The INFN-LNF Space Climatic Facility for the LARES mission and the ETRUSCO project

Claudio Cantone (INFN-LNF)

for the LARES and ETRUSCO Collaborations

International Workshop on

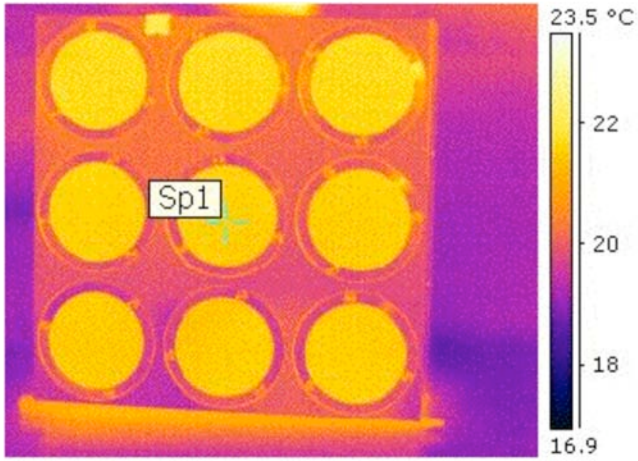
"ADVANCES IN PRECISION TESTS AND EXPERIMENTAL GRAVITATION IN SPACE"

Florence, ITALY, 28-30, Sep. 2006

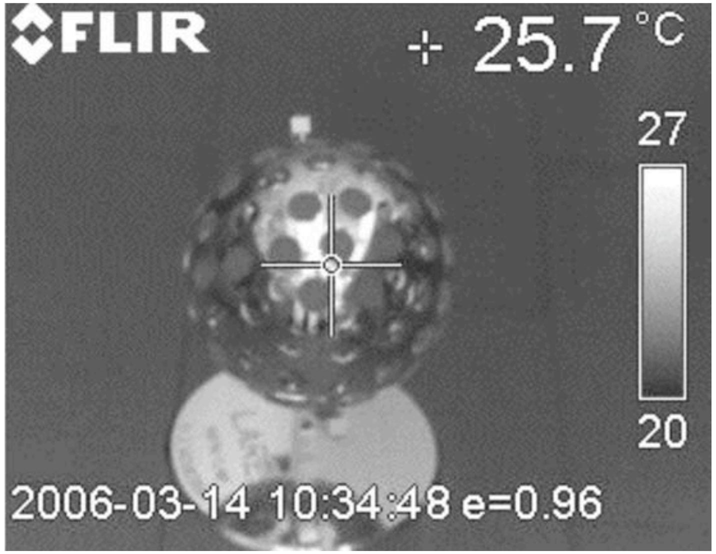
The LARES mission

- LARES: see talk by PI, I. Ciufolini
- Space climatic characterization
- Laser ranging tests
- LAGEOS I engineering proto from NASA
- (LAGEOS spin measurement)

LAGEOS 3x3 matrix and LARES 1:2 proto built at LNF



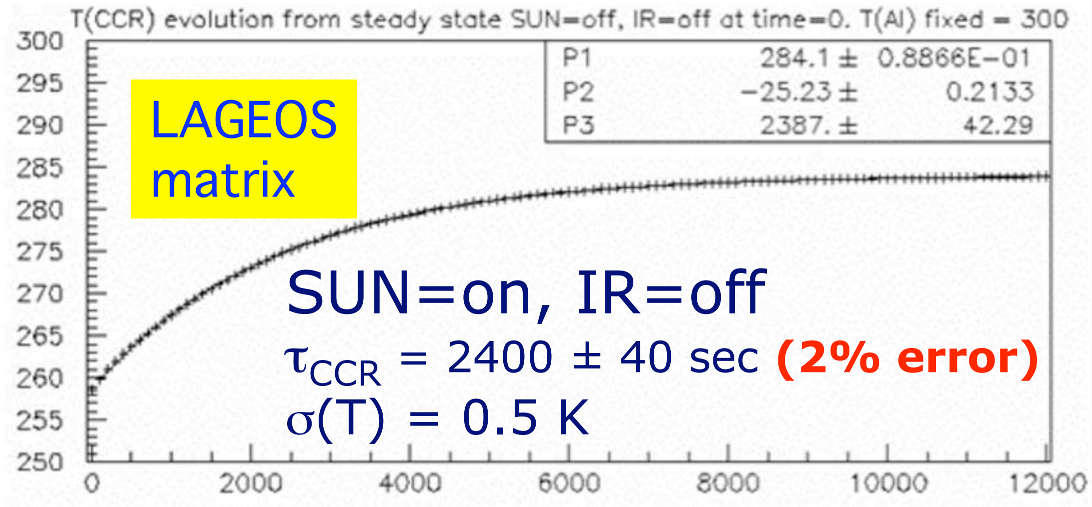
IR images



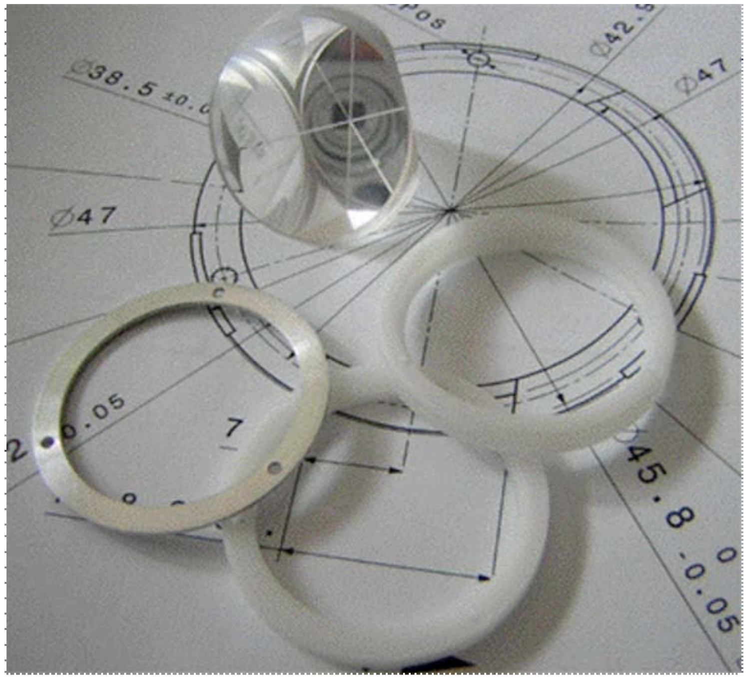
Simulation of τ_{CCR} (thermal relaxation time)

NEVER measured.
Computations vary by 300%.
Goal: measure τ_{CCR} at ≤**10% accuracy**. This will make the error on Lense-Thirring due to thermal thrusts negligible (permil level)

CCR T(K)

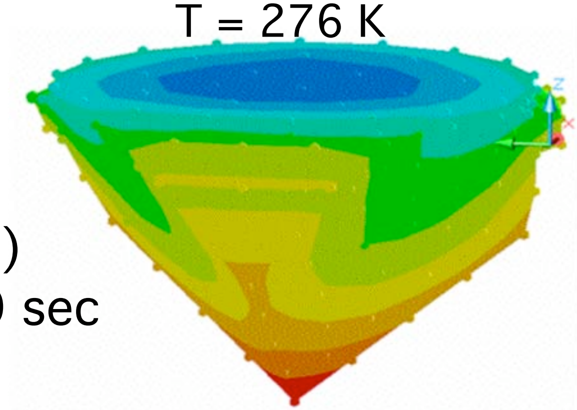


t(sec)



