Status of the LLRRA21/MoonLIGHT NASA LSSO Project

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Contributors

Ken Nordtvelt - Relativity and Cosmology Aspects
Jack Schmidt - Astronaut Cap. on Lunar Surface – esp. Drilling
Pippo Bianco - Lunar Laser Ranging Techniques – ASI/MLRO
Gia Dvali - Dark Energy & Role of Lunar Laser Ranging

ILRS International Workshop, Poznan, Poland, October 2008

Outline

- LLRRA21/MoonLIGHT:
  - Physics reach with 2nd generation Lunar Laser Ranging
  - Development of a new payload for NASA LSSO
  - Payload testing at the INFN "Satellite/lunar laser ranging Characterization Facility (SCF)"
  - Candidate for the International Lunar Network (ILN)

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

LLRRA21

An Approved NASA Project

Lunar Sortie Scientific Opportunities

NASA Lunar Science Institute

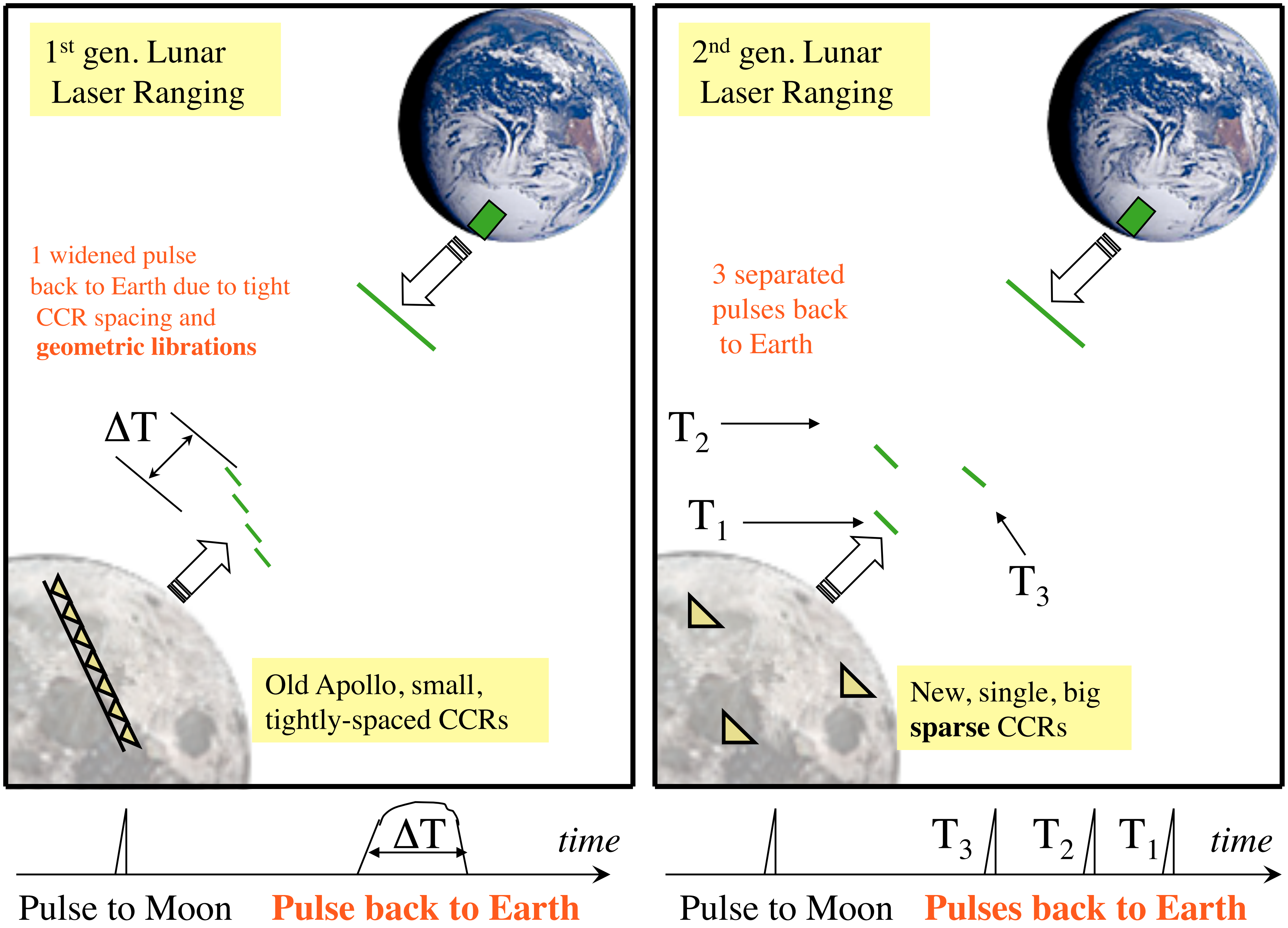
Moon Laser Instrumentation for High-accuracy General relativity Tests

MoonLIGHT

Supported by INFN-LNF

and by the 2007 ASI Lunar Study

Observation of the Universe from the Moon


1st gen. Lunar Laser Ranging
1 widened pulse back to Earth due to tight CCR spacing and **geometric librations**
ΔT
Old Apollo, small, tightly-spaced CCRs
ΔT
time
Pulse to Moon
Pulse back to Earth
2nd gen. Lunar Laser Ranging
3 separated pulses back to Earth
T2
T1
T3
New, single, big **sparse** CCRs
T3
T2
T1
time
Pulse to Moon
Pulses back to Earth

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

LLR data triggered 2000 papers 10000 refs

Table by T. Murphy

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

"BraNe new world": a quantum theory beyond GR

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.

- G. Dvali et al, PRD 68, 024012 (2003)
- Weak gravity; explains apparent universe acceleration without Dark Energy
- Gives anomalous precession of the Moon of **~ 1 mm/orbit**, in addition to geodetic precession of GR, which is **3m/orbit**
- LLR accuracy now **~cm**. New laser station APOLLO is achieving **< 1 cm**
- Confirm or deny with 10% experiment, that is, with **100 μm** LLR accuracy

