity	$\sim 10^{-11}$	$\sim 10^{-12}$	6–10 yr

PPN parameter β

Parameter α (see next slide)

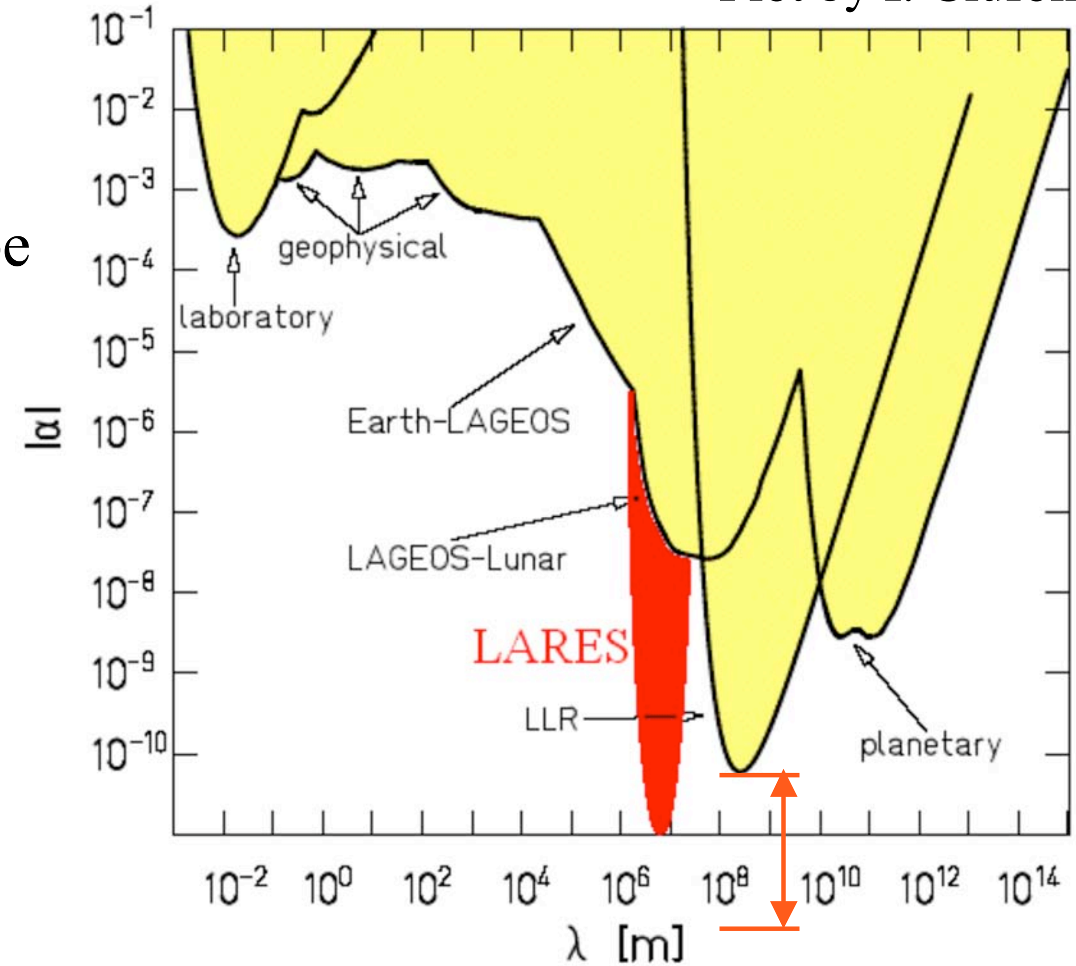
Limits on non-Newtonian gravity

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

Plot by I. Ciufolini

With MoonLIGHT current limit on α will be 10^{-12} for a ranging accuracy of 100 μm

Expected limit set by LARES artificial satellite at an orbit radius of about 8000 Km



“BraNe new world”: a model beyond General Relativity

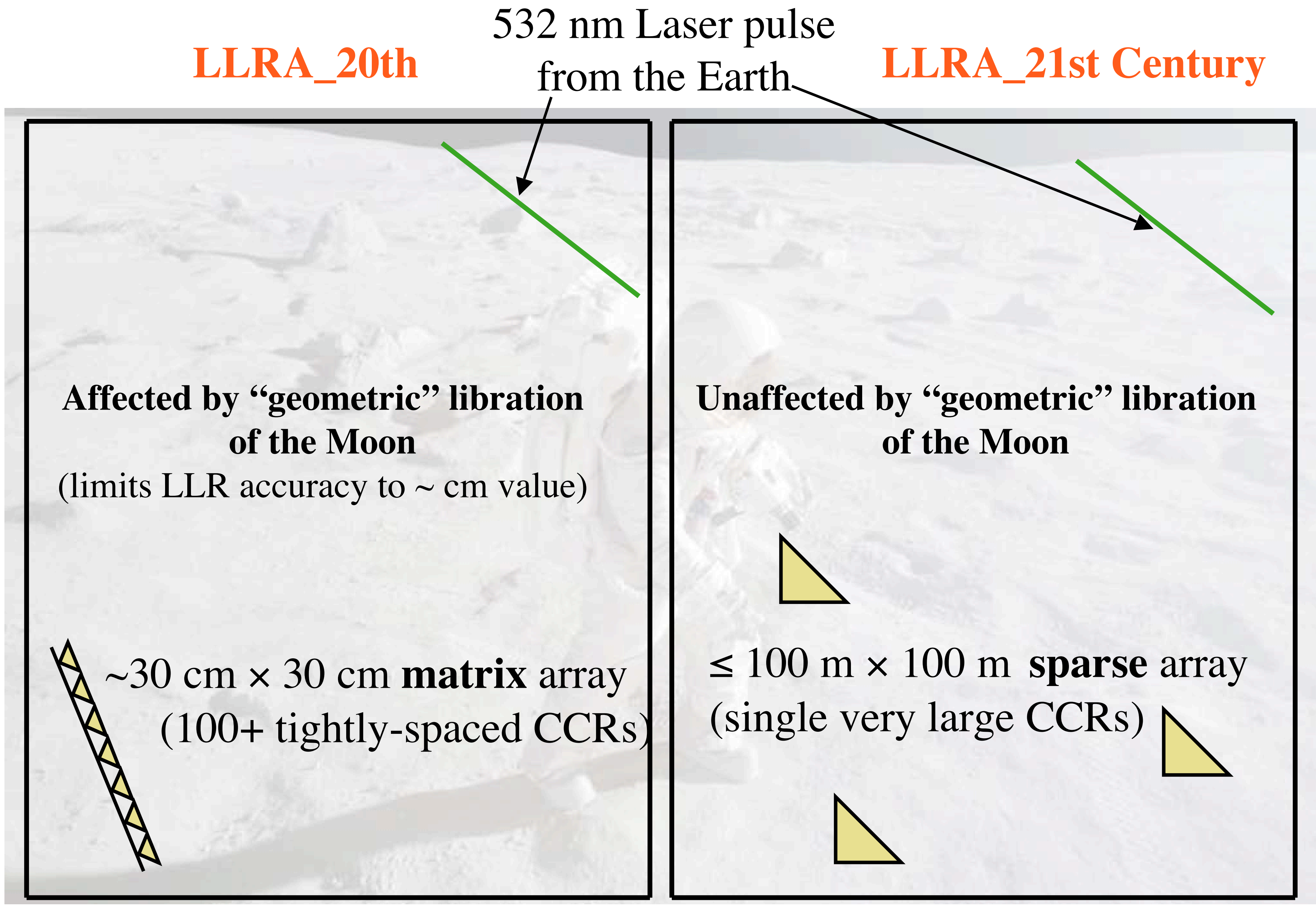
PHYSICAL REVIEW D **68**, 024012 (2003)

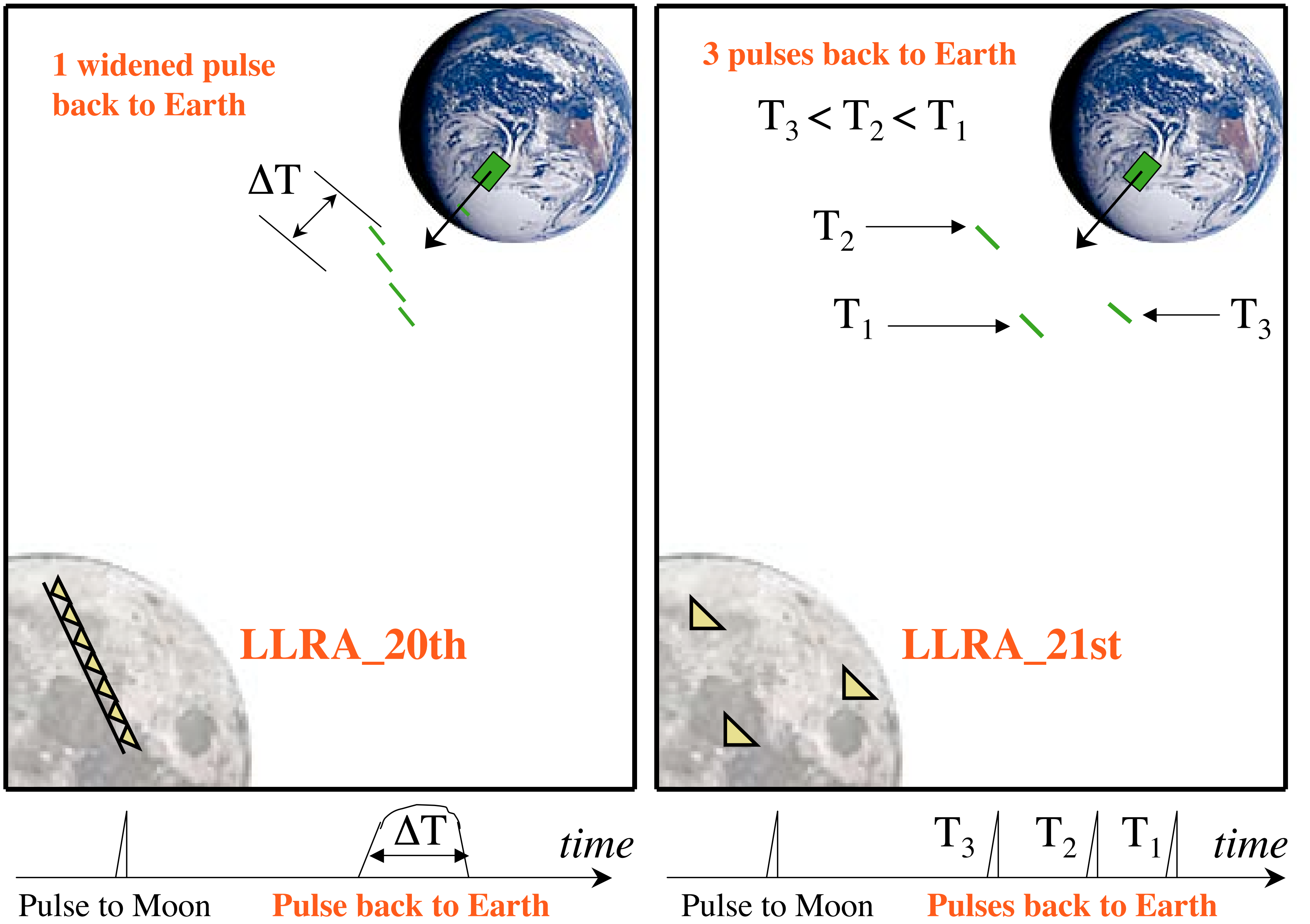
The accelerated universe and the Moon

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**, in addition to GR geodetic precession
- LLR accuracy now **O(1) cm**. APOLLO is reaching **~ 1mm**
- This model can be fully tested by MoonLIGHT with **100 μm** accuracy, i.e. w/factor 100 improvement over current LLR

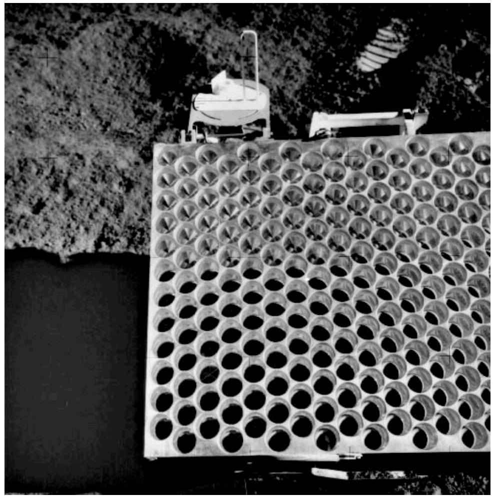

LLRA_20th
532 nm Laser pulse
from the Earth
LLRA_21st Century
Affected by “geometric” libration
of the Moon
(limits LLR accuracy to ~ cm value)
~30 cm × 30 cm matrix array
(100+ tightly-spaced CCRs)
Unaffected by “geometric” libration
of the Moon
≤ 100 m × 100 m sparse array
(single very large CCRs)