T = 276 K

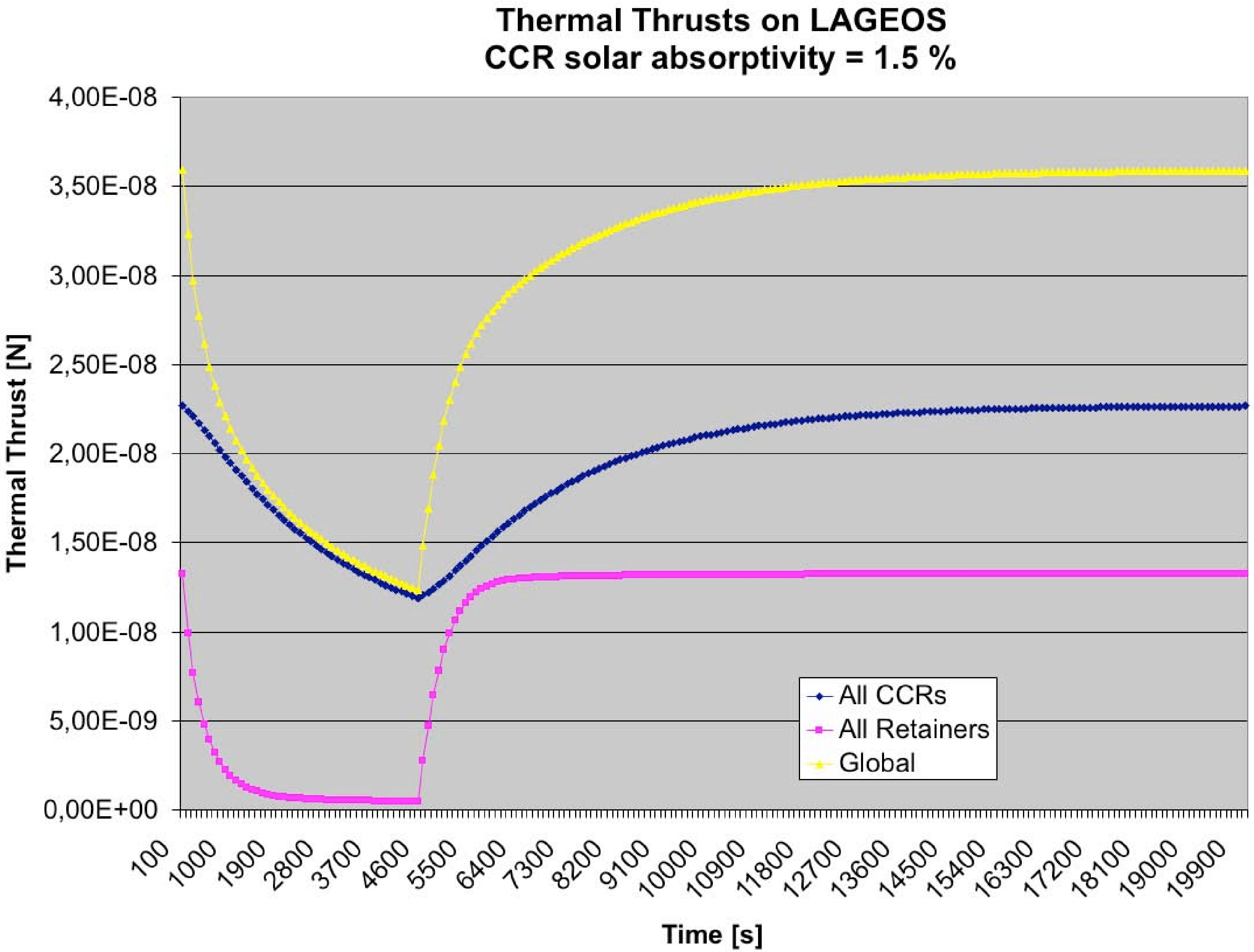
FEM model
(250 nodes)
at t = 2800 sec



T = 278 K

C&R TECHNOLOGIES
Hot Engineering ... Cool Software®

LAGEOS sw model of thermal thrusts



Steady state
t=0 sec
SUN=ON

SUN=OFF for
4500 s

then SUN=ON.

IR always ON

Measurement of IR ε, ρ with IR camera

LAGEOS matrix

Indoor, in-air measurement
at room temperature

- $Q_{camera} = Q_{emission} + Q_{reflected}$
- $T^4_{camera} = \varepsilon_{IR}\, T^4_{x} + \rho_{IR}\, T^4_{bkg}$
- $\varepsilon_{IR}(x) + \rho_{IR}(x) = 1$
- T_x w/thermocouple
- T_{bkg}: black disk with controlled temperature = 10 °C or 50°C