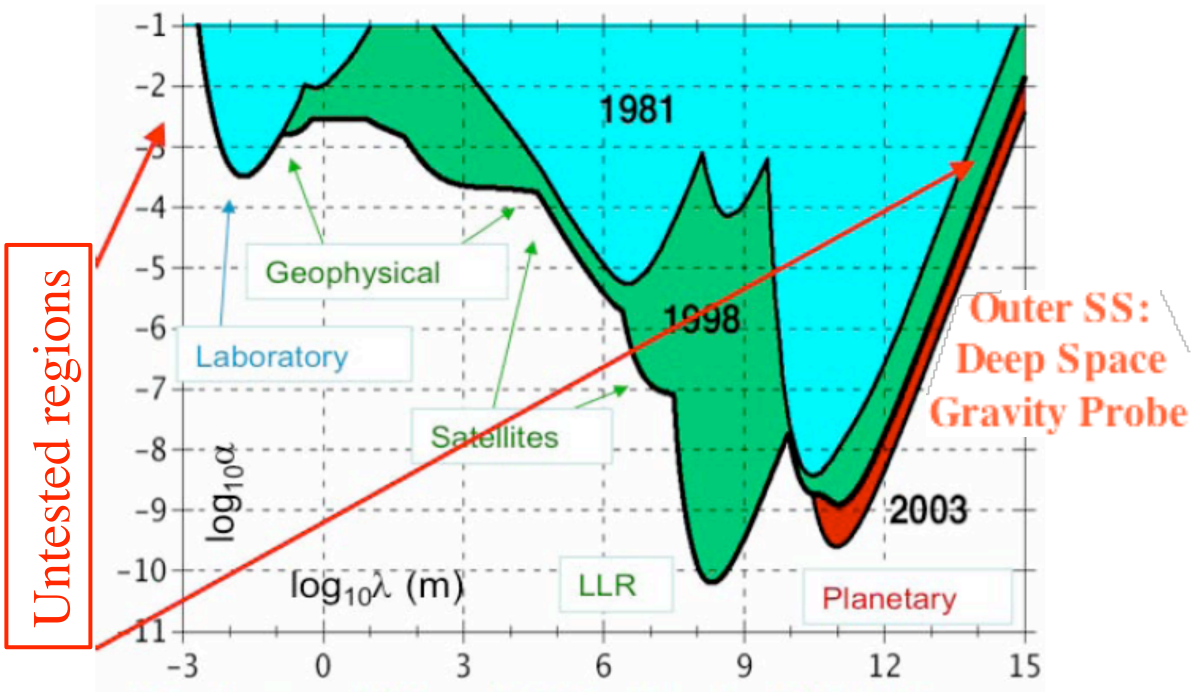
Limits on non-newtonian gravity in the Solar System

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

MoonLIGHT designed to provide accuracy of 100 μm 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 provide an improvement from ~10^{-10} to 10^{-12}.

Replacement of the Apollo CCRs with MoonLIGHT is a prerequisite to improve LLR



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

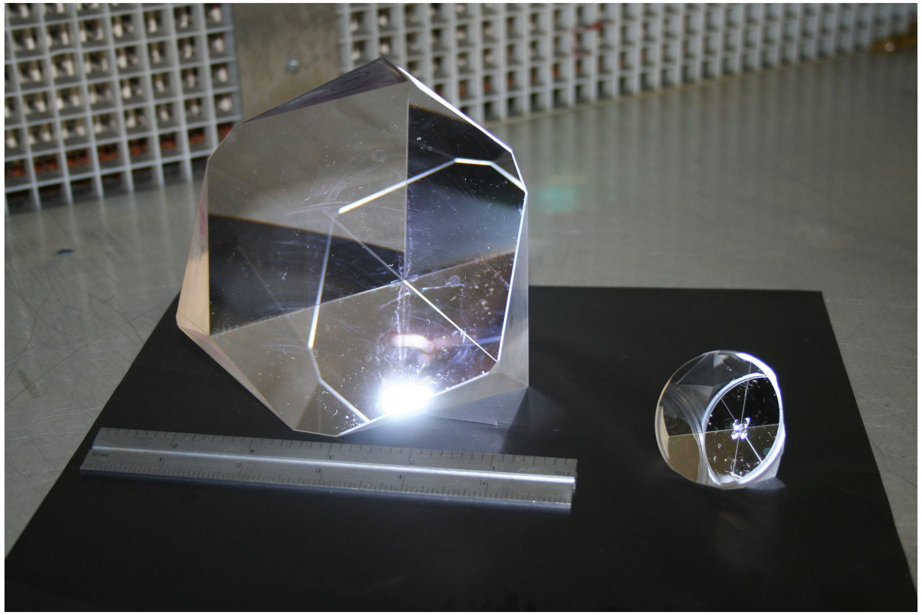
TECHNICAL CHALLENGES

- Fabrication of the CCR to Required Tolerances
- Thermal Distortion of Optical Performance
  - Absorption of Solar Radiation within the CCR
  - Mount Conductance - Between Housing and CCR
  - Pocket Radiation - Heat Exchange with Housing
  - Solar Breakthrough - Due to Failure of TIR
- Sufficient Return for Reasonable Operation
  - Ideal Case for Link Equation
- Stability of Lunar Surface Emplacement
  - Problem of Regolith Heating and Expansion
  - Drilling to Stable Layer for CCR Support
  - Thermal Blanket to Isolate Support
  - Housing Design to Minimize Thermal Expansion

CCR FABRICATION CHALLENGE

Results from Proto-CCR

- CCR Fabrication Using SupraSil 1 Completed
- Specifications / Actual
  - Clear Aperture Diameter - 100 mm / 100 mm
  - Mechanical Configuration - Expansion of Our APOLLO
  - Wave Front Error –
    - Specification 0.25 waves
    - **Measured 0.15 waves**
  - Offset Angles
    - **0.00, 0.00, 0.00 +/-0.20 /**
    - **0.18, 0.15, 0.07**
- Flight Qualified
  - with Certification