1 widened pulse
back to Earth
ΔT
LLRA_20th
ΔT
time
Pulse to Moon
Pulse back to Earth
3 pulses back to Earth
$T_3 < T_2 < T_1$
T_2
T_1
T_3
LLRA_21st
T_3
T_2
T_1
time
Pulse to Moon
Pulses back to Earth

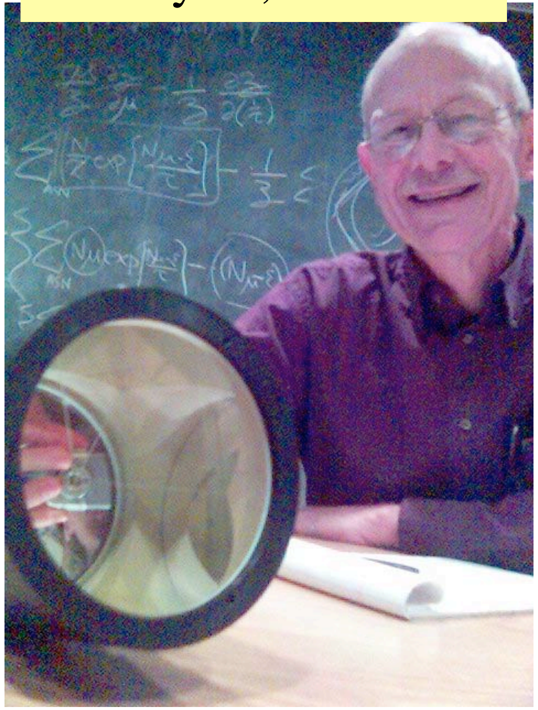
The MoonLIGHT array

- Distance among CCRs ? To be optimized; ~ 20 m
- Pattern of CCR positions ? Sparse over area $\leq 100 \times 100\ m^2$
- Installation location accuracy ? ~ 1 m
- Inclination ? For ex. 30^o degrees, but depends on landing site
- Inclination accuracy ? Few degrees
- Pointing to Earth ? Few degrees
- CCR diameter ? ~ 10 cm
- Length of support foot ? Few cm
- Number of CCRs ? 8 CCRs, **< 10 Kg total**

Apollo 15 CCR diameter ~ 1/3 of MoonLIGHT's



1969 jumbo CCR held by PI, D. Currie



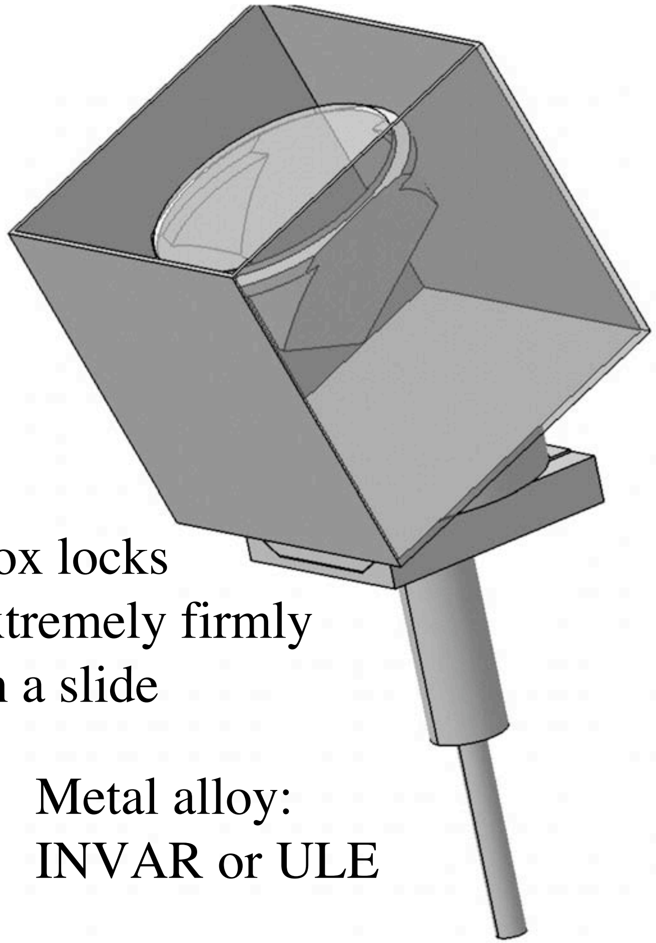
Next experimental challenges

- New array design removes the current largest source of error (~ 1 cm), i.e. the geometric librations
- Now other effects, never into account before, limit accuracy at 1 mm or better accuracy
  - Mechanical stability of P/L and its installation
  - Thermal/optical stability of P/L
- Tried to address these issues with
  - Proper mechanical design
  - Detailed thermal simulations
- Next: experimental tests at the SCF

Suitcase and basic P/L unit

Concept design by Astronaut Roberto Vittori

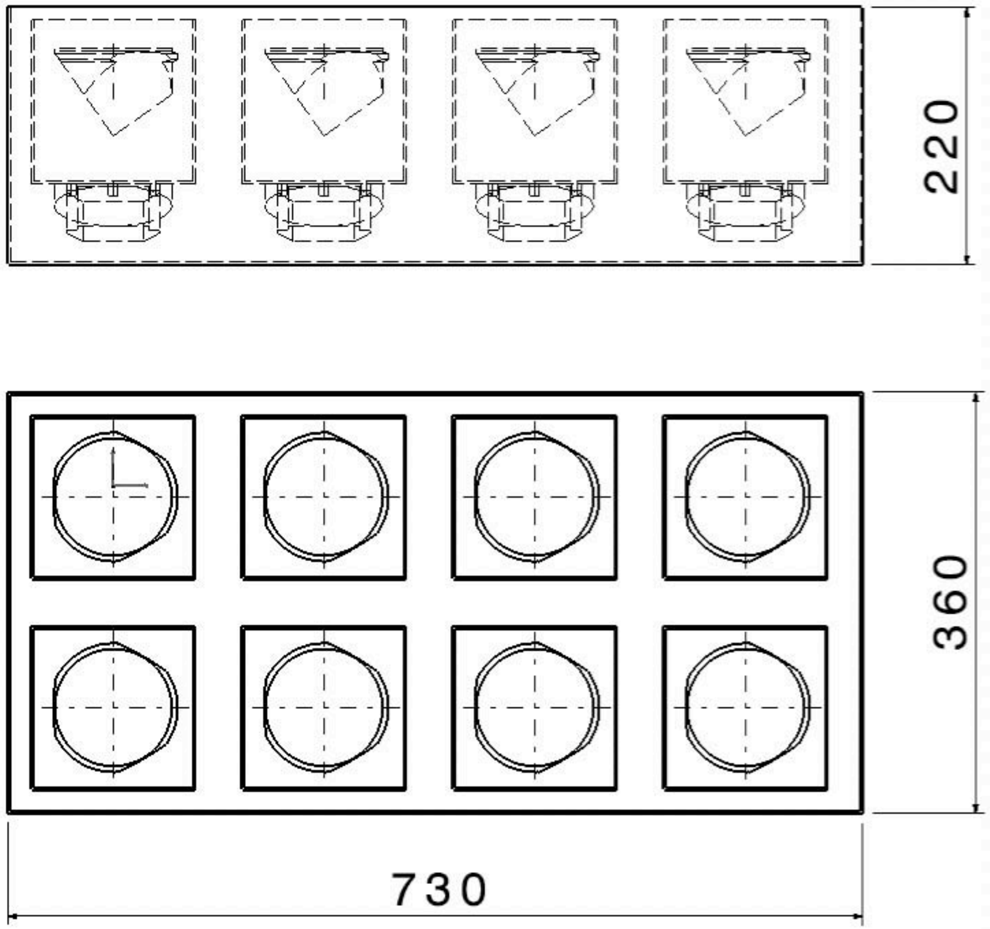
Retro-reflector: 10 cm diam.
Box: 14 cm side



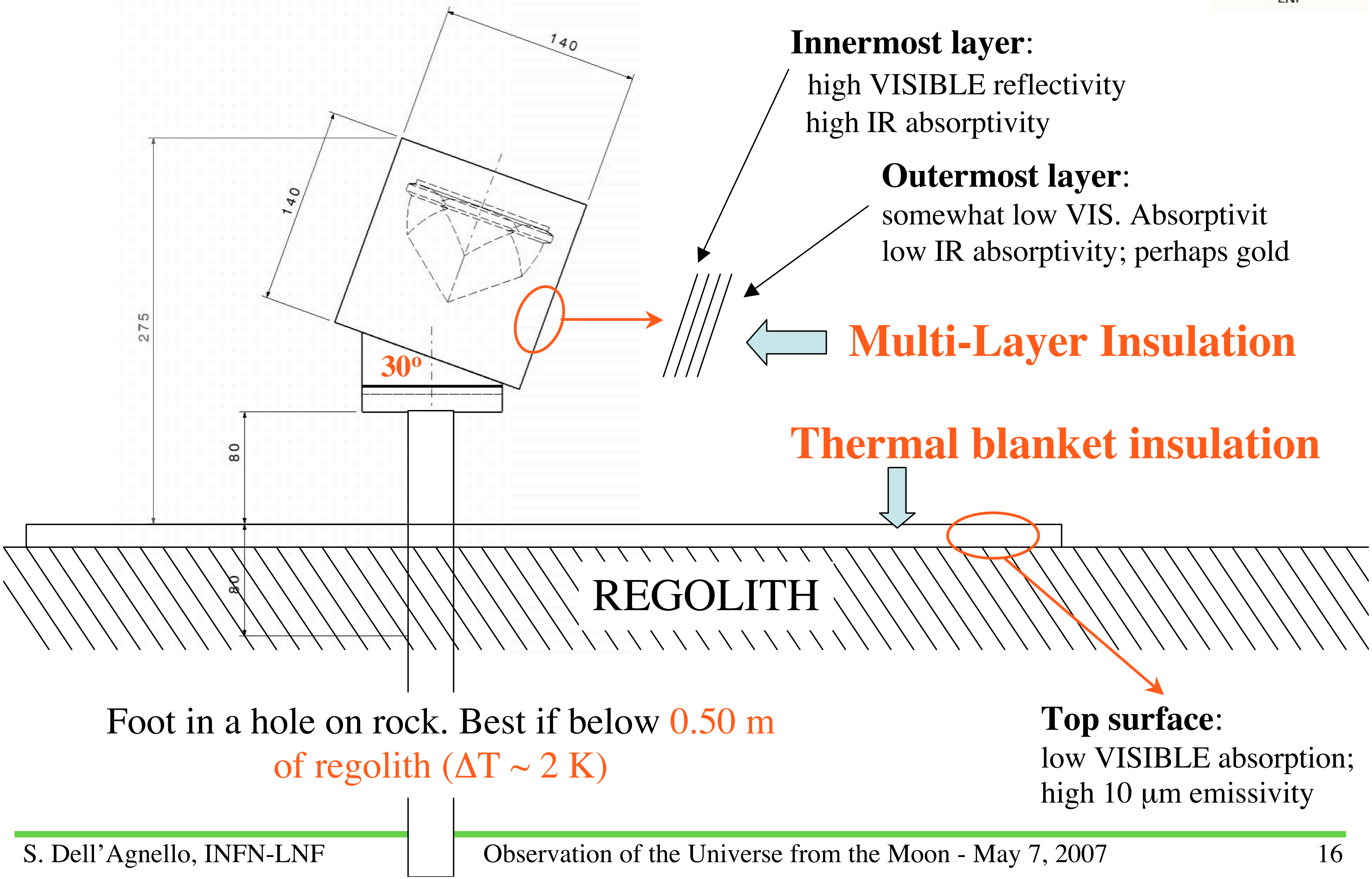
Box locks extremely firmly on a slide

Metal alloy:
INVAR or ULE

Suitcase for the CCR boxes (mm)



Installation on the surface



Mechanics/installation requirements

- CCR boxes
  - Avoid relatively high heat absorption typical of current closed-cavity CCR mounting
    - Semi-open geometry
  - CCR thermally insulated from box
    - KEL-F plastic holder
  - Avoid radiative coupling with Moon surface
    - CCR recessed in the box
- CCR installation
  - Box must lock very tightly and easily on support
    - slide at the top of foot support to ease manned deployment
  - Foot implanted steadily on ~ISOTHERMAL rock
    - beneath ≥ 50 cm regolith
    - like a platform to extract oil at sea
  - Maximize thermal insulation from regolith
    - thermal blanket on the regolith around the foot/box

Drilling by A15/16/17

- Paintings by Alan Bean
  - 4th man on the Moon (Apollo 12, Pete Conrad commander) and Skylab
  - **Unique visual archive**
- Drilling by Dave Scott, commander of A15
  - James Irwin, LEM pilot
  - Heat Flow Experiment

BATTERY-POWERED DRILLING

http://www.alanbeangallery.com/

"When I got the first two borestems in, it was apparent I was hitting something very hard. The first three feet or so was quite easy to drill, and then it was difficult to get it in any further. We'd never seen this in training nor had we ever seen any material that was compacted as hard as this material." Although Dave could not drill either hole to the planned 10-foot depth, the holes were deep enough to allow him to partially insert the temperature sensors.