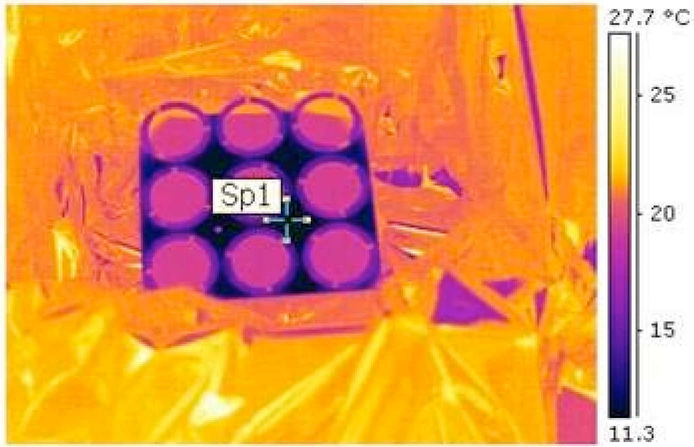
ε_{IR}(CCR) ~ 0.82 emissivity

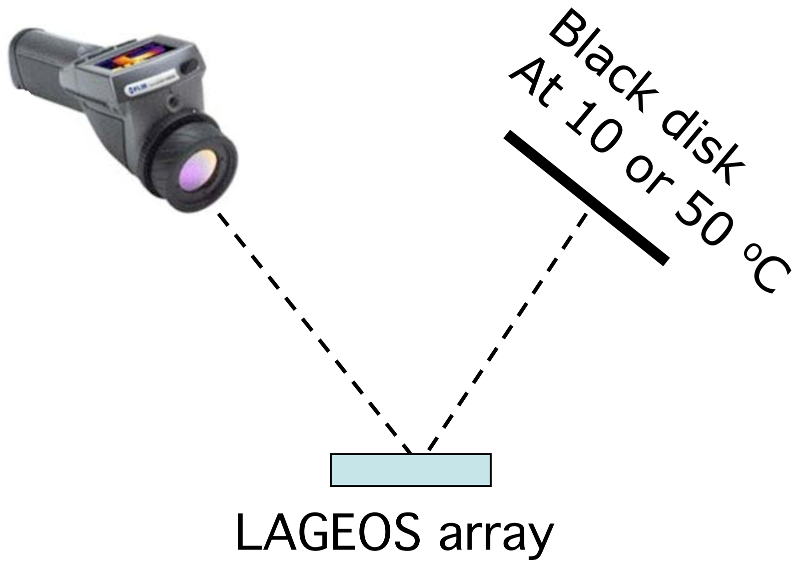
ρ_{IR}(CCR) ~ 0.18 reflectivity

ε_{IR}(Al) ~ 0.15

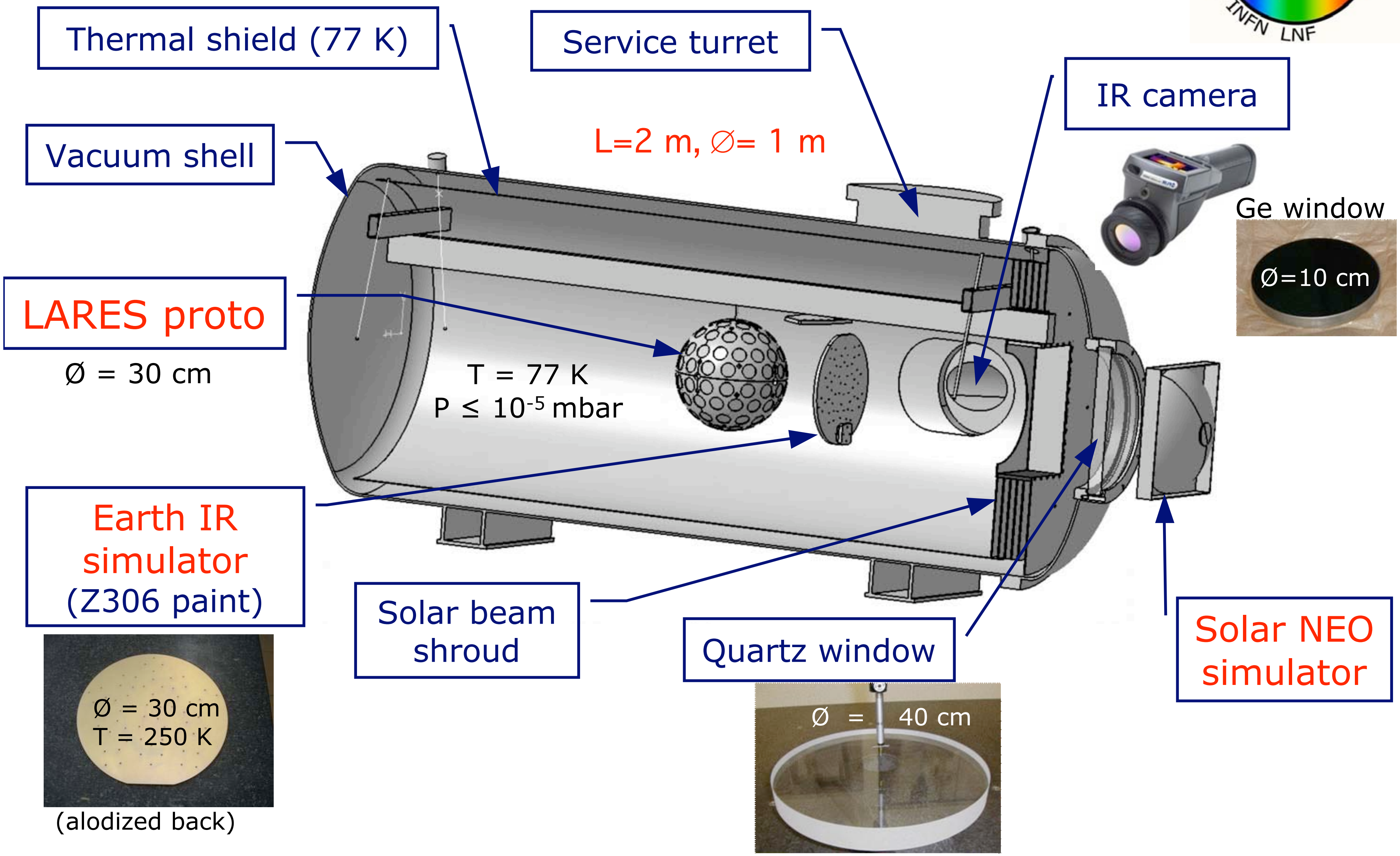
ρ_{IR}(Al) ~ 0.85

IR pictures of the LAGEOS array



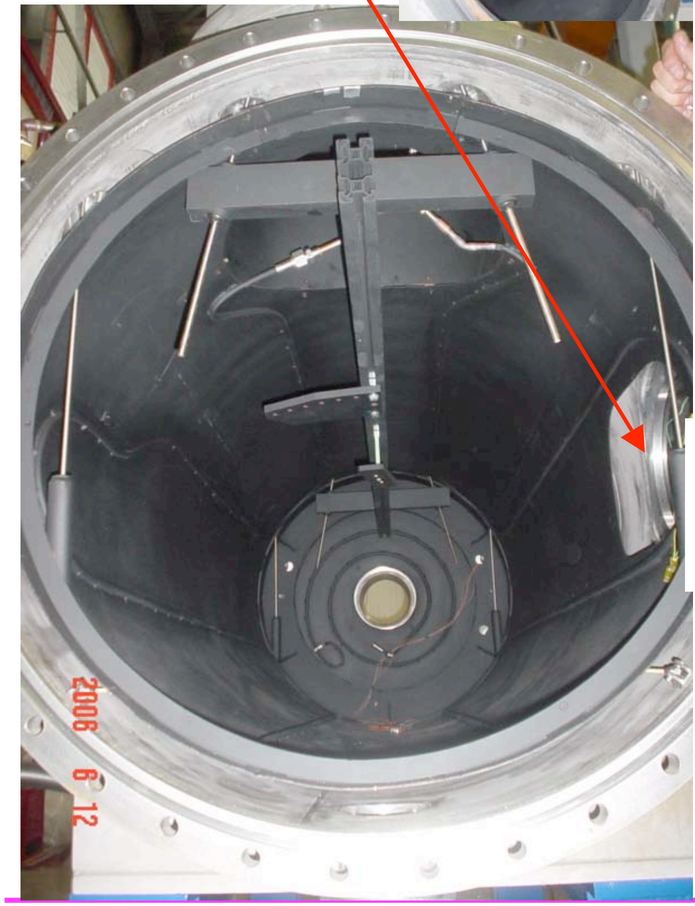


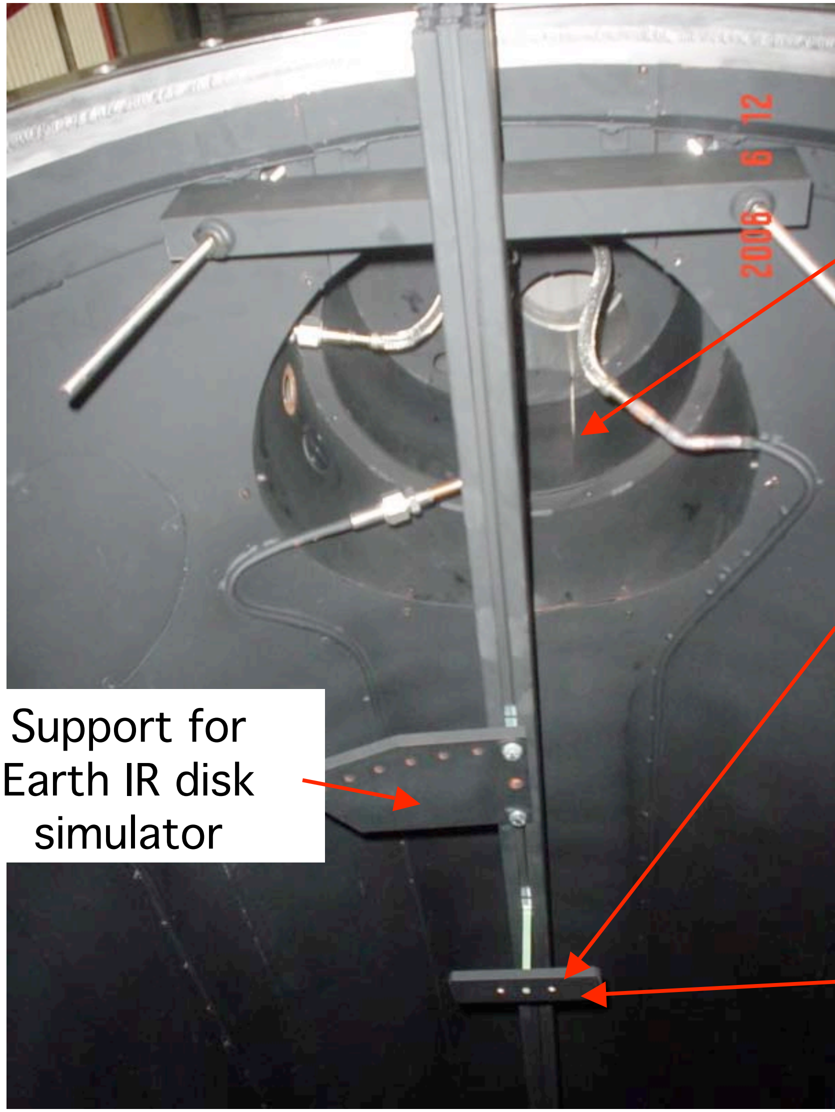
INFN-LNF Space Climatic Facility



Inside the LNF SCF

Side tunnel for IR camera



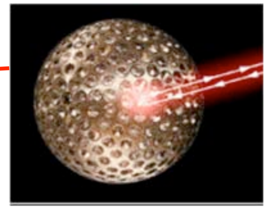


Support for Earth IR disk simulator

Service turret

Support for GNSS array...