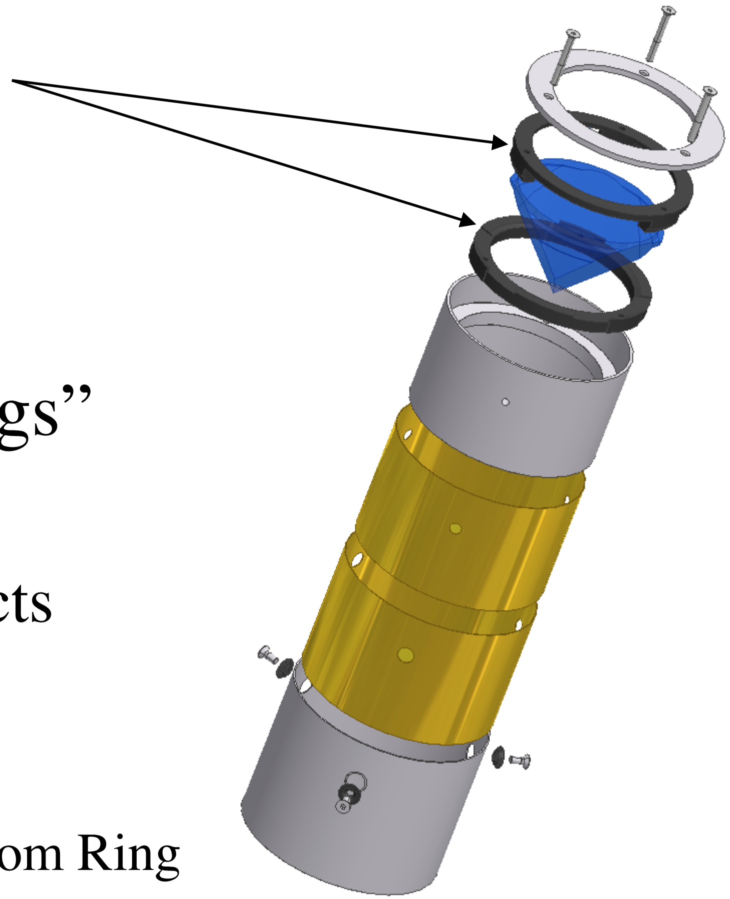


INTUTIVE LINK EQUATION

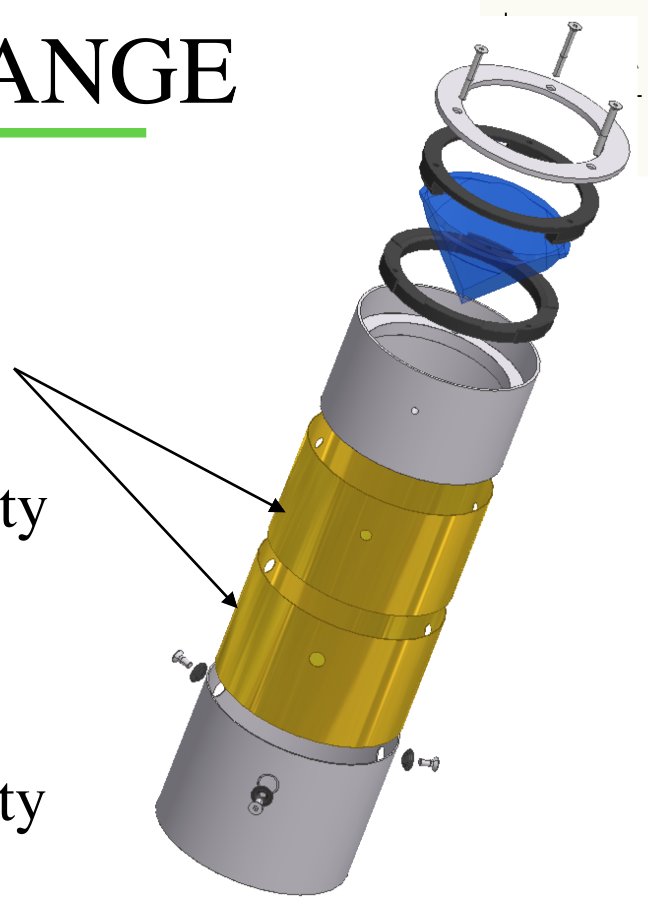
- **Laser Return Strength Goes as D^4**
  - On-Axis – That is, No Velocity Aberration
  - Iso-Thermal – That is, No Thermal Distortion
- **Ratio $(100mm/38.1mm)^4 = 47.5$**
- **Single 100 mm CCR = 49 APOLLO CCRs**
- **Therefore ~½ return of APOLLO 11 & 14 Arrays**
  - Current APOLLO Station "Always" Gets More than 60 Returns
  - We Expect >15 Returns for Most Observations - Plenty
  - Allows for Any Degradation that May Have Occurred for APOLLO

MOUNT CONDUCTANCE

- Challenge:
  - Heat flow from Housing to CCR
  - Optical Distortion due to Heat Flux
- Support of CCR with KEL-F "Rings"
  - Intrinsic Low Conductivity
  - Use of Inserts with Only Line Contacts
    - Line Support Reduces Heat Flow
  - Supports Launch Environment
    - Wire Compresses and Support Comes from Ring
- Estimated (to be Validated in SCF) 0.1 Milli-W/^{o}K



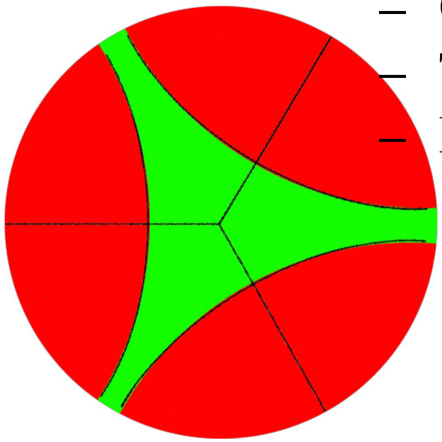
POCKET RADIATION EXCHANGE

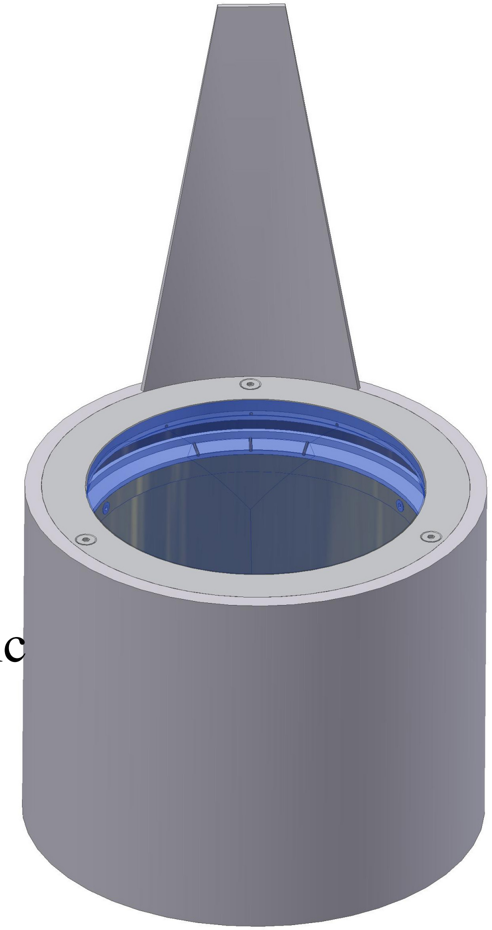


- Challenge:
  - Radiation Between CCR & Housing
  - SiO_2 Has High IR Absorptivity/Emissivity
  - Heat Flux Causes Optical Distortion
- Isolation Between CCR and Housing
  - Low Emissivity Coatings – 2% Emissivity
  - Successive Cans or Multiple Layers
- Simulation Indicates Isolation is Effective
- Thermal Vacuum Chamber Validation - Partial
  - Started In September at SCF at INFN-LNF in Frascati