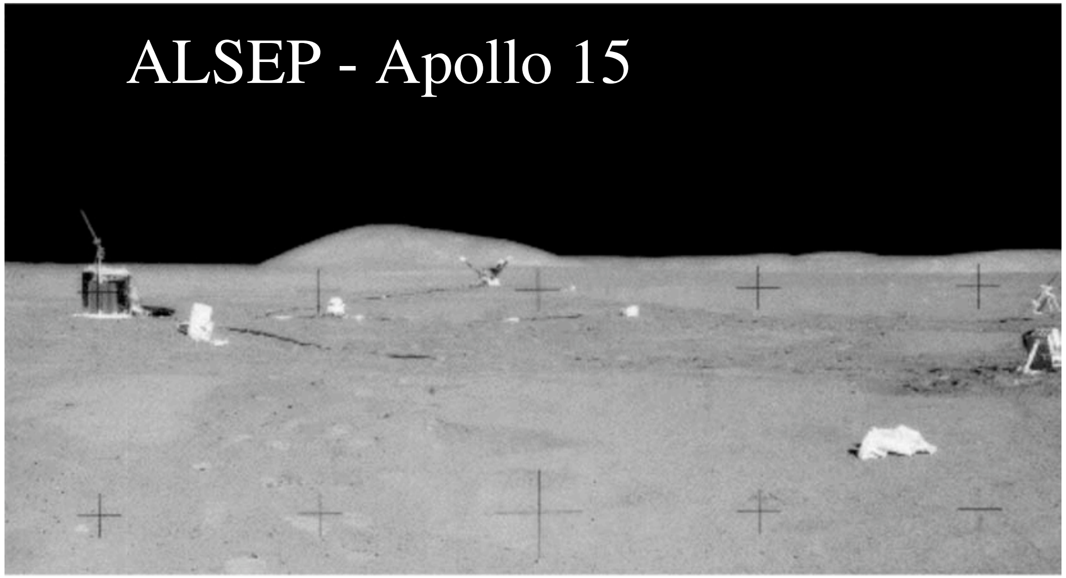
Soil Mechanics Investigation (SMI)

- Painting by Alan Bean
- Experiment by Charles Duke, A16 LM pilot
  - John Young commander
  - **Drilling, 3 m: success !**
- R. Vittori will contact Apollo astronauts if MoonLIGHT-M approved by NASA

The **penetrometer** consists of a metal shaft with a precisely designed cone and movable reference plate on one end and a recording drum on the other. As Charlie pushes in on the drum end, the cone and shaft penetrate the lunar soil, recording the force and the depth. The recorder will be brought back to Earth to better understand the mechanical properties of the lunar soil.

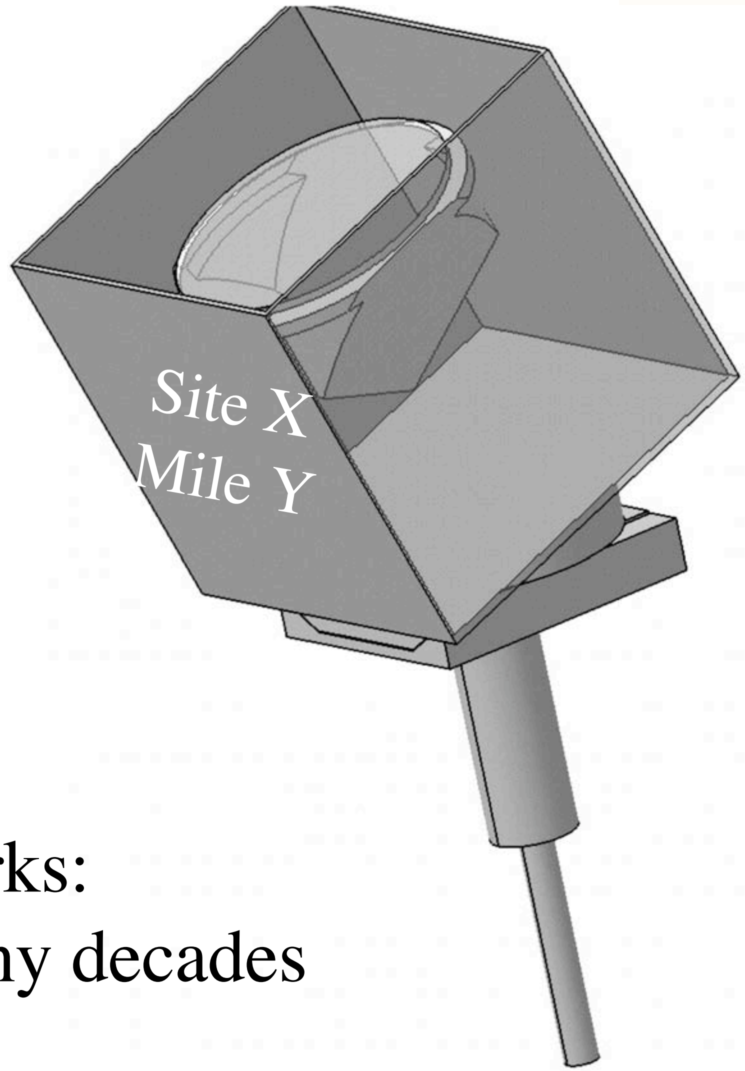
ALSEP reborn ?

- ALSEP = Apollo Lunar Surface Experiment Package
  - combination of experiments taken to a site sufficiently far from the LM
  - central processing station to which all experiments were connected, with telemetry to Earth
  - power by RTGs
- MoonLIGHT CCRs can be used to locate different payloads, telemetry station(s), auxiliary equipment, etc



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 (to come …)
  - Int. Moon Reference Frame

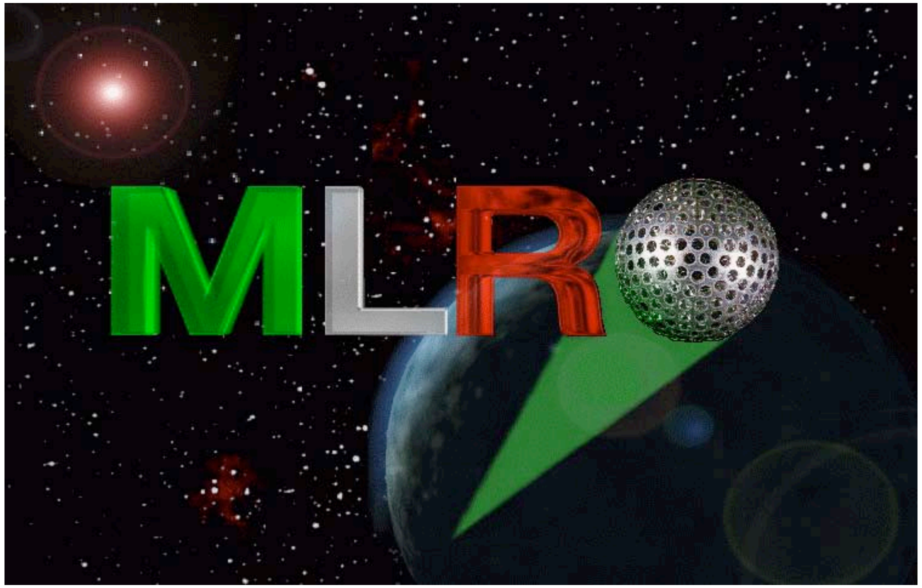


MoonLIGHT landmarks:
light, passive and last for many decades

Everybody should know that …

- The Geo-center (Earth center of mass) is determined mainly with the laser-ranged LAGEOS orbits
- The Scale of Length of the International Terrestrial Reference Frame (ITRF) is determined mainly with the laser-ranged LAGEOS orbits

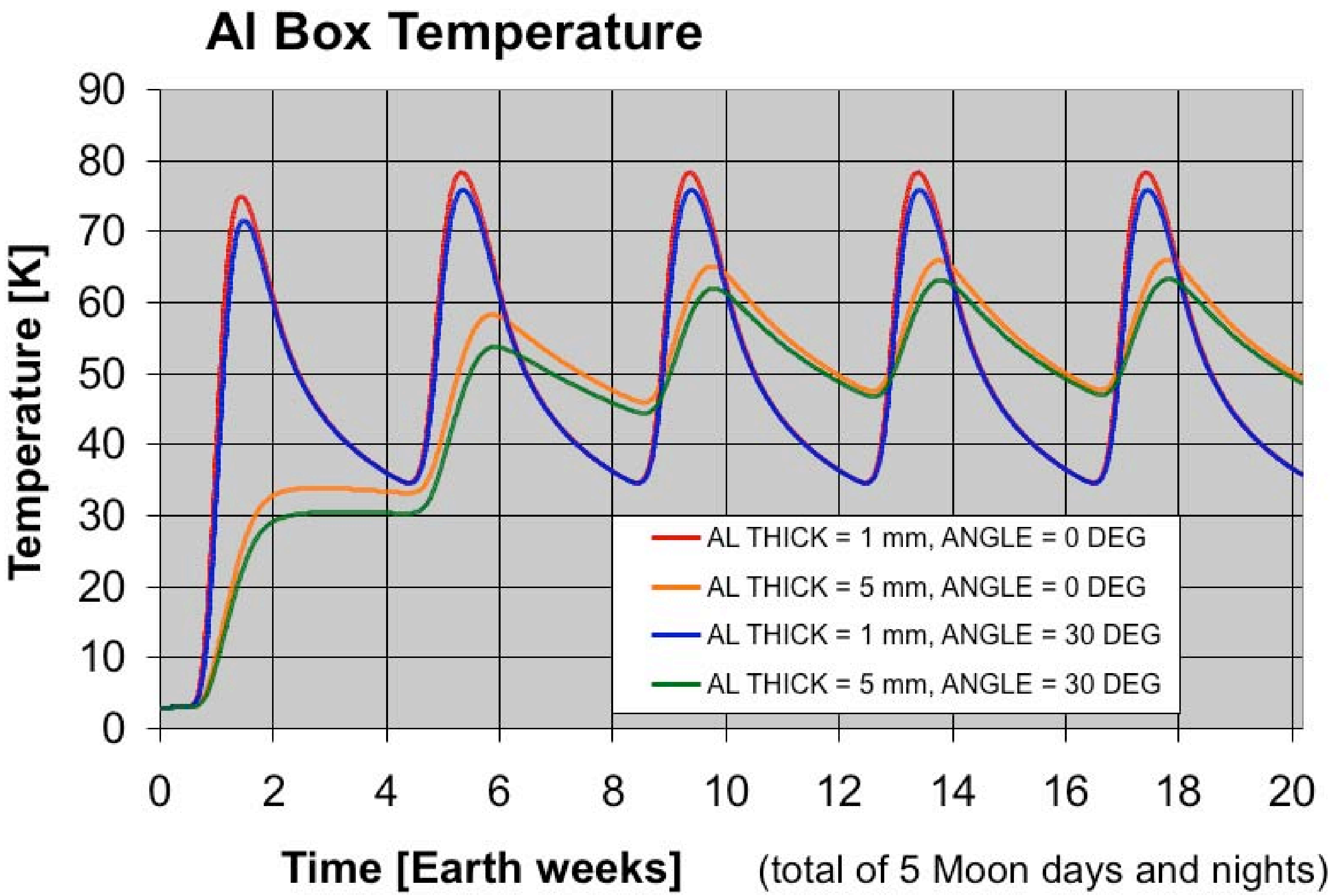
ASI Matera Laser Ranging Observatory



- One of the analysis centers of the Intl. Laser Ranging Service (ILRS) which define the position of the GEO-CENTER is in Matera, the ASI-CGS
  - G. Bianco, V. Luceri, …