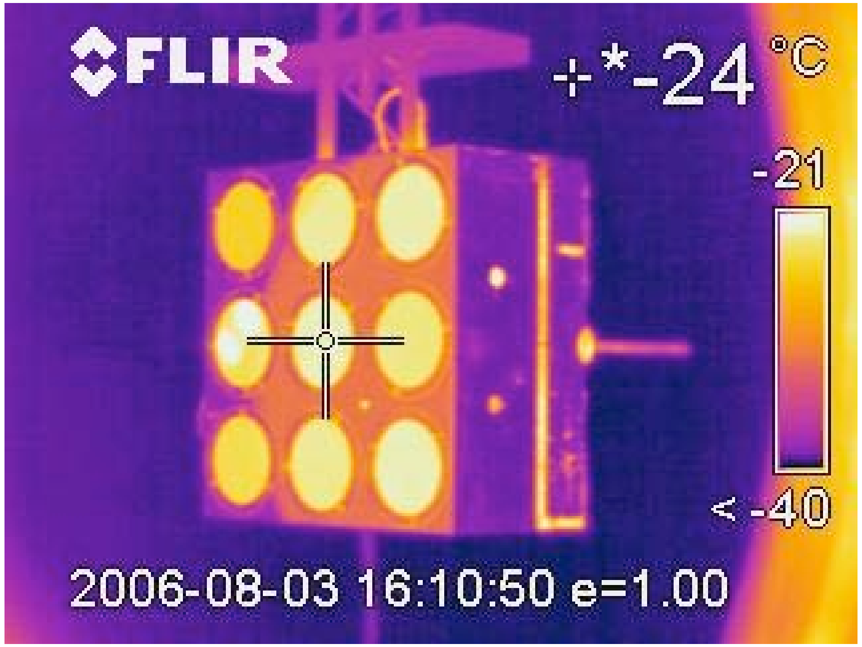
... or spherical test-mass



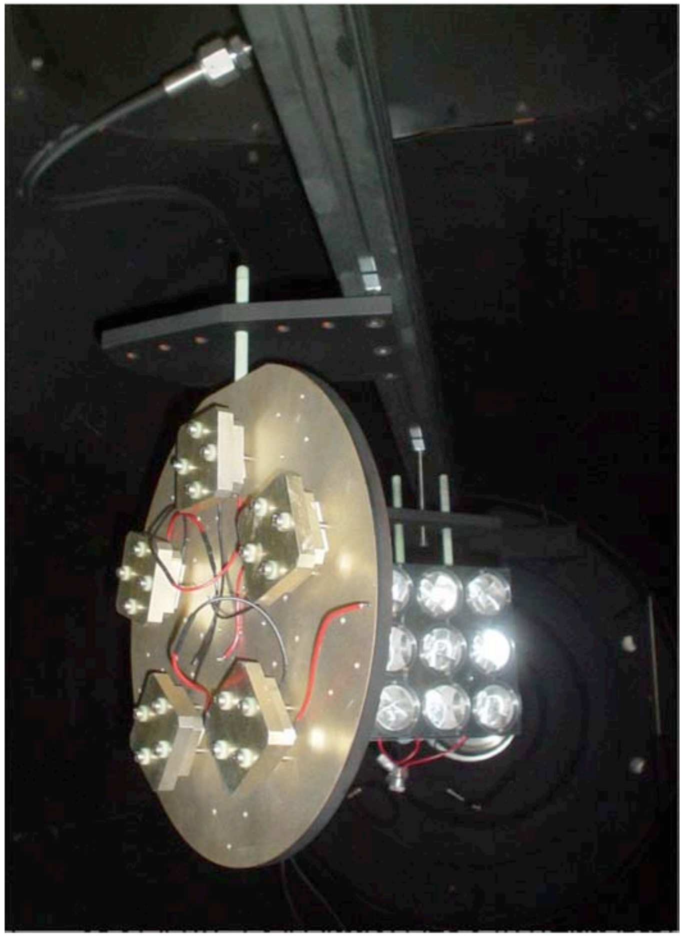
SCF commissioning complete

T = 77 K, P = 2 x 10^{-6} mbar
Sun simulator tested in August,
Earth IR simulator tested in Sep.

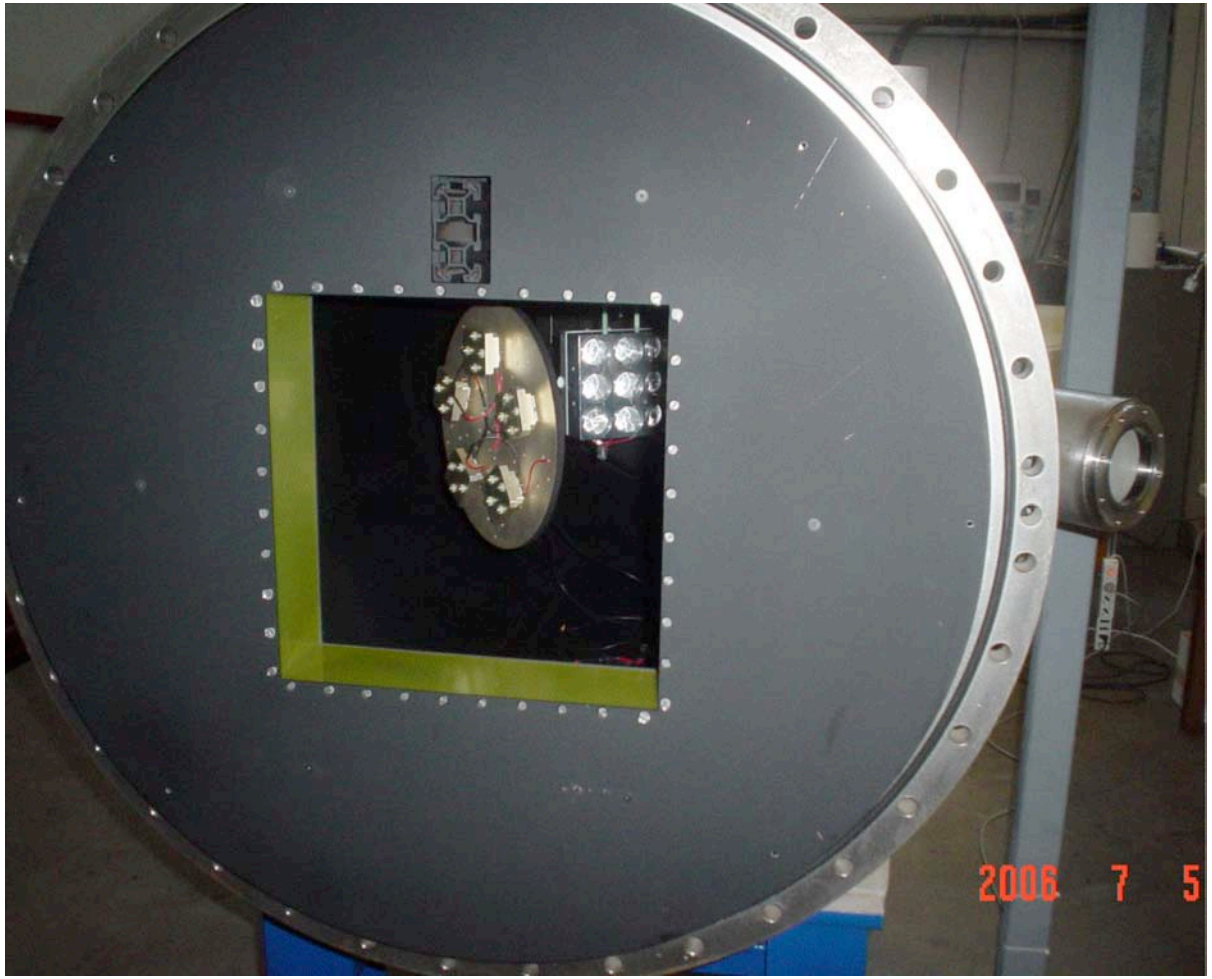
Thermogram of the LAGEOS array inside SCF in August