SOLAR BREAKTHROUGH

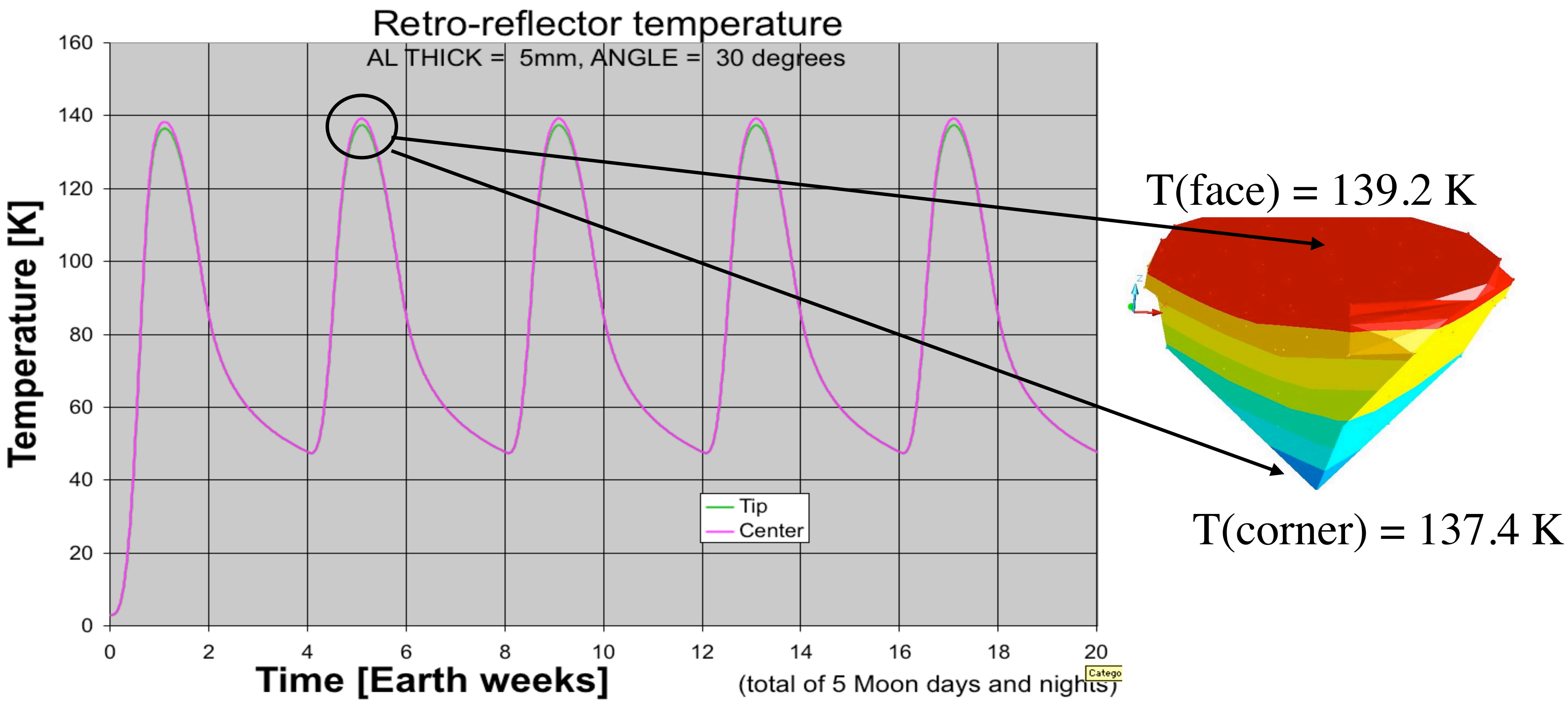
- **Reflection By Total Internal Reflection**
  - No Intensity Loss due to Metal Coating
  - No Heat Input due to Metal Coating Absorption
  - Phase Offsets Broadens the Return Beam
- **Loss of TIR for Off-Normal Incidence**
  - Low Sun Can Break Through Opposing Face
  - Dumps Heat into Pocket or Cavity
- **LLRRA-21 Solution**
  - Rotate CCR so Real Edge Faces "West"
  - Expect Breakthrough in the "Morning"
  - Put up Shield to Block Morning Sun
  - OK at Noon and in Afternoon due to TIR
  - Therefore No Breakthrough Problem
  - Feasible – Lunar Spin Axis Normal to Ecliptic





Preliminary Thermal Analysis: CCR

CCR thermal gradient under for Early Concept: ΔT < 2 K



With Improved Housing Design and Worst Case Sun: ΔT < 0.2 K

PSF Degradation with this variation of the index of refraction seems OK;

Soon we will Validate this with an **SCF-Test of the flight payload @INFN-LNF**

SIMULATION PROCESSING

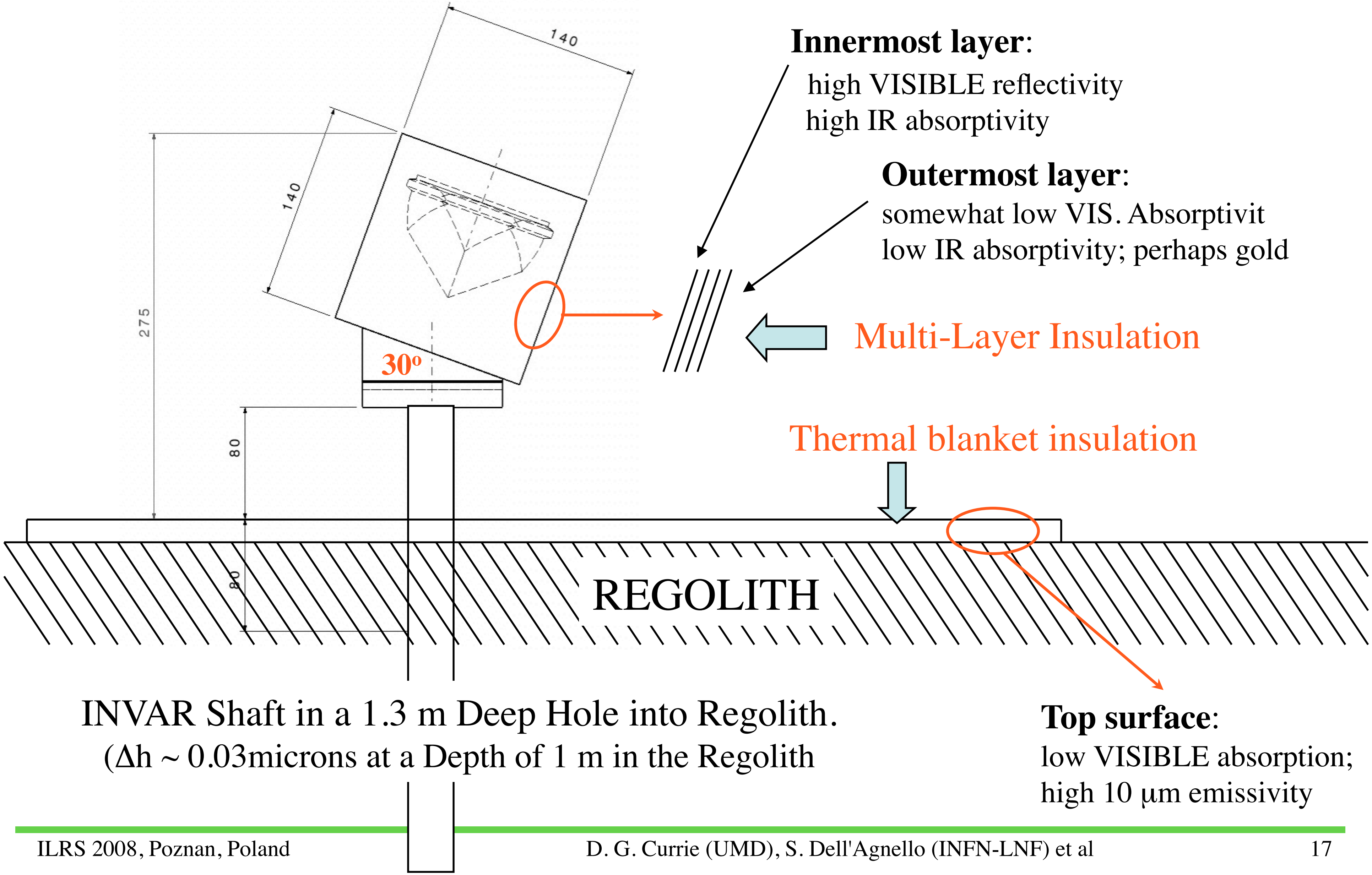
- **Code V – ORA => Interferogram**
  - Phase Changes due to TIR
  - Effects of Offset Angles in CCR
- **Thermal Desktop – C&R Technologies**
  - Solar Input to CCR and Radiation to Space
  - Mount Conductance between Housing and CCR
  - Monthly Thermal Behavior of Regolith and Thermal Blanket
  - Solar, Regolith and Thermal Blanket Effects on Housing
- **IDL – RSI**
  - 3D Temperatures to 2D Phases (Interferogram)
  - Combination of Interferograms
    - From Code V and Thermal Desktop
  - Convert to Point Spread Function
  - Evaluate Velocity Aberration in terms of Strehl Ratio