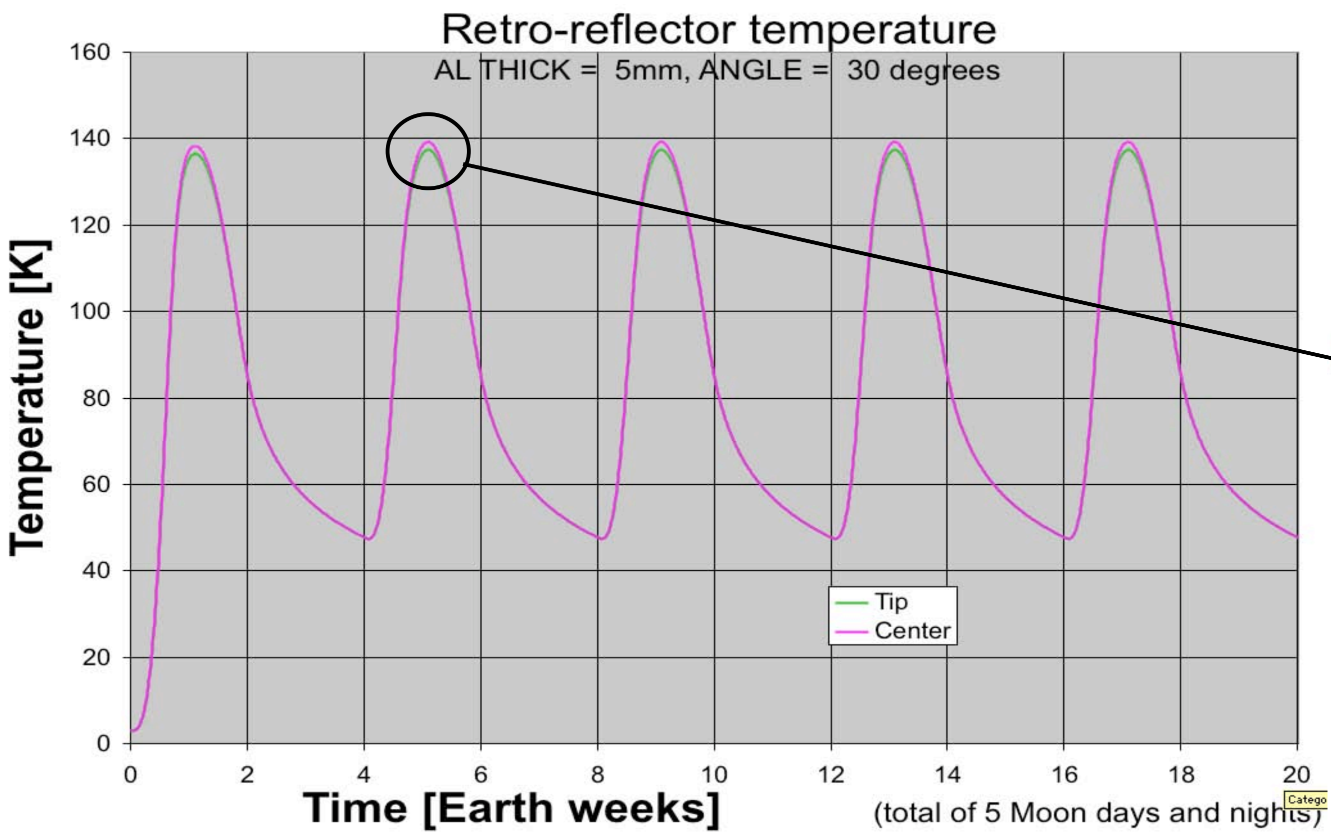
Preliminary thermal analysis: Al box

- Worst case, with Al box temperature floating
  - no thermal link to rock, no MLIs, no ULE …
- Sun illumination: varying intensity, but two fixed angles

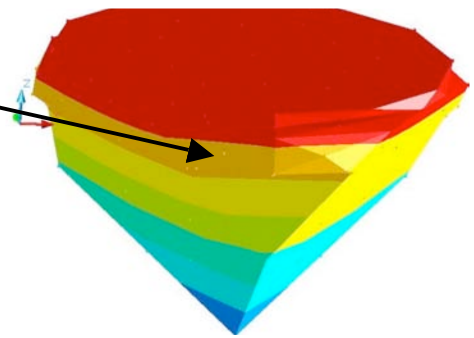


Preliminary thermal analysis: CCR

DESPITE THIS IS THE WORST CASE the thermal CCR conditions are 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)

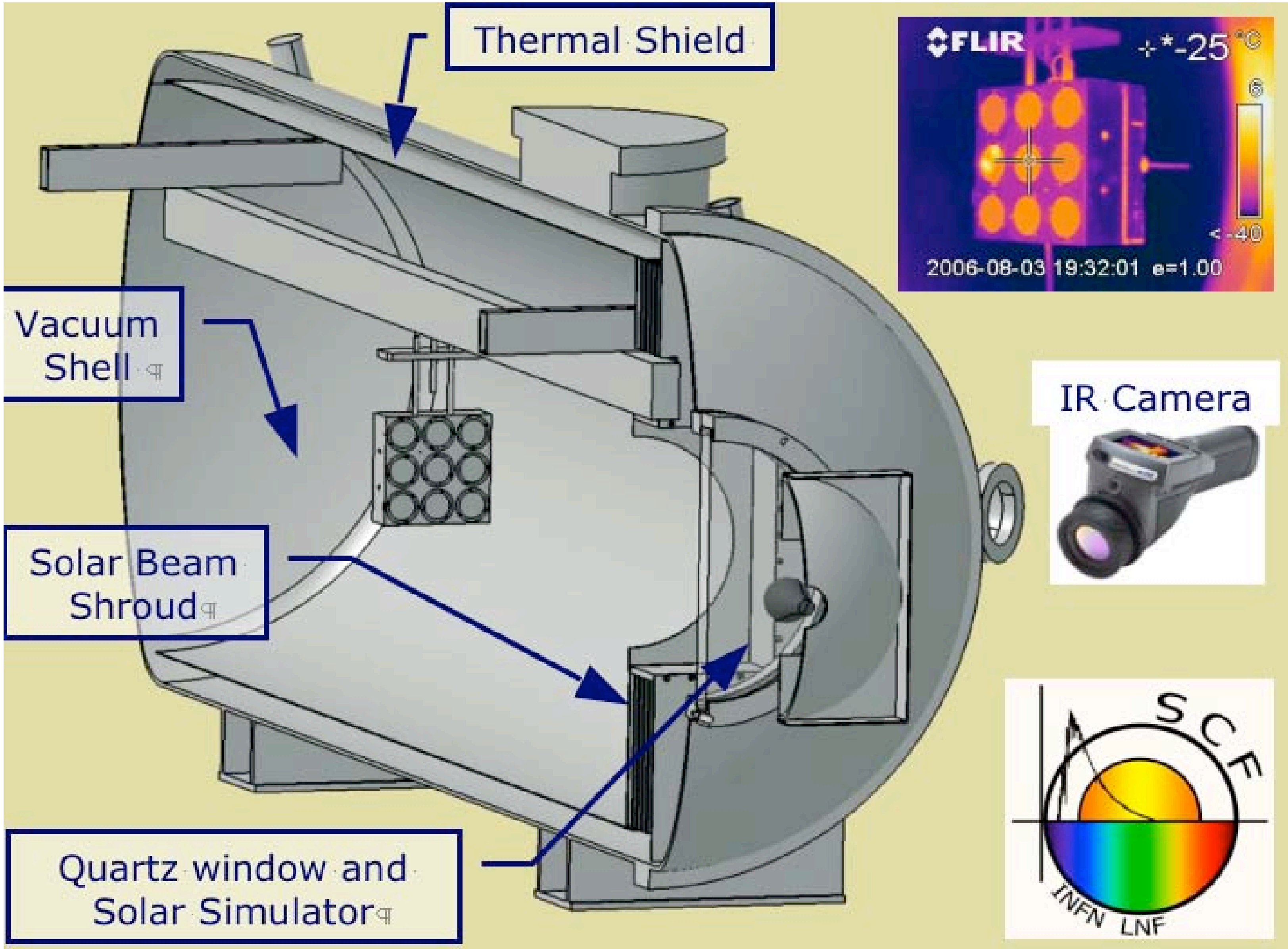


T(center) = 139.2 K



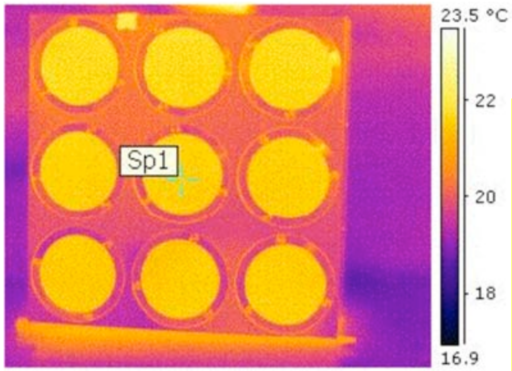
T(tip) = 137.4 K

The INFN-LNF Space Climatic Facility



Satellite laser ranging prototypes at LNF

LNF LAGEOS matrix



NASA LAGEOS
“sector”
sent from Goddard
to LNF for testing at
the SCF

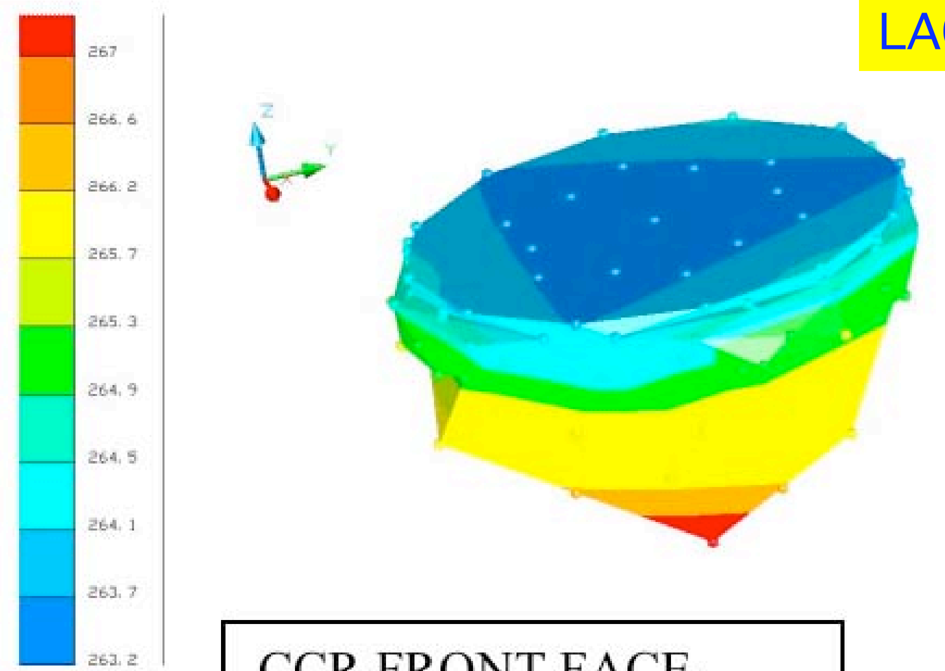
Flight model of CCR
array for the GPS
constellation
Sent by U. of Maryland
and NASA-Goddard for
testing at the SCF

Climatic measurement with Earth simulator

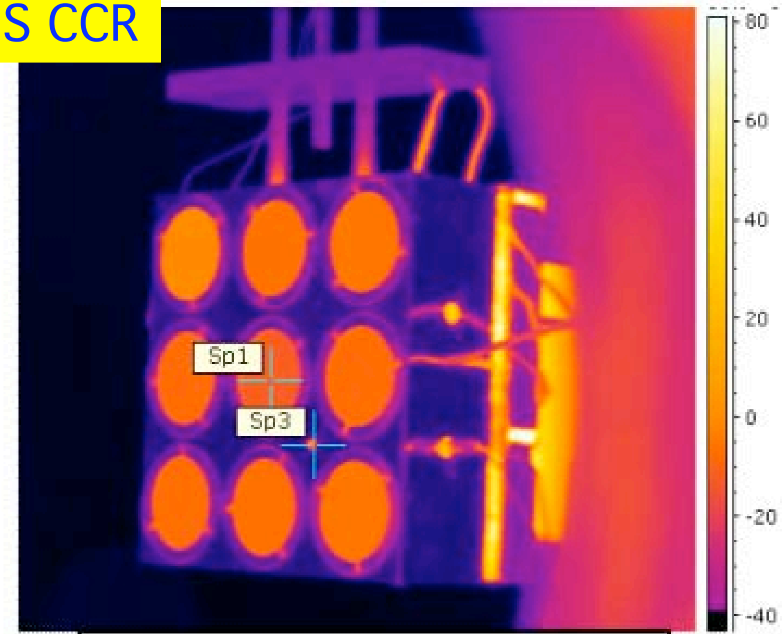
PRELIMINARY

Comparison of IR thermo-optical parameters measured with IR CAMERA (Earth simulator, Sun simulator) VS. software thermal modeling