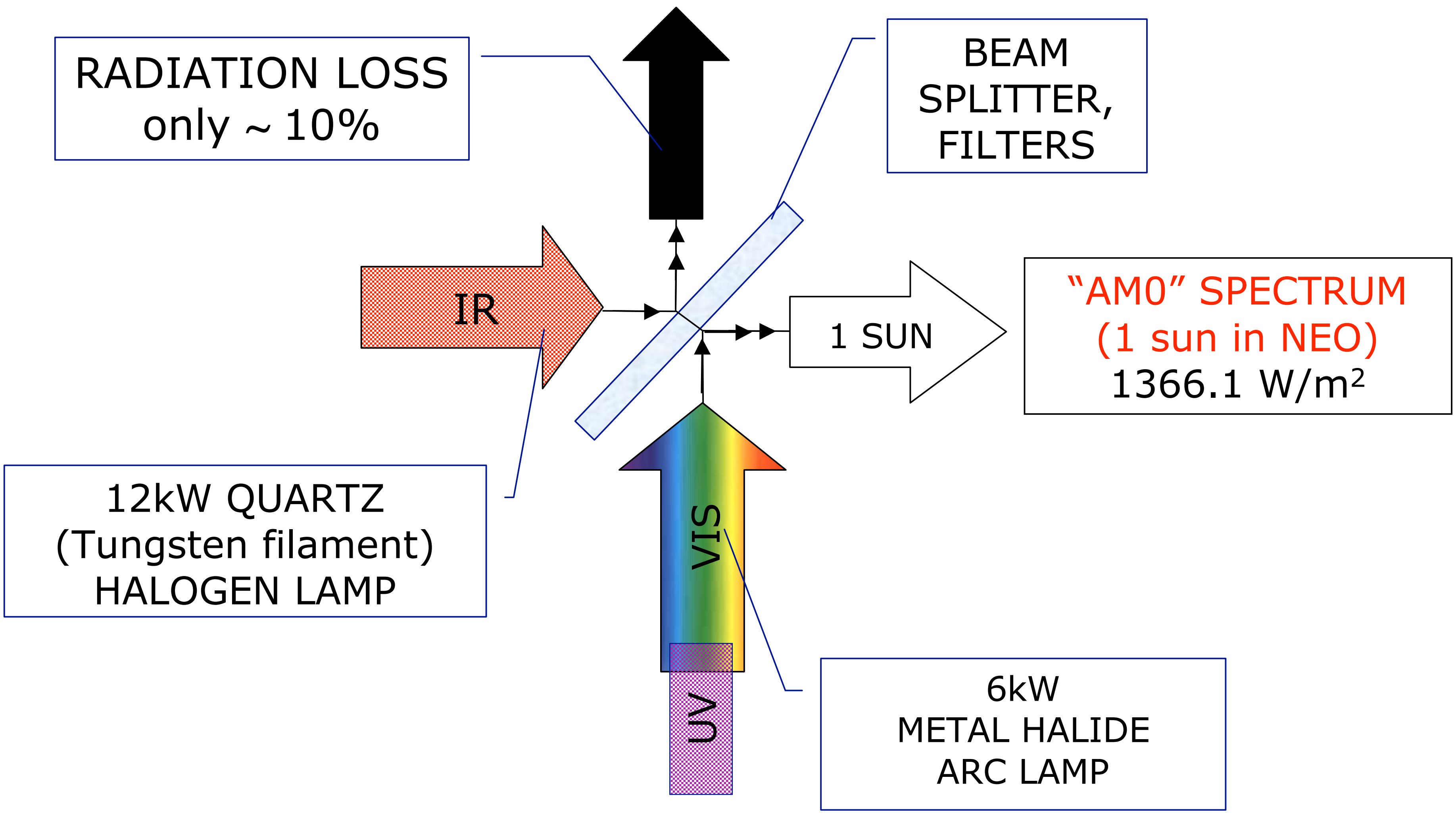
Earth IR simulator



Al disk painted with Z306 kept at 254 K by
Thermo Electric Coolers (TECs)



Solar simulator



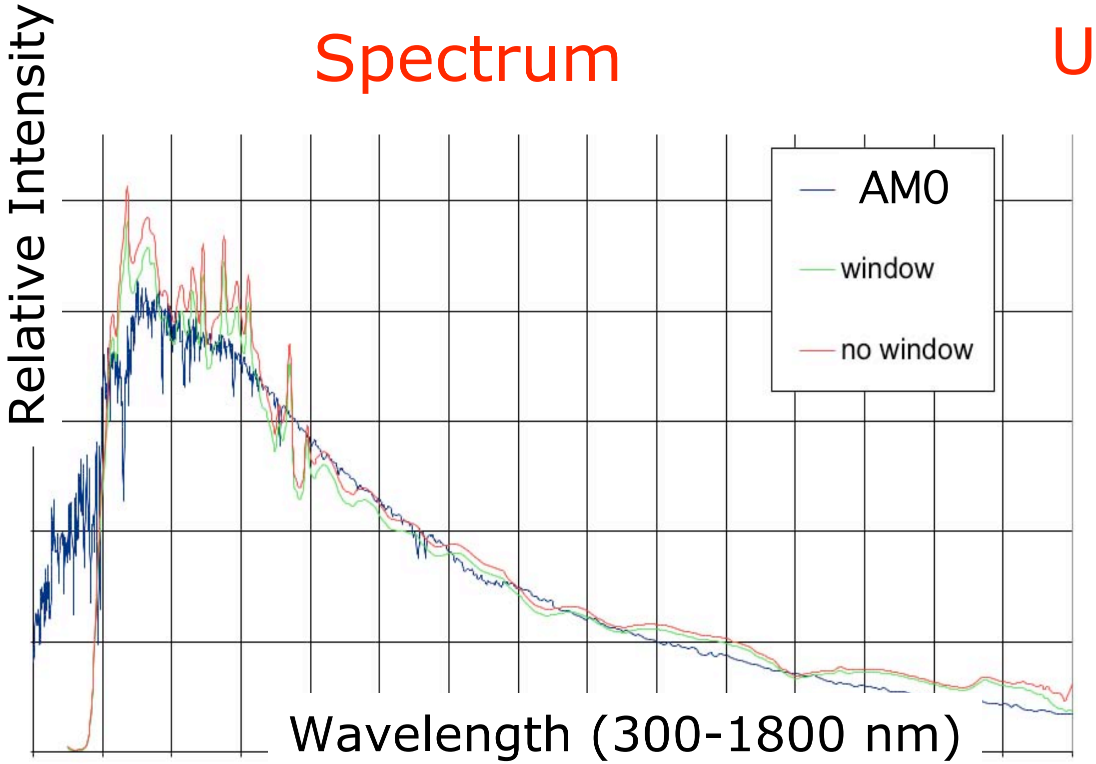
Solar simulator

- Acceptance test at TS-Space (UK) in June
- Delivered to LNF on July 12
- Final calibration at LNF end of July

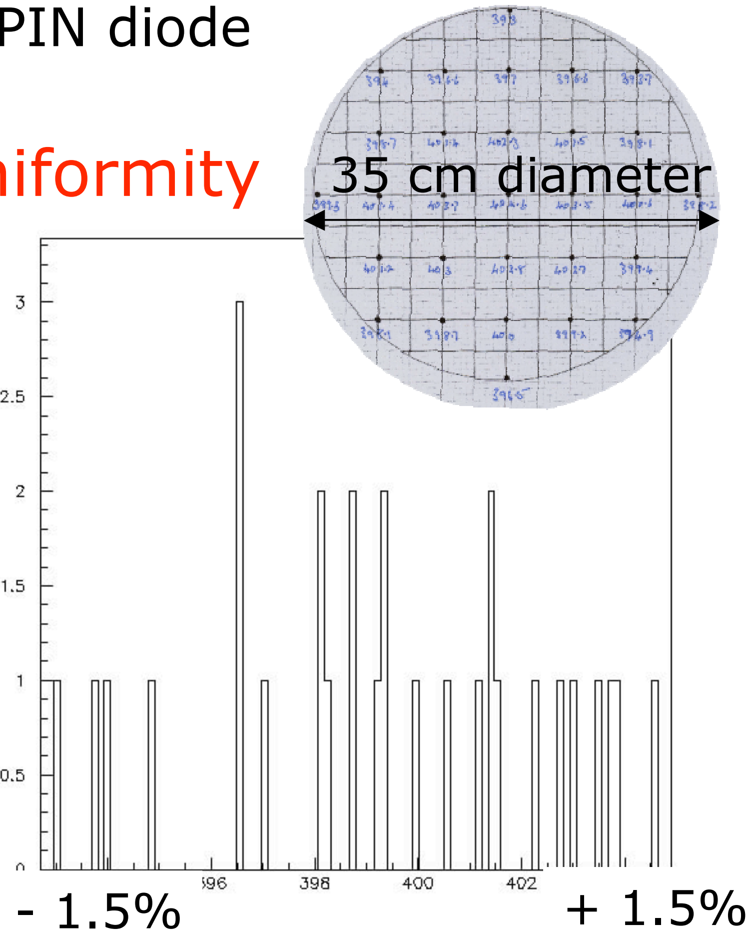
Measured Solar Simulator spectrum and uniformity

- "AM0" standard spectrum (400-3000 nm)
- Absolute calibration @1% w/Solarimeter
- HV adjusted for lamp ageing w/PIN diode