LUNAR SURFACE EMPLACEMENT

- CCR Optical Performance at Sub-Micron
  - Want to Assure as Much of This as Possible
- We Have Sufficiently Strong Return
- Emplacement Issues - Diurnal Heating of Regolith
  - ~ 500 Microns of Lunar Day/Night Vertical Motion
- Solutions – Dual Approach for Risk Reduction
  - Drill to Stable Layer and Anchor CCR to This Level
    - ~ 1 meter – APOLLO Mission Performed Deeper Drilling 1.8 m
    - ~ 0.03 microns of motion at this depth
  - Stabilize the Temperature Surrounding the CCR
    - Multi Layer Insulation Thermal Blanket – 4 meters by 4 meters

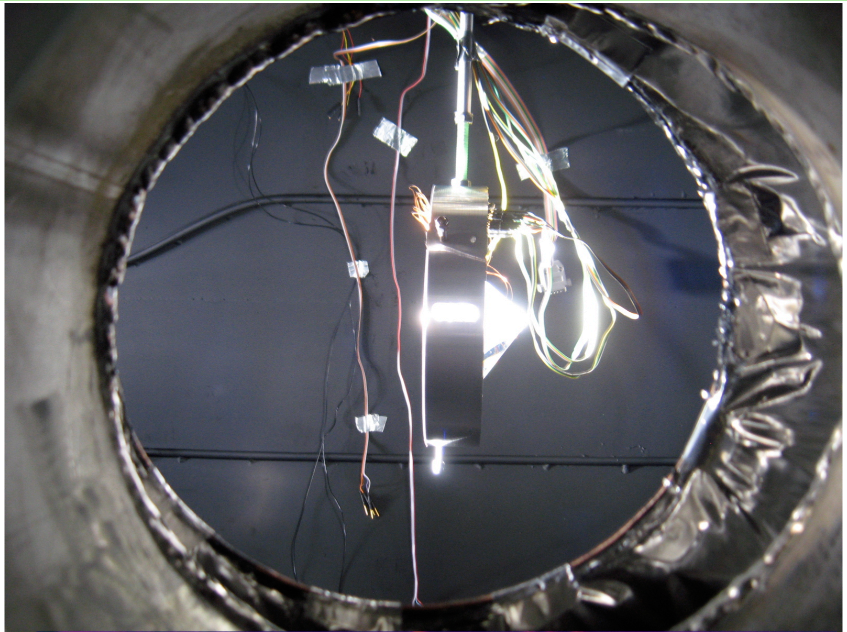
Payload installation on the surface

Early concept by D.G. Currie, D. Carrier. R. Vittori



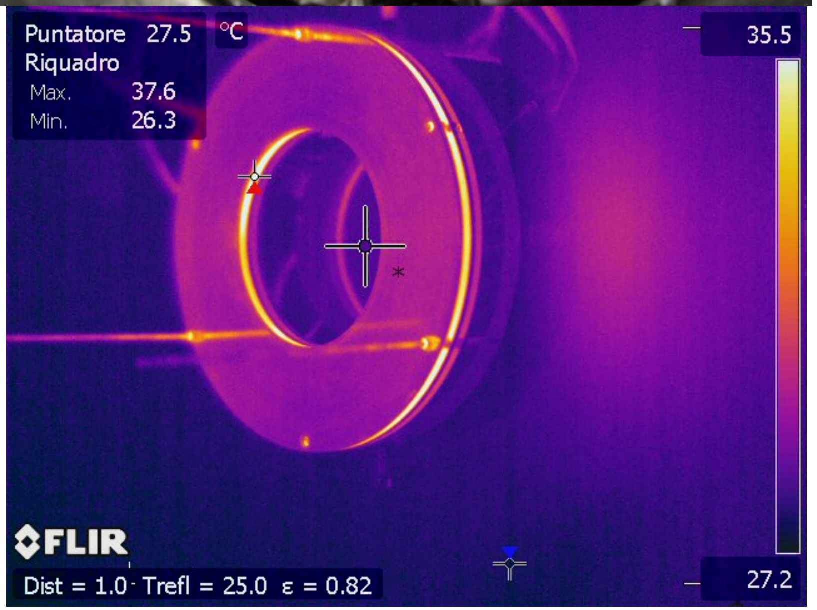
INVAR Shaft in a 1.3 m Deep Hole into Regolith.
($\Delta h \sim 0.03$microns at a Depth of 1 m in the Regolith

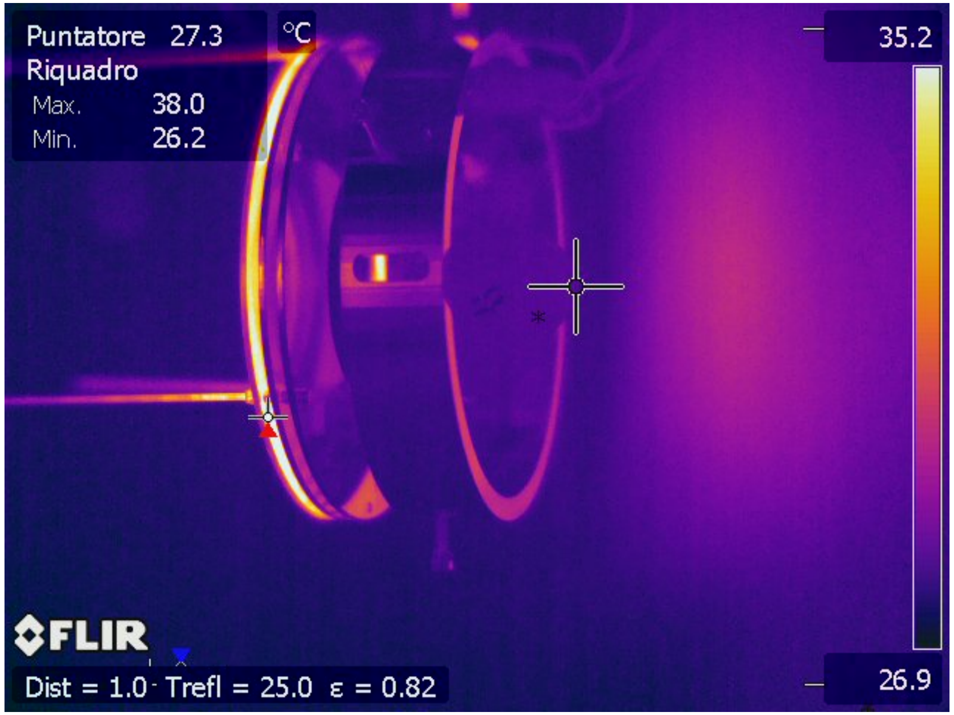
MoonLIGHT 100 mm CCR Thermal-Vacuum Test in SCF