LAGEOS CCR



CCR FRONT FACE
SIMULATED T = 263 K

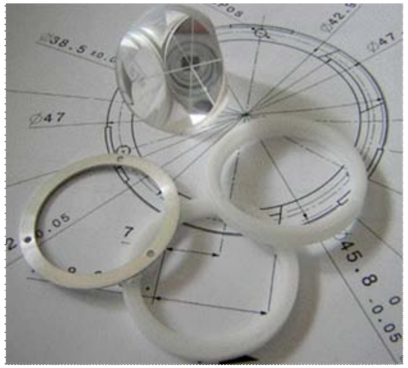


CCR FRONT FACE
MEASURED T = 261 K

The IR camera T-scale was re-calibrated based on these measurements

Climatic measurement w/Sun simulator

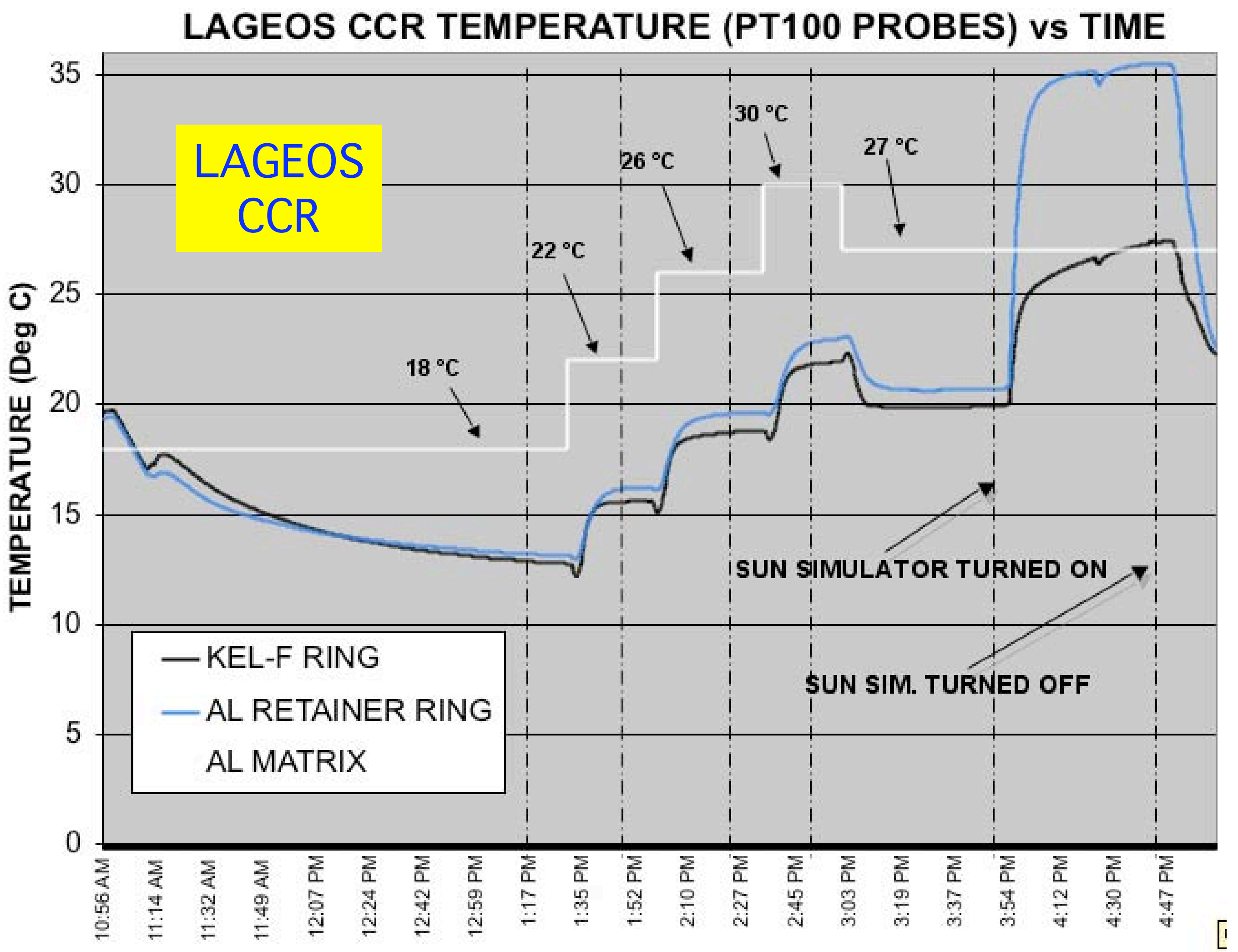
CCR mounting with:
- NASA Al screws and KEL-F plastic rings
- nominal screw torque



Al ring temperature gradient and thermal relaxation time at the Earth eclipse determine thermal thrusts on LAGEOS

Final result will have an impact on the design of LARES

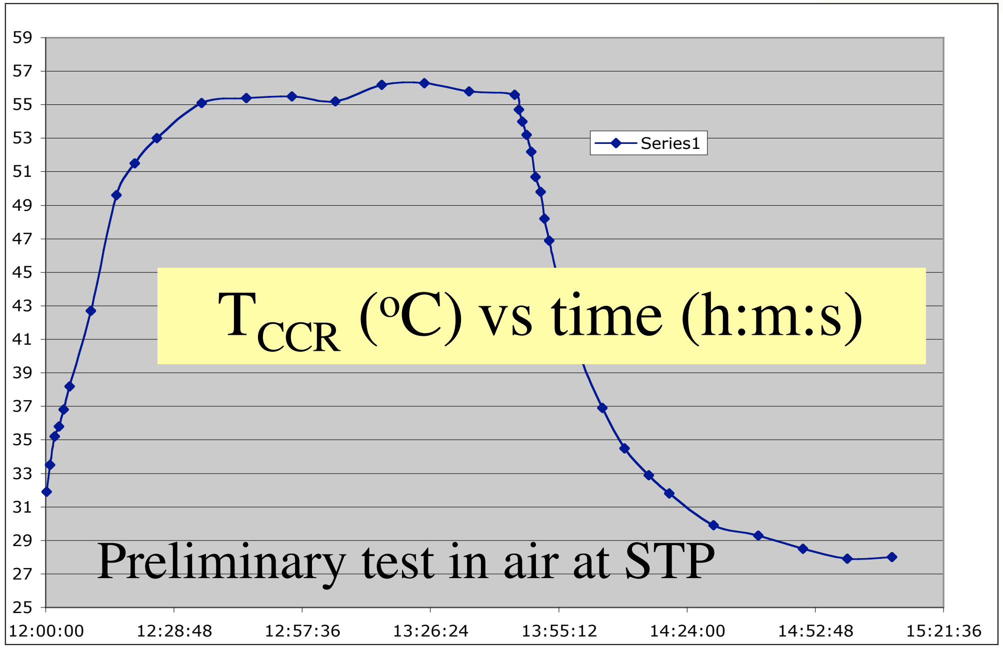
PRELIMINARY

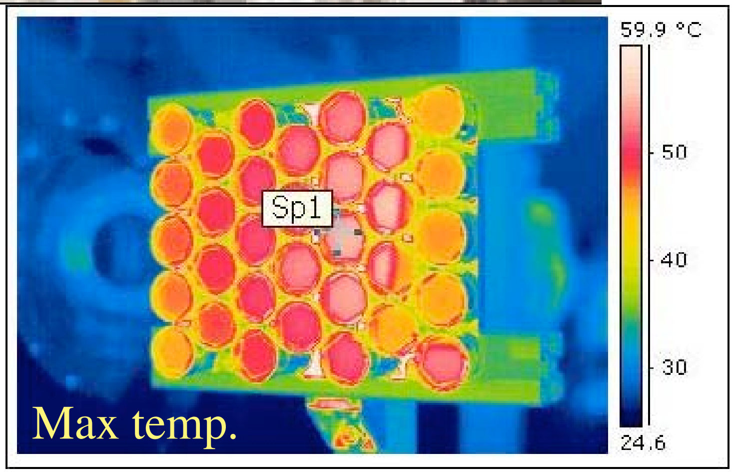


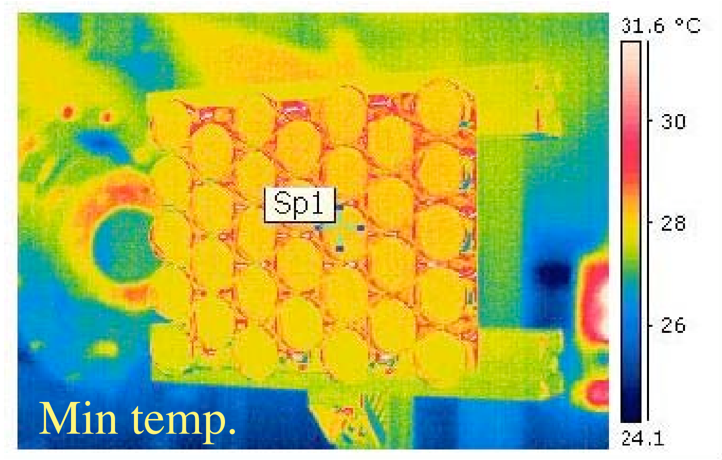
NASA LAGEOS “sector” prototype

- LAser GEOdynamics Satellite
- Prototype property of NASA, Goddard Space Flight Center
- Sent to LNF by GSFC for thermal characterization and laser tests (FFDPs) at the Space Climatic Facility