Spectrum



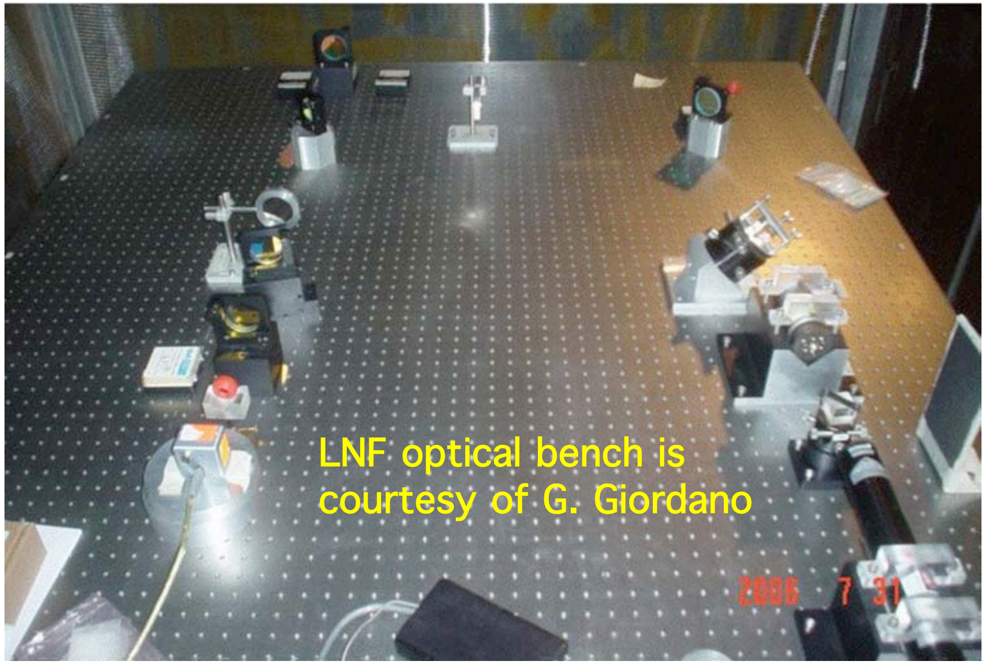
Uniformity



Optical characterization of CCRs at LNF

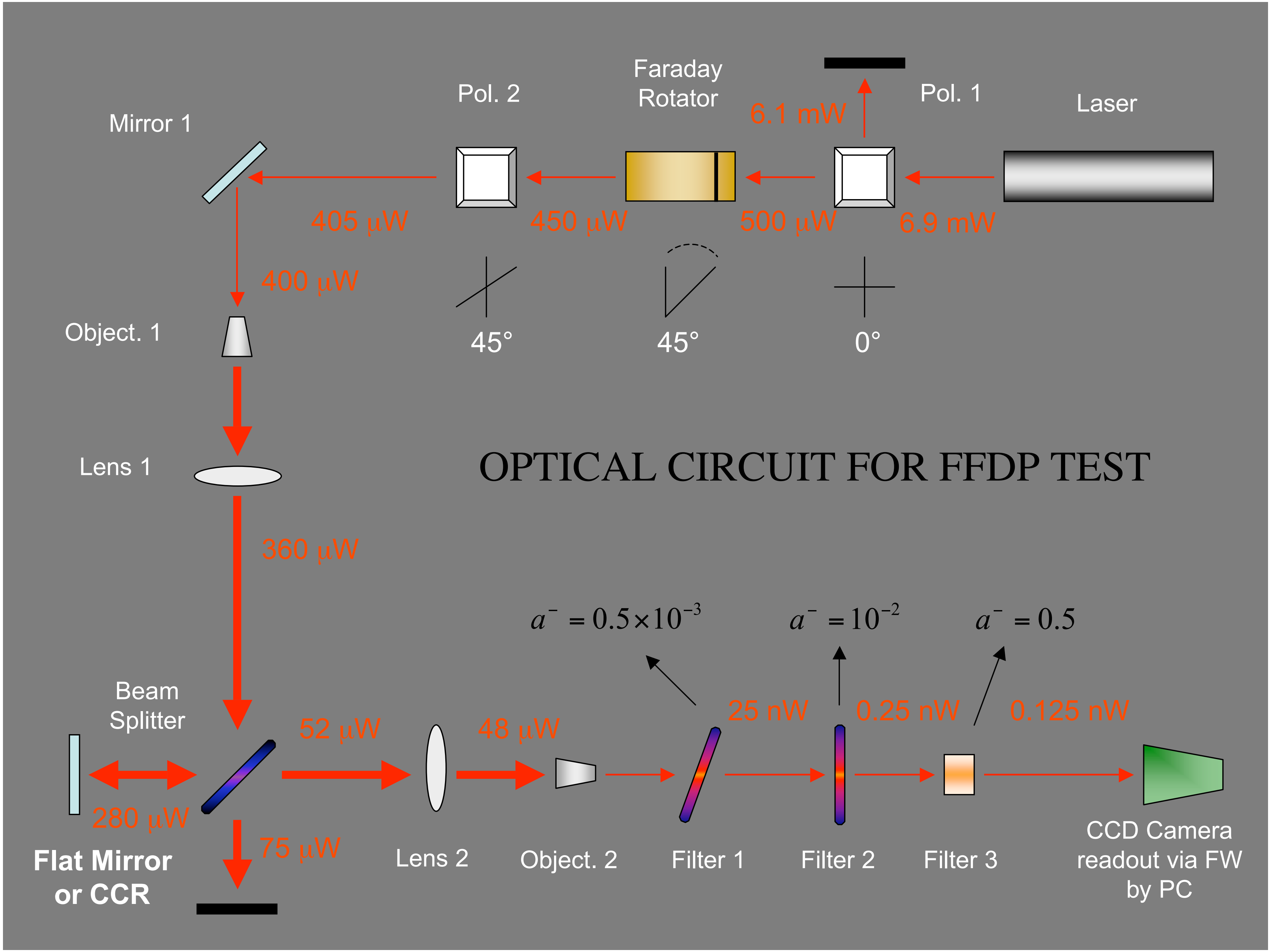
Test 1: Far-Field Diffraction Pattern (FFDP) of single CCR return with CW laser

- "Optical FLAT" (mirror) for normalization
- 2 CCDs as laser beam profilers. PC DAQ, firewire interface, commercial sw.



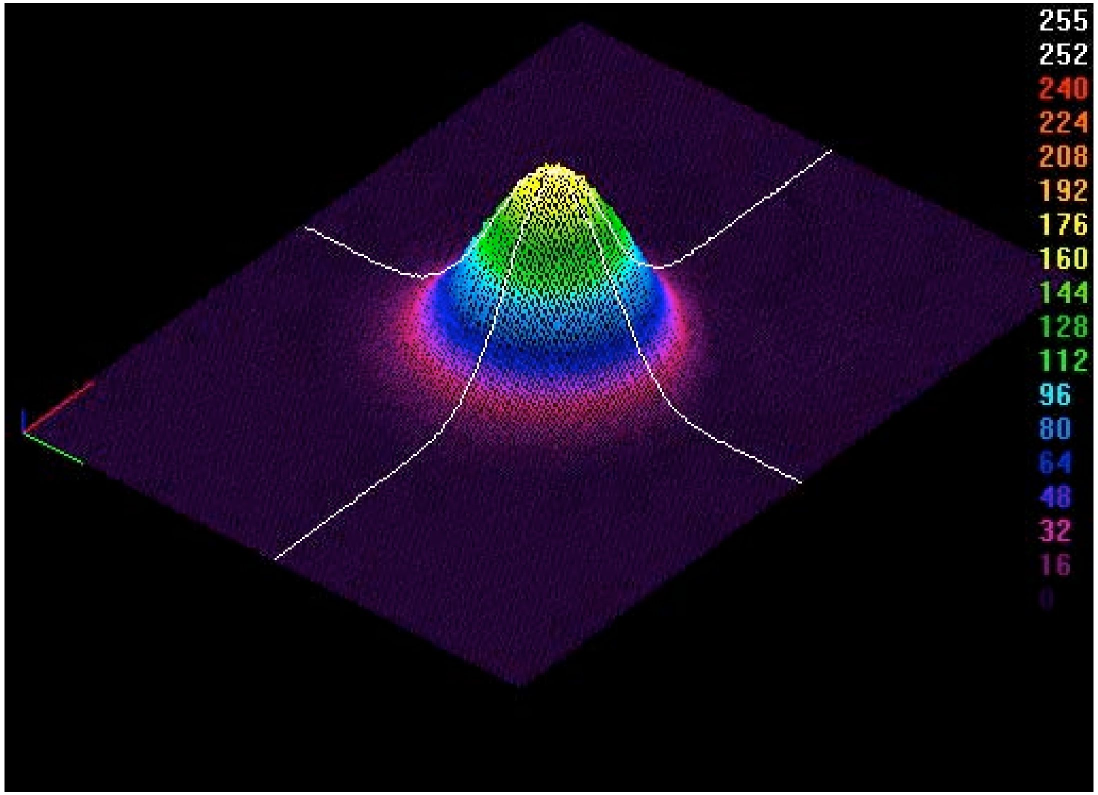
Repeat test inside the SCF

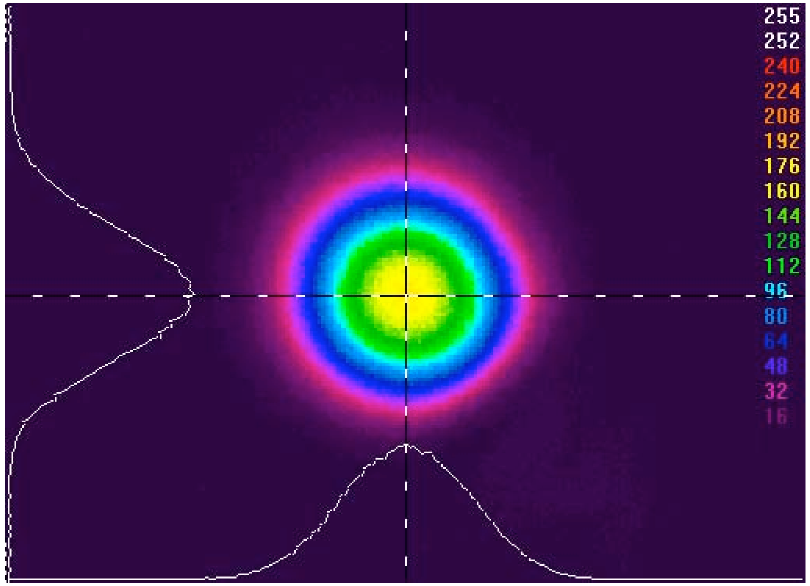
Thanks to John Degnan, Dave Arnold, Erricos Pavlis (ILRS), Jan McGarry (NASA-GSFC) for advise and to Doug Currie (Univ. of Maryland) for help on setting up the optical tests at LNF