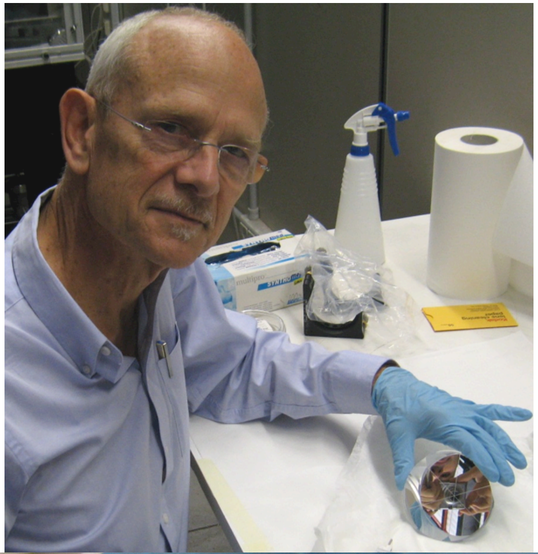
We started by measuring the CCR solar absorptivity. Very important number. More easily measured on a large volume – and this IS a large CCR.

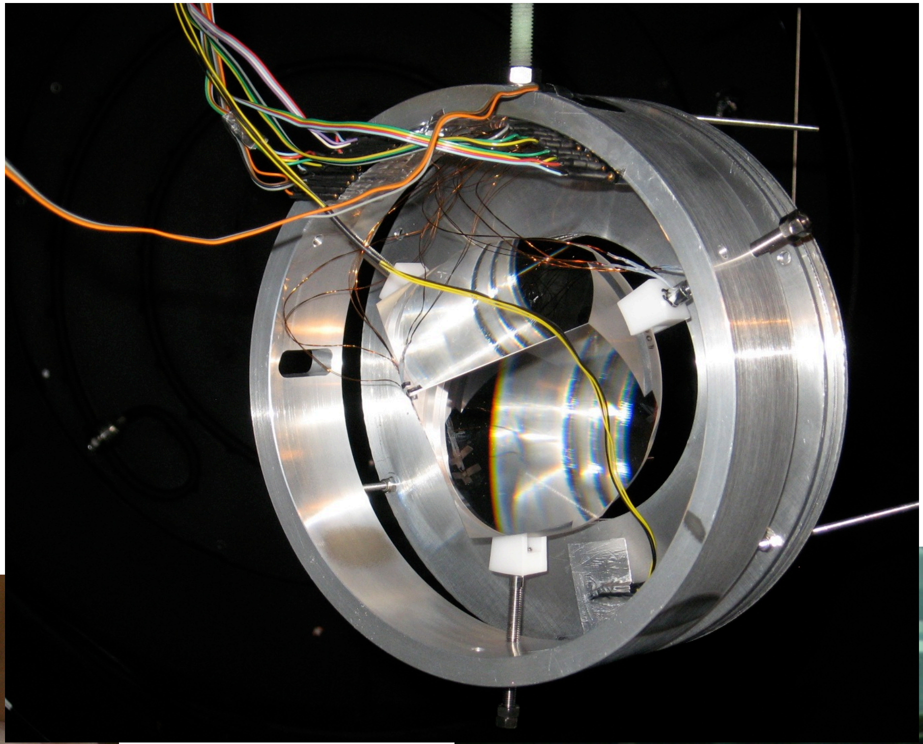
IR themometry, PT100 probes, lots of thermal analysis

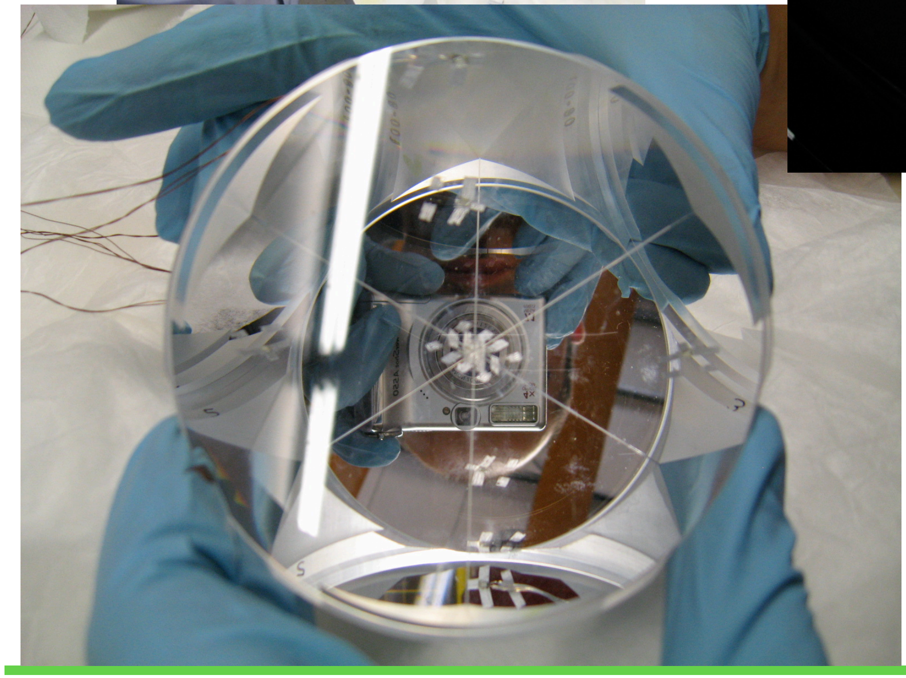


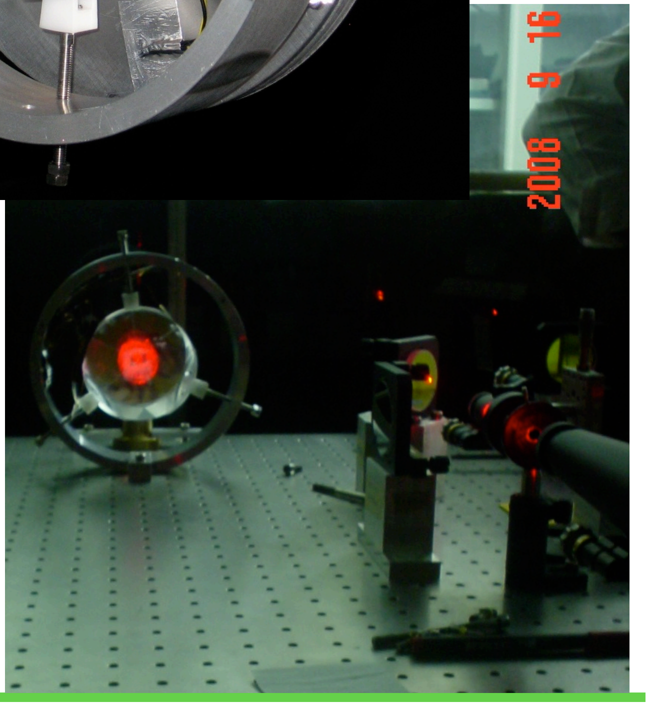


MoonLIGHT CCR at INFN-LNF









The International Lunar Network SoI (NASA AMES, 24 Jul, 08)

Statement of Intent
Regarding
The International Lunar Network

We, the signatories of this document, affirm that a robotic network on the surface of the Moon, which we propose to call the International Lunar Network (ILN), should provide significant scientific value to the exploration of the Moon. With this document, we hereby state our intention to explore ways in which to structure a partnership of space agencies to maximize the scientific return to all of the participants in the ILN concept. This partnership is an expression of the efforts to coordinate exploration activities consistent with the May 2007 *Global Exploration Strategy: The Framework for Coordination* which articulated a shared vision of space exploration focused on solar system destinations where humans may someday live and work.