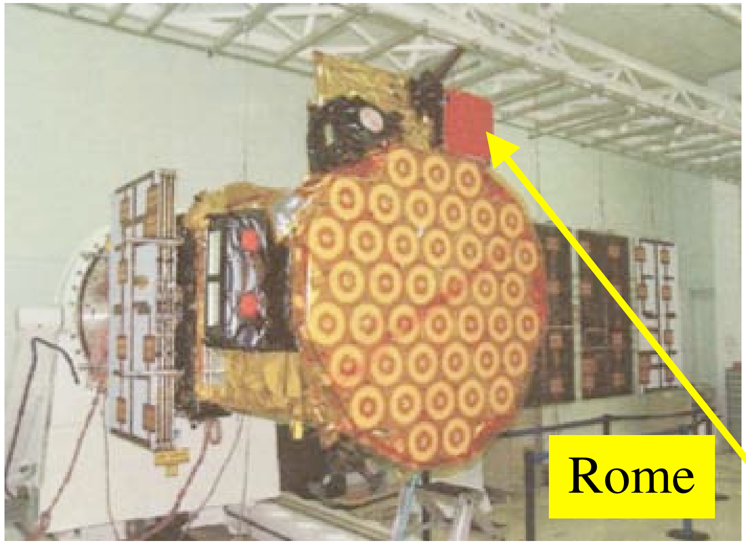
Thermal measurement of GPS flight model







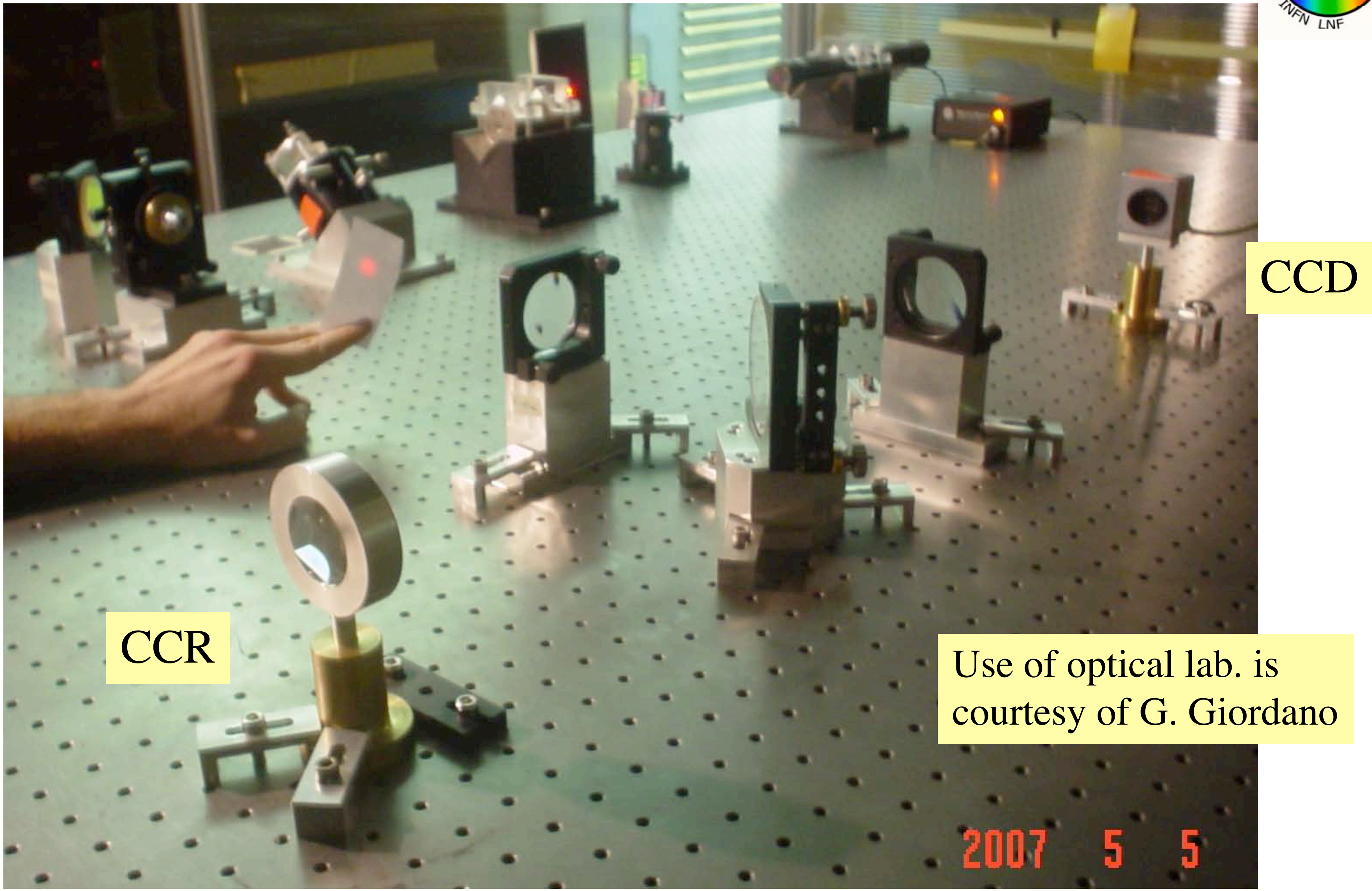
GIOVE-B now at Alcatel Alenia Space, Rome

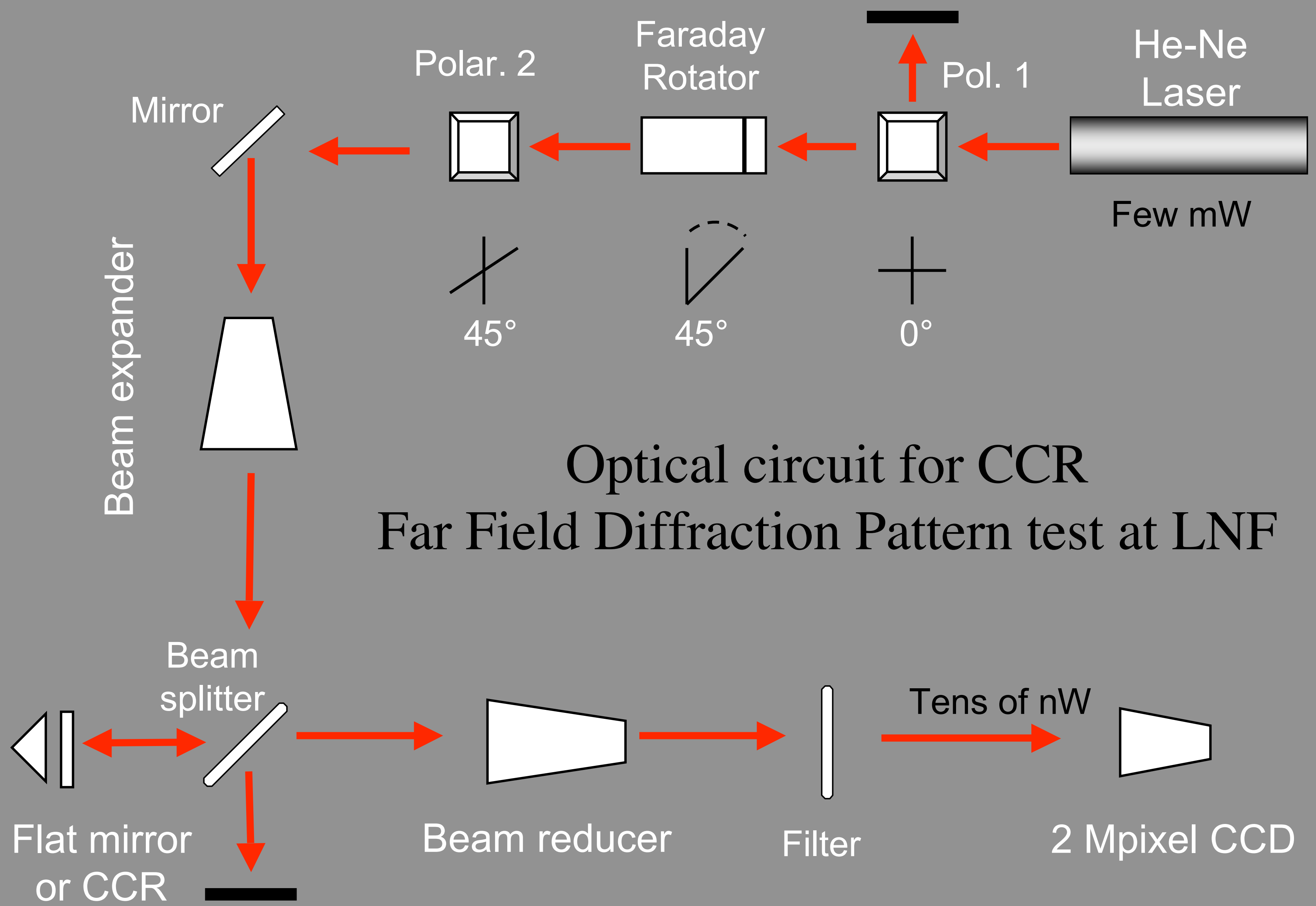


R. Vittori at Alenia, Rome

D. Currie
W/UMD
GPS array
at LNF

Optical measurements (FFDP circuit)



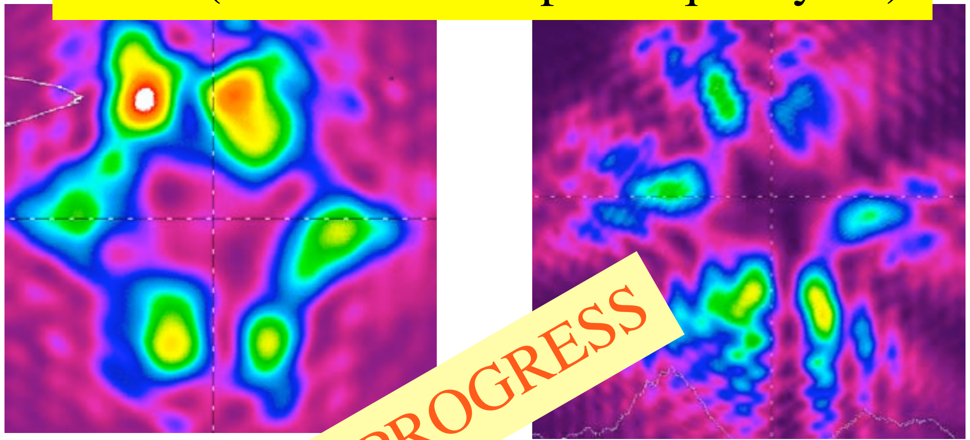


Optical circuit for CCR
Far Field Diffraction Pattern test at LNF

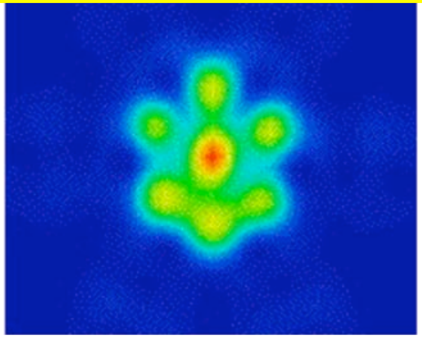
CCR Far Field Diffraction Pattern (FFDP)

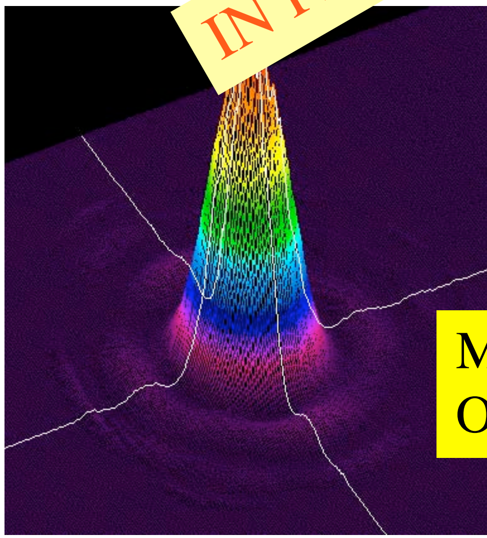
- "Optical FLAT" (mirror) for normalization
- FFDP measured by 2 CCDs as laser profilers, readout via firewire
- Repeat with CCR inside SCF with integrated thermal and laser measurements

Measured LAGEOS FFDPs - at STP, so far (CCRs of low optical quality …)



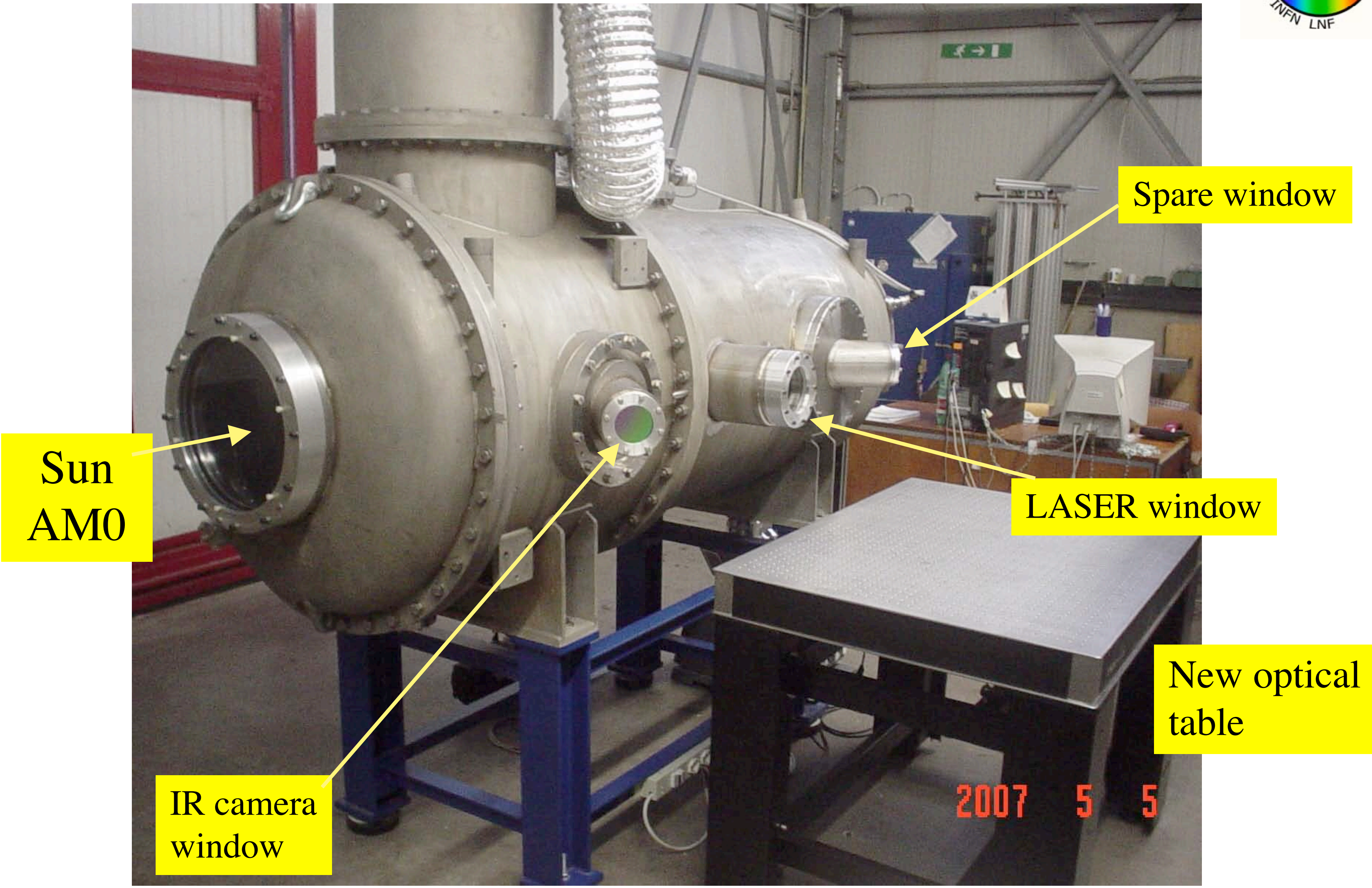
LAGEOS FFDP simulated with CodeV (typical 6-lobe pattern)