OPTICAL CIRCUIT FOR FFDP TEST
Laser
Pol. 1
6.1 mW
6.9 mW
500 μW
Faraday Rotator
450 μW
Pol. 2
405 μW
Mirror 1
400 μW
45°
45°
0°
Object. 1
Lens 1
360 μW
Beam Splitter
Flat Mirror or CCR
280 μW
75 μW
52 μW
Lens 2
48 μW
Object. 2
Filter 1
Filter 2
Filter 3
25 nW
0.25 nW
0.125 nW
$a^{-} = 0.5 \times 10^{-3}$
$a^{-} = 10^{-2}$
$a^{-} = 0.5$
CCD Camera readout via FW by PC

He-Ne laser beam readout by CCD



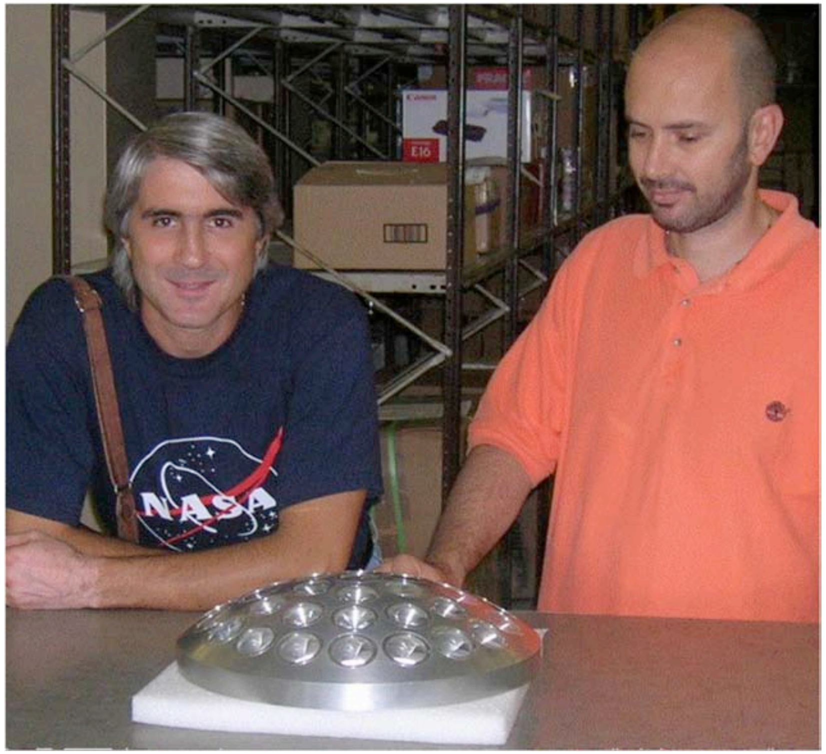


Laser profiles in varying conditions to test CCD dynamic range and laser beam attenuation needed to avoid CCD damage. Testing also sw functionality.

Now: perform optical circuit alignment. Next: take FFDPs

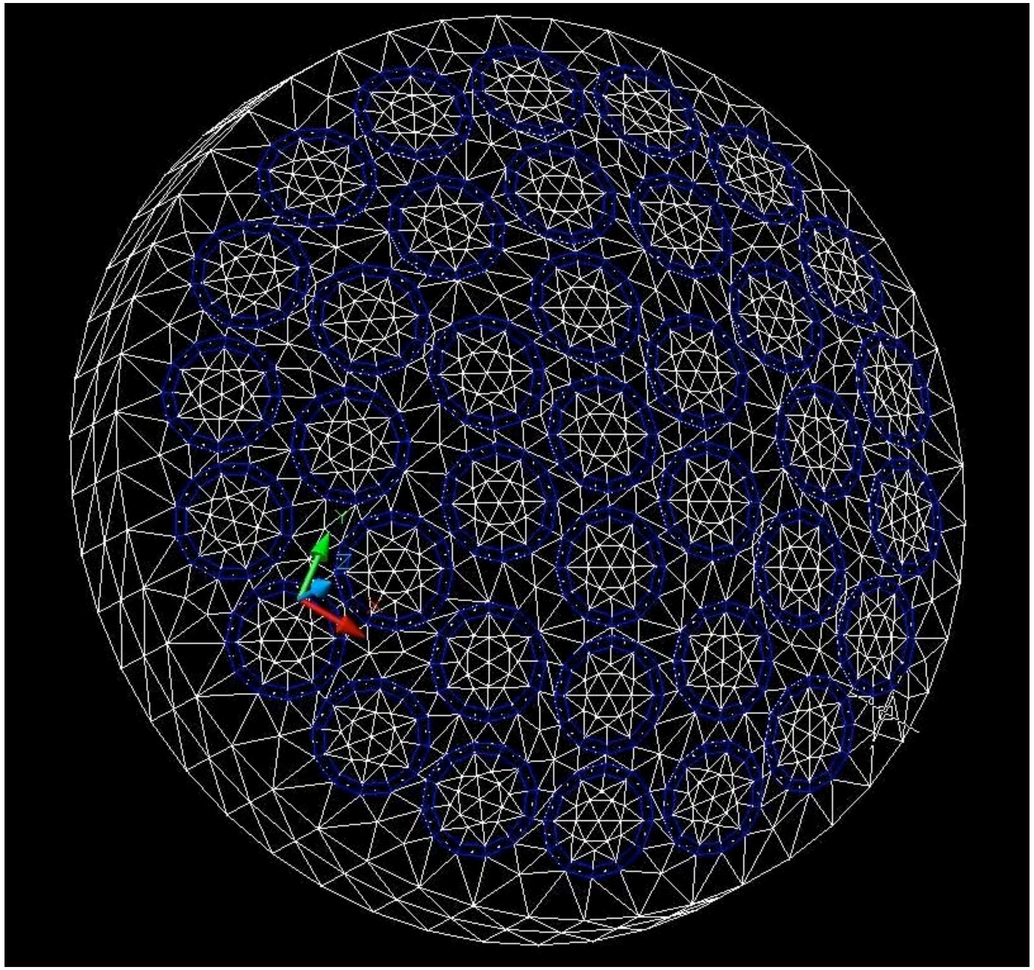
LAGEOS I prototype sent by NASA-GSFC to LNF

Engineering model property of NASA-GSFC to LNF for test in the SCF

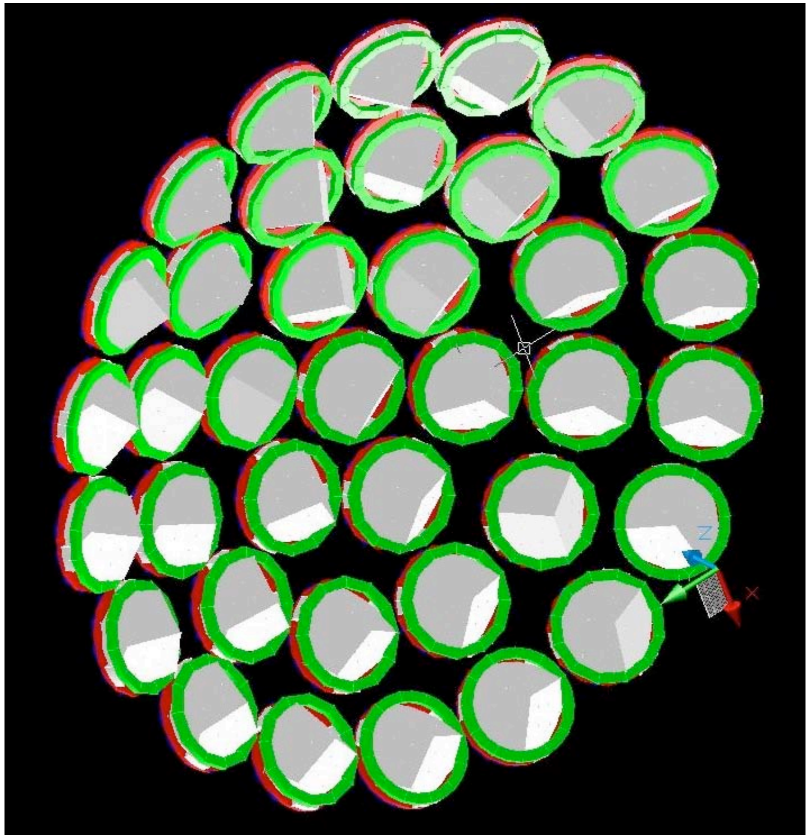


40 cm outer Al diameter.
37 original CCRs, of good Laser-optical quality

FEM model of the NASA LAGEOS I “sector”