As conceived, the network would be gradually established by placing on the surface of the Moon, potentially including its far side and/or polar regions, robotic landers or other vehicles equipped with instruments from a to be agreed-upon set of scientifically equivalent core instrumentation to carry out specific measurements. This core set of instrumentation is fundamental to the ILN concept, since it will allow intercomparison of measurements from instruments from different countries. Space agencies taking part in the ILN concept would, at their discretion, be free to include their own instruments or capabilities beyond those in the core suite.

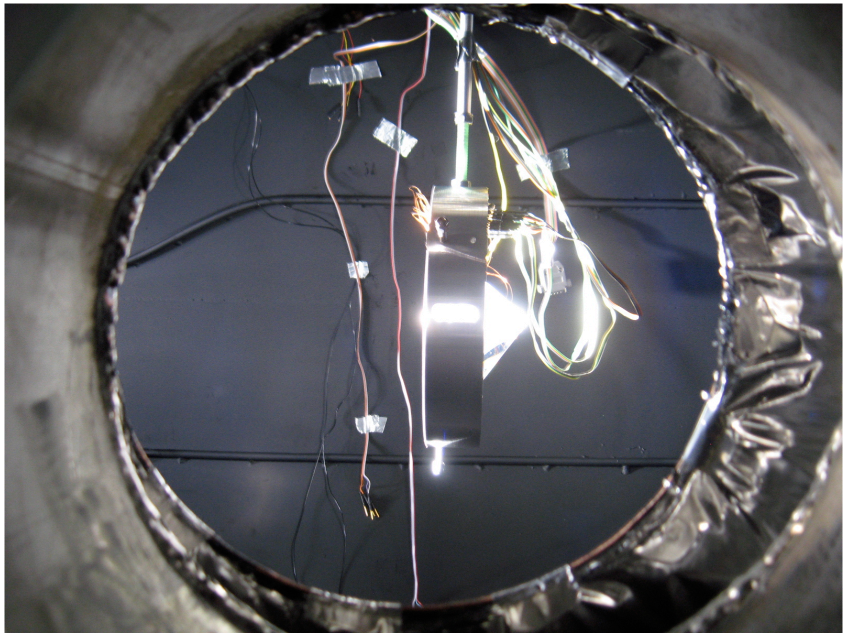
Science questions:
PHYSICS: GR, beyond GR (Brane Worlds/weak gravity), strange quark nuggets
PLANETOLOGY: Selenodesy, Lunar interior

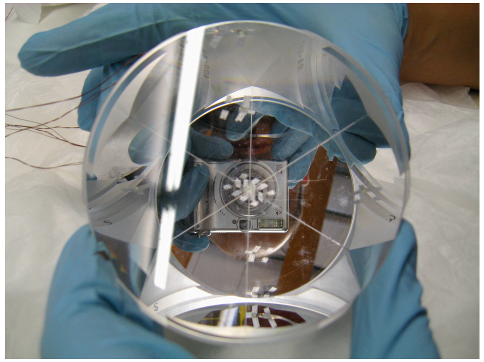
Core instruments: 4 foreseen so far (at least on NASA anchor nodes):
seismometer, EM sounding, heat probe, CCR
MoonLIGHT CCR meets specs set by NASA for its two "anchor nodes": **10cm, 1Kg+hinge**

2nd generation LLR payload for LSSO & ILN

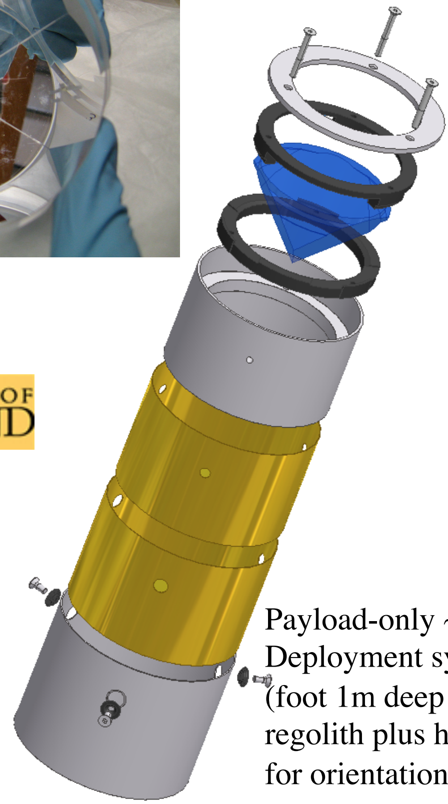
- Candidate as core instrument of **ILN** (Int. Lunar Network) – robotic landings
  - MoonLIGHT meets specs for retro-reflector of NASA anchor nodes
  - NASA, ASI & other space agencies signed ILN SoI @NASA-AMES on July 24, 2008

- NASA **LSSO** project – manned landings
- Precursor test on **MAGIA** – orbiter mission proposed to ASI, now in Phase A study





D. Currie (UMD, PI)
S. Dell'Agnello
(INFN, CoPI)



Payload-only ~ 1Kg
Deployment system (foot 1m deep in regolith plus hinge for orientation) ~1Kg

Concusions: LLRRA-21 INNOVATIONS

- Escape from Lunar Libration Problem
  - An Array of Single, Well-Separated CCRs
- Better Control of Velocity Aberration Effect
  - Offset of Single Face with Defined Orientation w.r.t Velocity Aberration
- Control of Local Environment Problems due to Lunar Cycle Heating
  - Sub-Surface Anchoring of CCR to Thermally Stable Regolith
  - Thermal Blanket to Exclude Lunar Cycle Temperature Variations
  - Control of Thermal Effects on Support and Housing
- New Housing Concepts for Thermal Control
  - Gold Coated Isolation of CCR from Housing Temperature
  - Line Supports of CCR in Housing for Reducing Mount Conductance
- Addressing Solar Absorption within SiO_2 of CCR
  - Detailed Volumetric Simulations to Optimize Performance
  - Thermal Vacuum Measurements to Validate Simulations
  - Possible IR Coating to Control Most Significant Absorption
  - External Shield to Prevent Solar Break-Through into Pocket
- Much More Detailed Simulation, Analysis and Thermal Vacuum Tests
  - Combined Thermal and Optical Simulation
  - Thermal Vacuum Testing of Simulation with the SCF at INFN-LNF

Outer Solar system: the Pioneer Anomaly

- In the outer SS the probes with the most accurate and robust navigation capabilities are the PIONEERS
  - VOYAGERS: Deep Space, but factor 50 “less accurate”
  - GALILEO: inaccurate, up to Jupiter only
  - CASSINI: being studied, but still, only up to Saturn
  - Outer planet motions? Saturn?