Measured FFDP Of optical flat

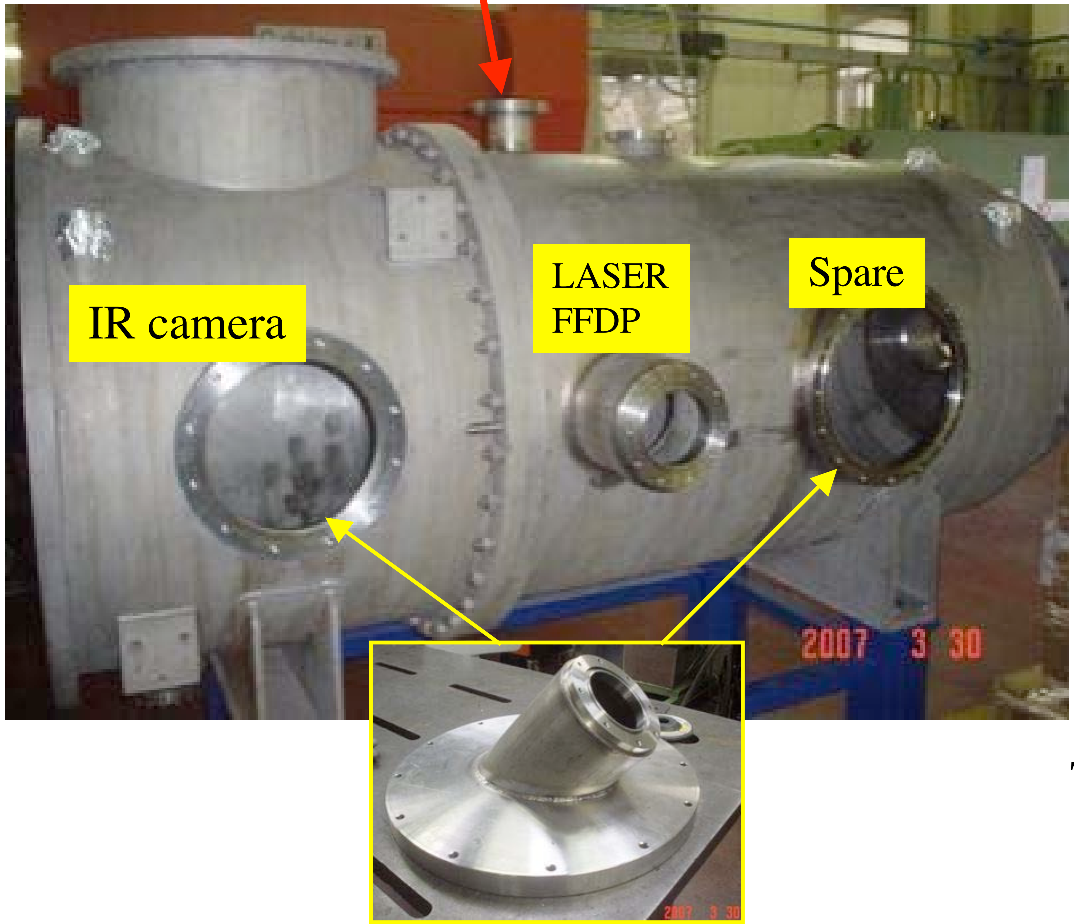
SCF upgraded for optical tests

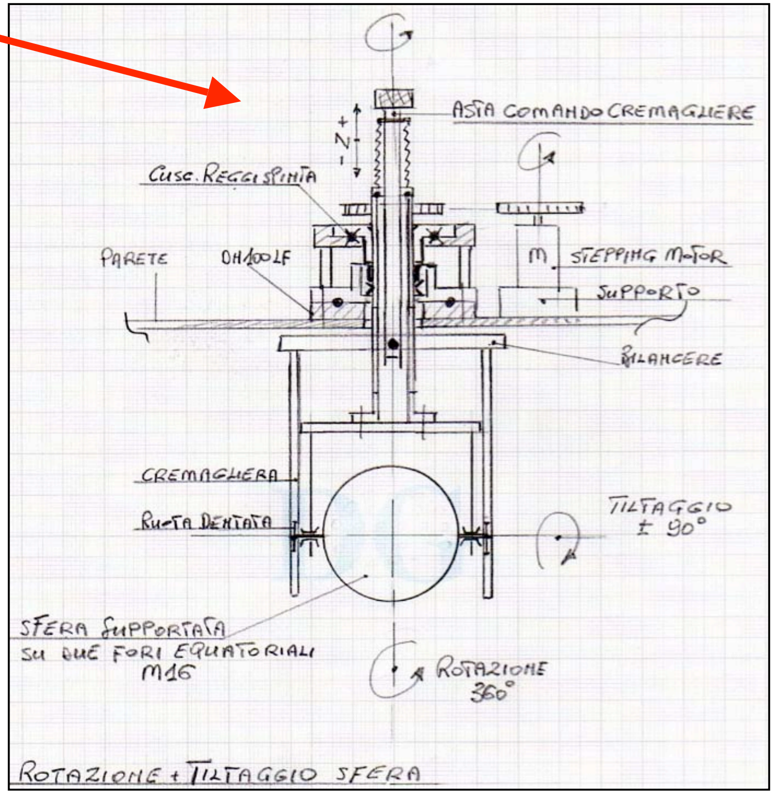


SCF upgrade for laser tests

Rotation and tilt movement from top flange

External motor. Additional external support for heavy loads (LARES is 100 Kg or more)

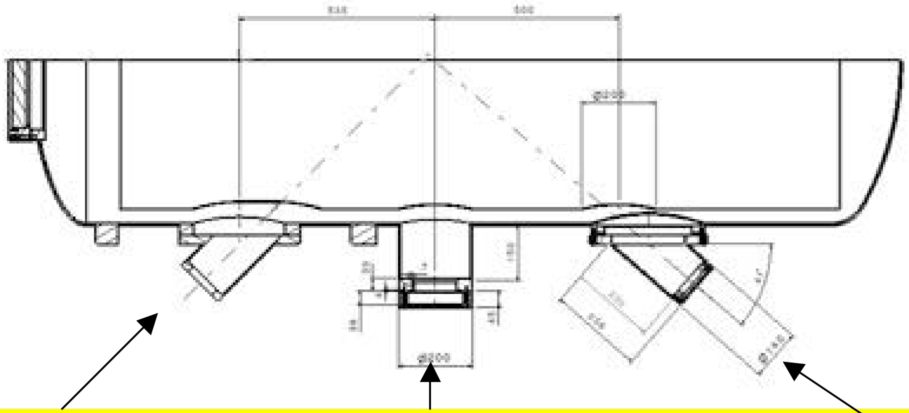




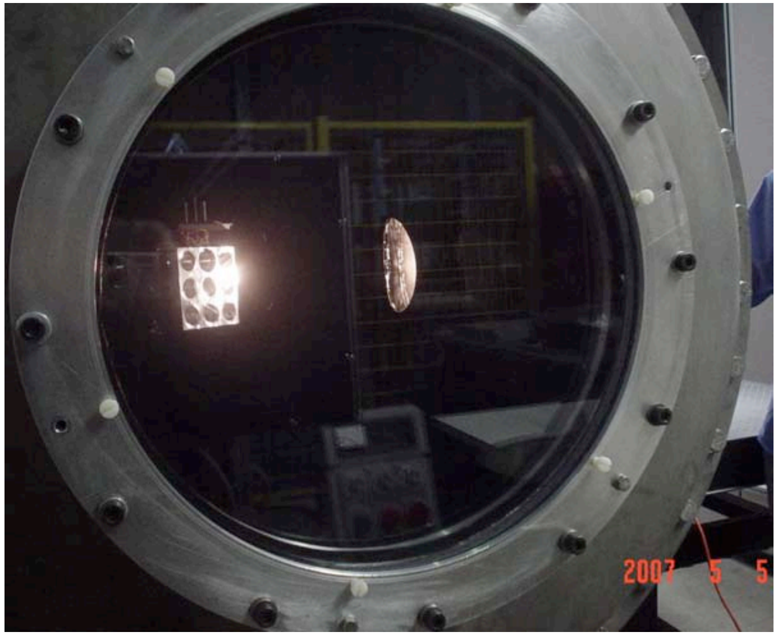
Translations for GNSS planar arrays might need an internal motor. To be done

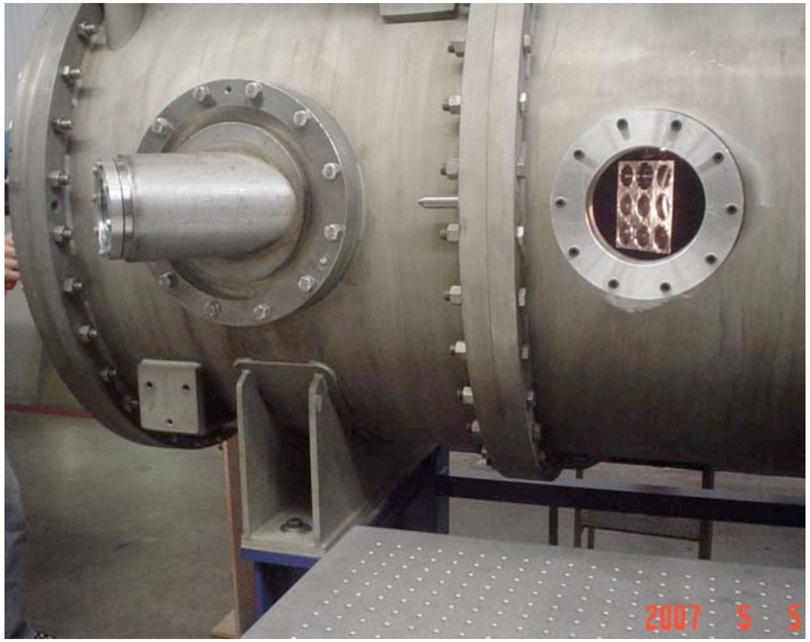
Integrated thermal and optical tests

1) **Sun AM0**
2) **IR camera**
3) **Rotation/tilt**
4) **Laser FFDP**



Windows: IR camera laser FFDP Spare





SLR/LLR P/L characterization at the SCF

- Space climatic **thermal** test and **laser ranging** tests
  - Far Field Diffraction Pattern (FFDP) now
  - Timing tests (actual measurement of time/distance) later

- We recently upgraded the SCF for this
  - Optical table next to SCF, new optical window (λ/20 TWF)
  - **Ultimate measurement:** Far Field Diffraction Pattern of each CCR in varying space climatic conditions
  - FFDP simulations with CodeV
  - Will try integration of CodeV with thermal software
  - For LLR will use a He-based cryo-cooler to lower the SCF internal temperature from current T(LN2) to ~10 K

Challenges at LLR accuracies of 1 mm and below

1) WHAT WE DISCUSSED TODAY

- Optical/Thermal/Mechanical Design of Package
  - This is in progress
  - Initial Analysis is Very Favorable
- Diurnal Thermal Motion of Regolith
  - Very Preliminary Analysis is Quite Favorable