- Doppler data (1987-1998, 40-70.5 AU) provide clear anomalous deceleration. Pioneer Explorer Collaboration.

$$a_{PIO} = (8.74 \pm 1.33) \times 10^{-10}\ m/s^2$$

  - ~10 times the largest LAGEOS thermal acceleration, that we test with the SCF!

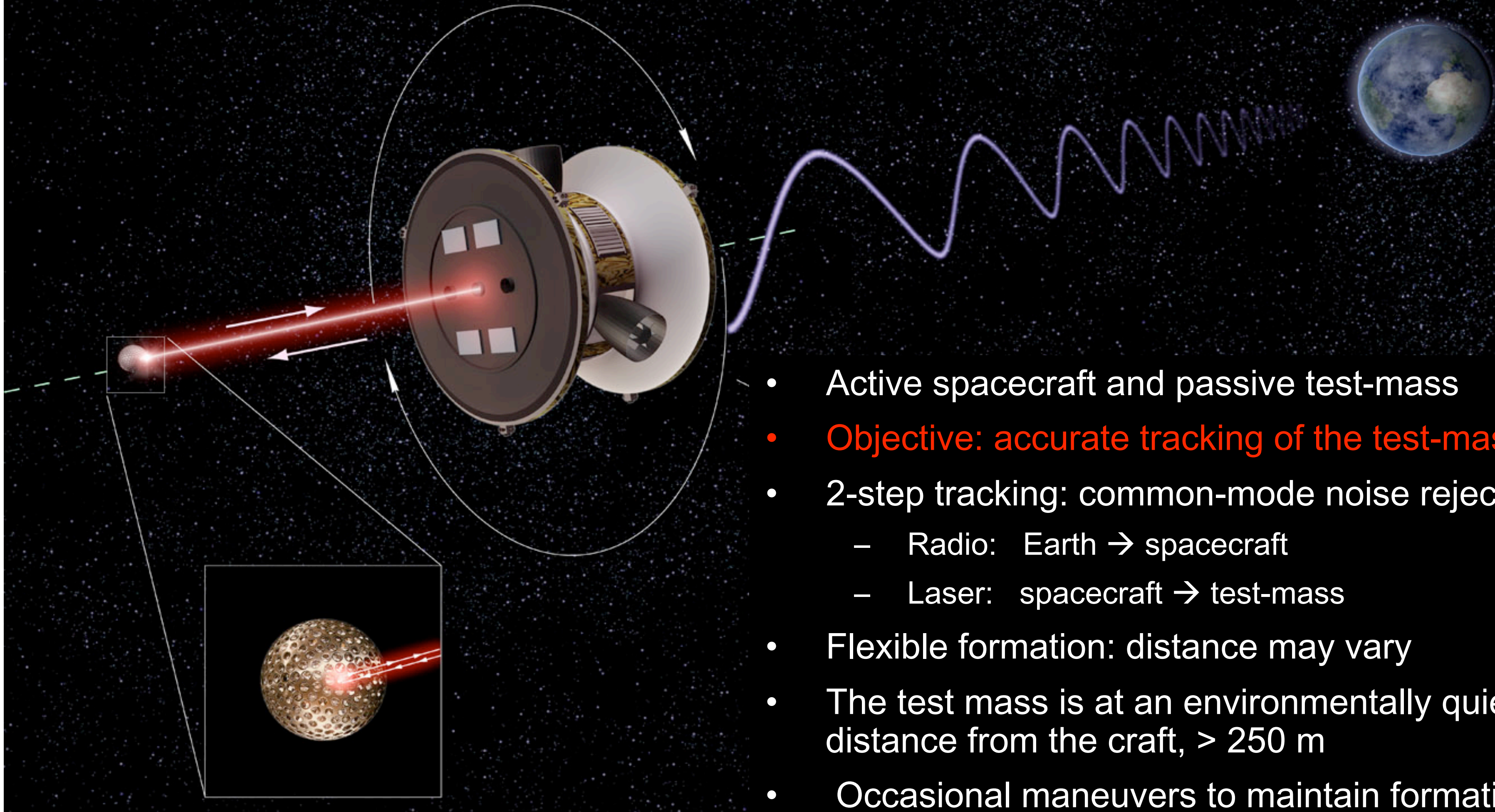
- Effect of asymmetric thermal forces due to forward-backward asymmetric thermo-optical parameters? RTGs?
- New physics?
- New mission, DSGP (S. Turyshev of JPL is the PI) proposed to ESA’s Cosmic Visions

A MISSION TO EXPLORE THE PIONEER ANOMALY

Measurement Concept: Formation-flying

Satellite Laser Ranging in deep space:

the proposed Deep Space Gravity Probe



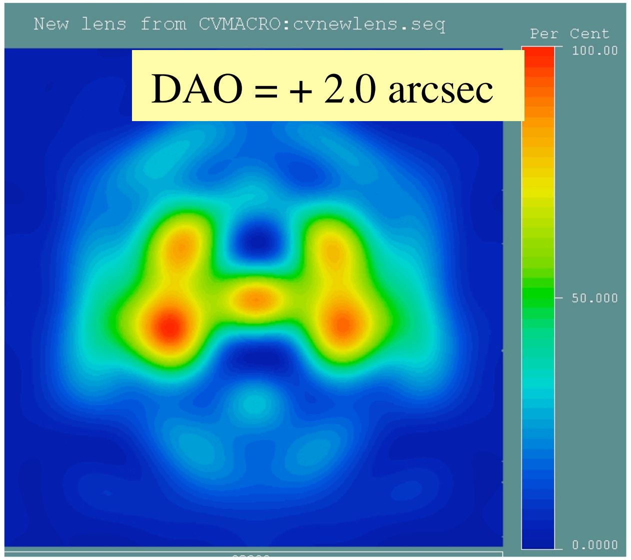
- Active spacecraft and passive test-mass
- Objective: accurate tracking of the test-mass
- 2-step tracking: common-mode noise rejection
  - Radio: Earth → spacecraft
  - Laser: spacecraft → test-mass
- Flexible formation: distance may vary
- The test mass is at an environmentally quiet distance from the craft, > 250 m
- Occasional maneuvers to maintain formation

DSGP laser-ranged test masses

- DSGP proposed for ESA's Cosmic Vision
- **Laser ranging** at ≤ **1 Km distance:** can release the expensive tight tolerance on dihedral angle offsets of the retro-reflectors
- LNF is designing the laser-ranged test masses financed with the 3-yr ASI study "Cosmology and Fundamental Physics" led by de Bernardis
- **Pioneer anomaly** ~ 10^{-9} m/s^2; LAGEOS largest thermal thrusts ~ 10^{-10} m/s^2; solar constant @Saturn = 10^{-2} × Earth Solar constant

==> Thermal NGPs will be under control with SCF-Test

Max intensity of FFDP ~ 40-60 mm @1Km



Al prototype being prepared at LNF
∅= 160 mm