2) WHAT NEEDS TO BE ADDRESSED

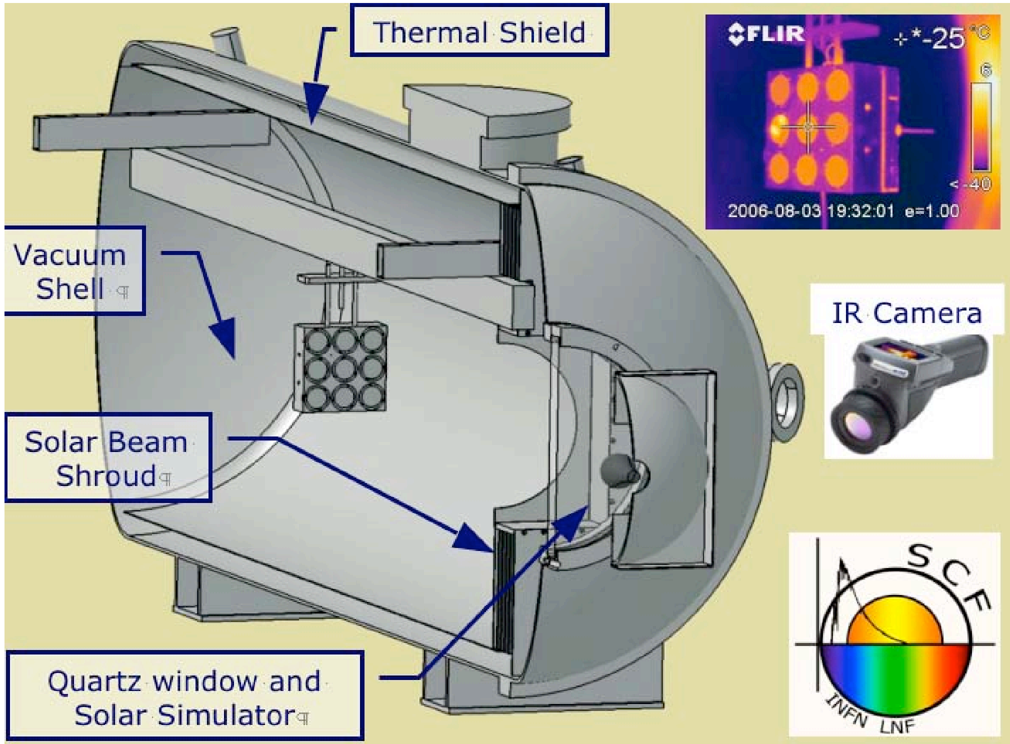
- Irregular Motions of the Earth's Surface
  - Ocean Loading, Atmospheric Loading etc.
  - Difficult – One Possible Solution will be Investigated
- Delay in Earth's Atmosphere
  - Weather Gradients, Wind Effects
  - Difficult – One Possible Solution will be Investigated
- By whom ? Us, you, the Intl. Geodesy community, the ILRS (!!) …

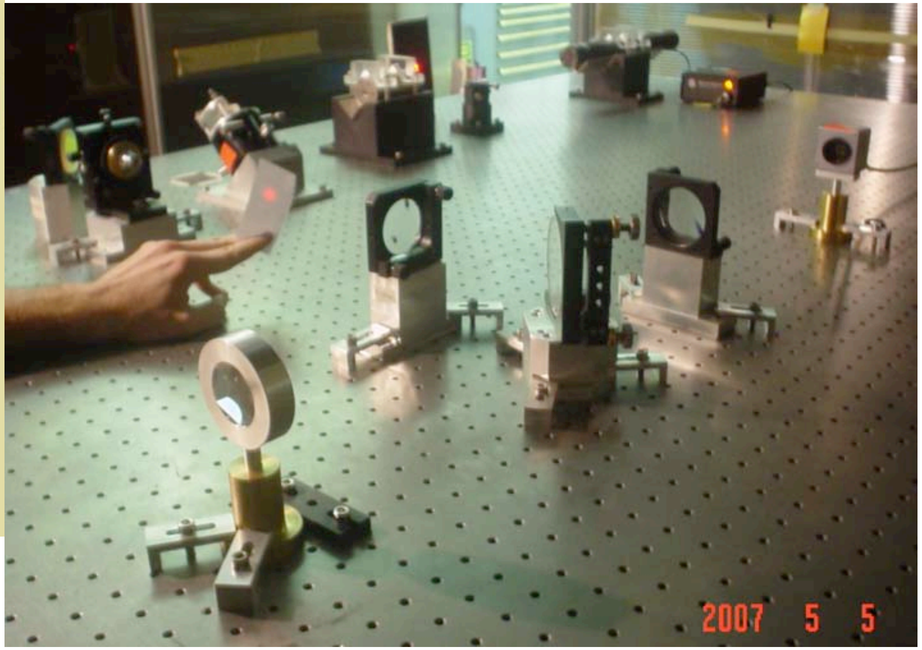
REMEMBER: we do not claim to solve all problems at once. We meant to provide a winning tool for progressive and relentless improvement of LLR in the next few decades, just like it happened for 1st generation LLR

Conclusions and prospects

- Well defined goals of Gravitation science
  - Several accurate tests of General Relativity
  - Full-test of String-inspired (mem)Brane World model
    - "The accelerated universe and the Moon" (Dvali's modified Gravity)
- Moon exploration
  - Standard passive Moon "land-marks" and P/L locators
- First-pass P/L design
  - **preliminary thermal simulations by LNF**
  - **preliminary scheme for manned deployment by R. Vittori**
- Thermal and laser tests at the LNF Space Climatic Facility
- Industrial Partners
  - Mechanic, installation, "Suitecase"
- Possible synergic effort with NASA
  - RTP proposal on manned version, MoonLIGHT-M

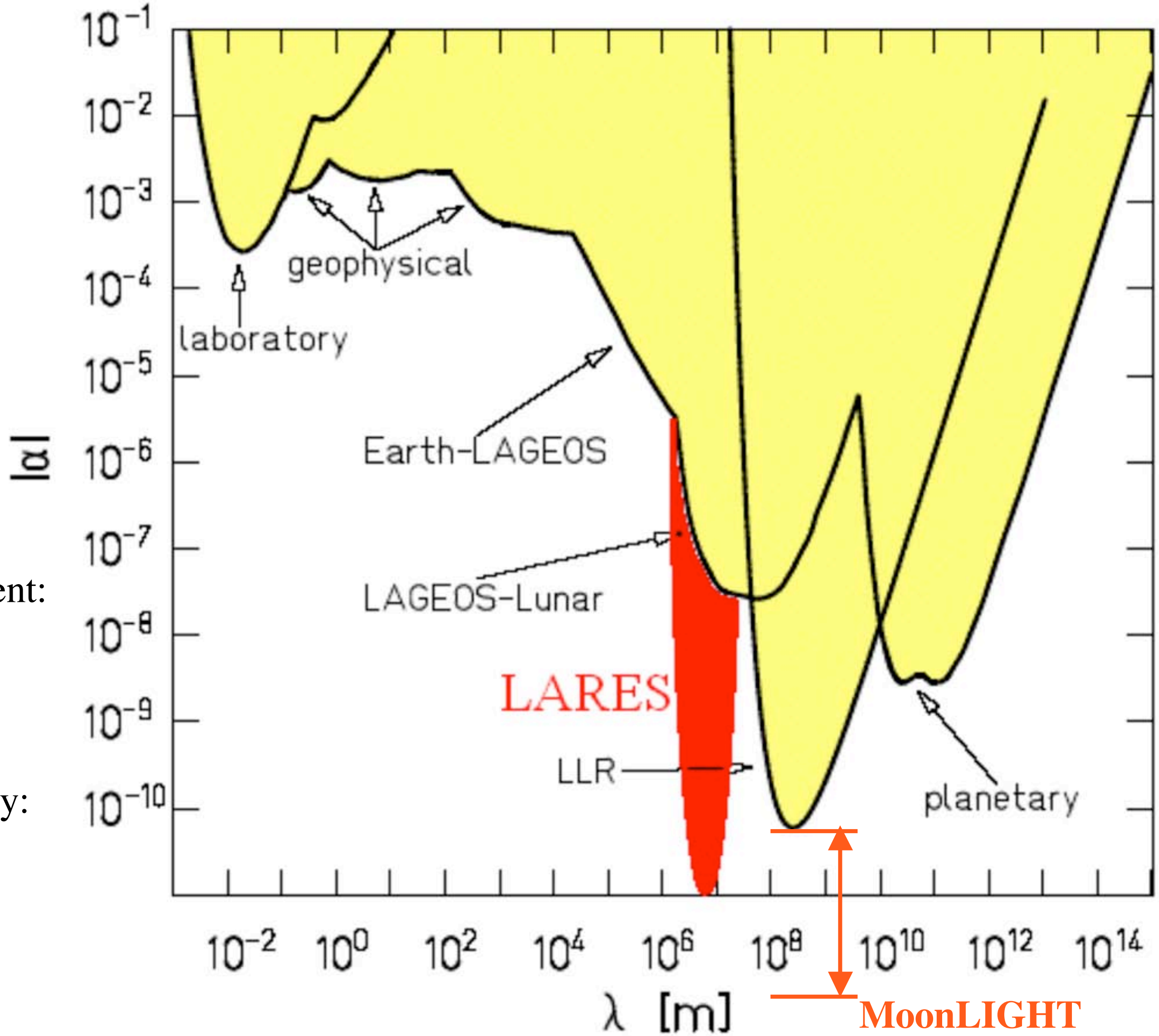
You’re welcome to visit SCF and optical lab

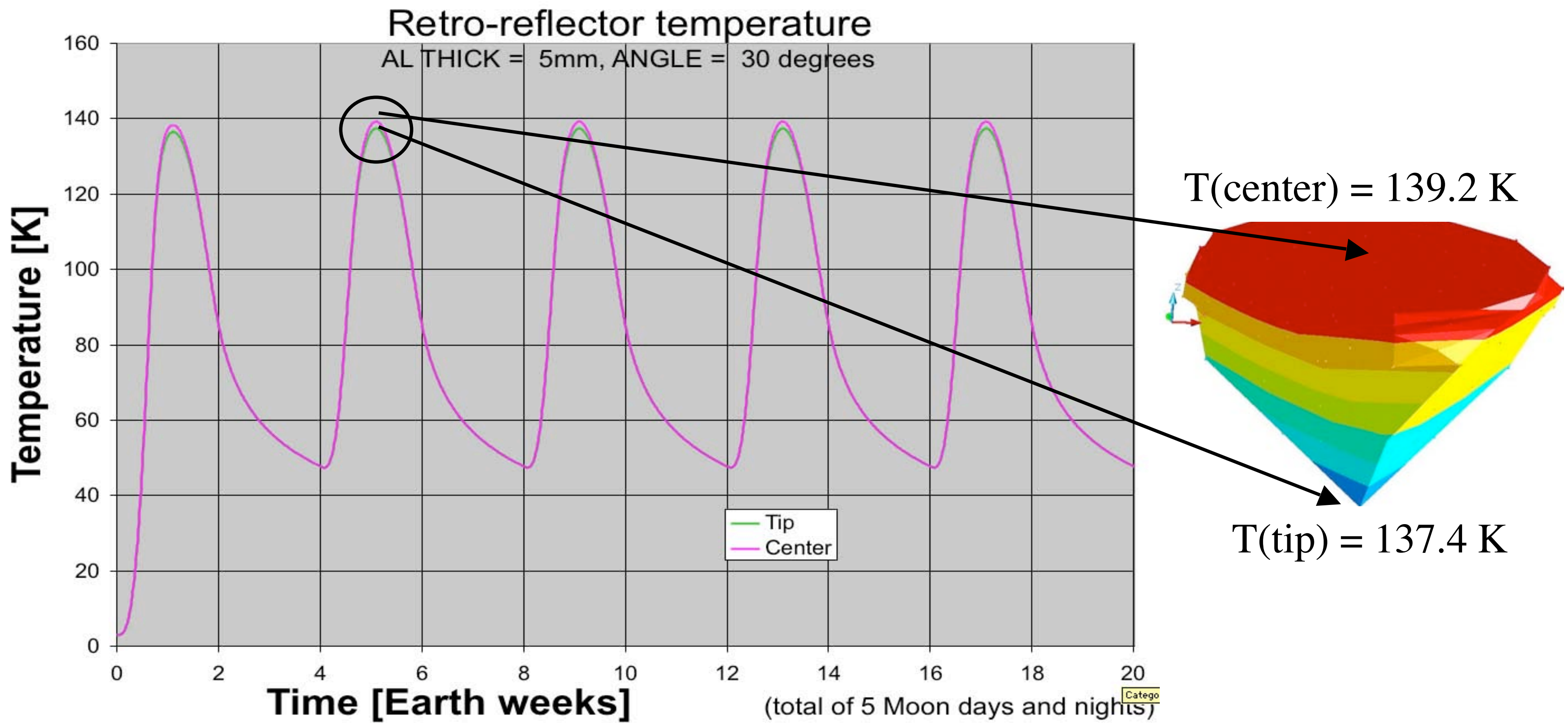




LARES improvement:
source I. Ciufolini

LLR improvement
w/MoonLIGHT array:
source T. Murphy




Retro-reflector temperature
AL THICK = 5mm, ANGLE = 30 degrees
Temperature [K]
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
Time [Earth weeks]
(total of 5 Moon days and nights)
Tip
Center
T(center) = 139.2 K
T(tip) = 137.4 K

Installation on the surface