Al and CCR FEM mesh, front view

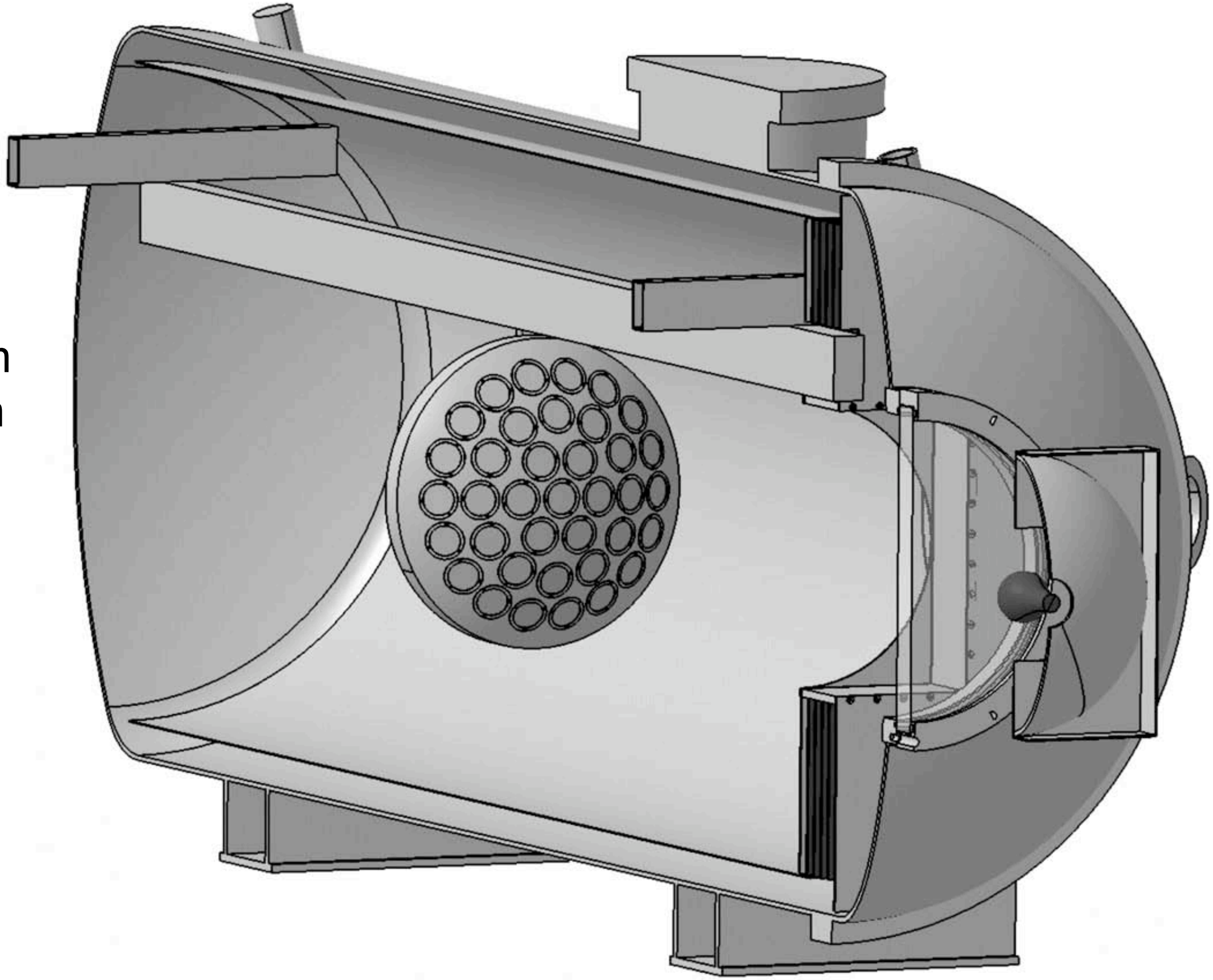


CCRs and mounting
Rings, back view

The NASA LAGEOS I “sector” inside the SCF

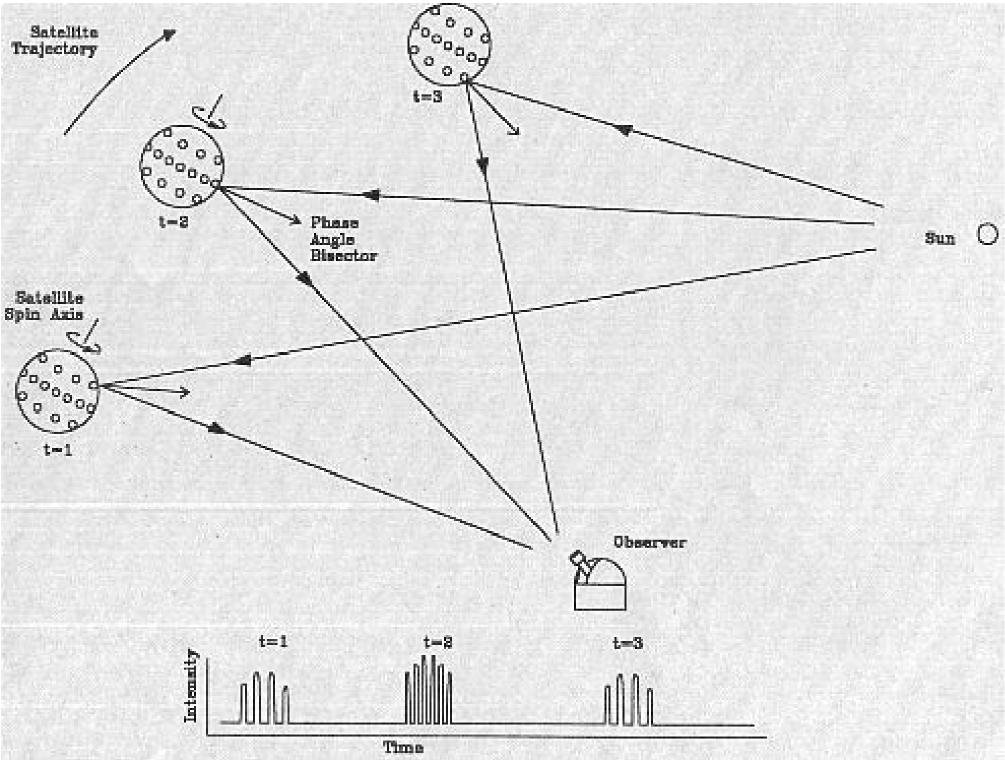
The CCR outer diameter is 34 cm and the sun beam is 35 cm:

Perfect match !



Measurement of spin

- Measurements of spin direction and rate at UMCP
- LOSSAM (LageOS Spin Axis Model): based on past measurements predicts future direction and rate (DELF+UMCP)
- SW revived and now run by R: Taurasat LNF



The INFN ETRUSCO project

- The SCF was funded with a small contribute of the INFN Astroparticle Committee and by the LNF Director. We used heavily existing LNF resources
- The Director asked us to use it for LARES and, possibly, find other projects of space physics and technology to maximize the output

Extra Terrestrial Ranging to Unified Satellite COnstellations

"Extra Terrestrial Ranging": measurement of satellite space-time coordinates with optical e.m. waves (laser ranging)

"Unified Satellite COnstellations": addition of LASER ranging to standard MICROWAVE ranging

INFN-LNF Group

R. Vittori (ESA, Italian Air Force)
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G. Delle Monache (LNF)
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M. Garattini (LNF)
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G. Bellettini (Univ. Rome Tor Vergata)
R. Tauraso (Univ. Rome Tor Vergata)

Foreign Collaborations

- Intern. Laser Ranging Service(ILRS)
  M. Pearlman, E. C. Pavlis
- NASA-GSFC J. McGarry, T. Zagwodski,
  D. Arnold
- Univ. Maryland, College Park
  D. G. Currie, C. Alley
- S. Turyshev (NASA-JPL)
- Sigma Space Corporation, J. Degnan

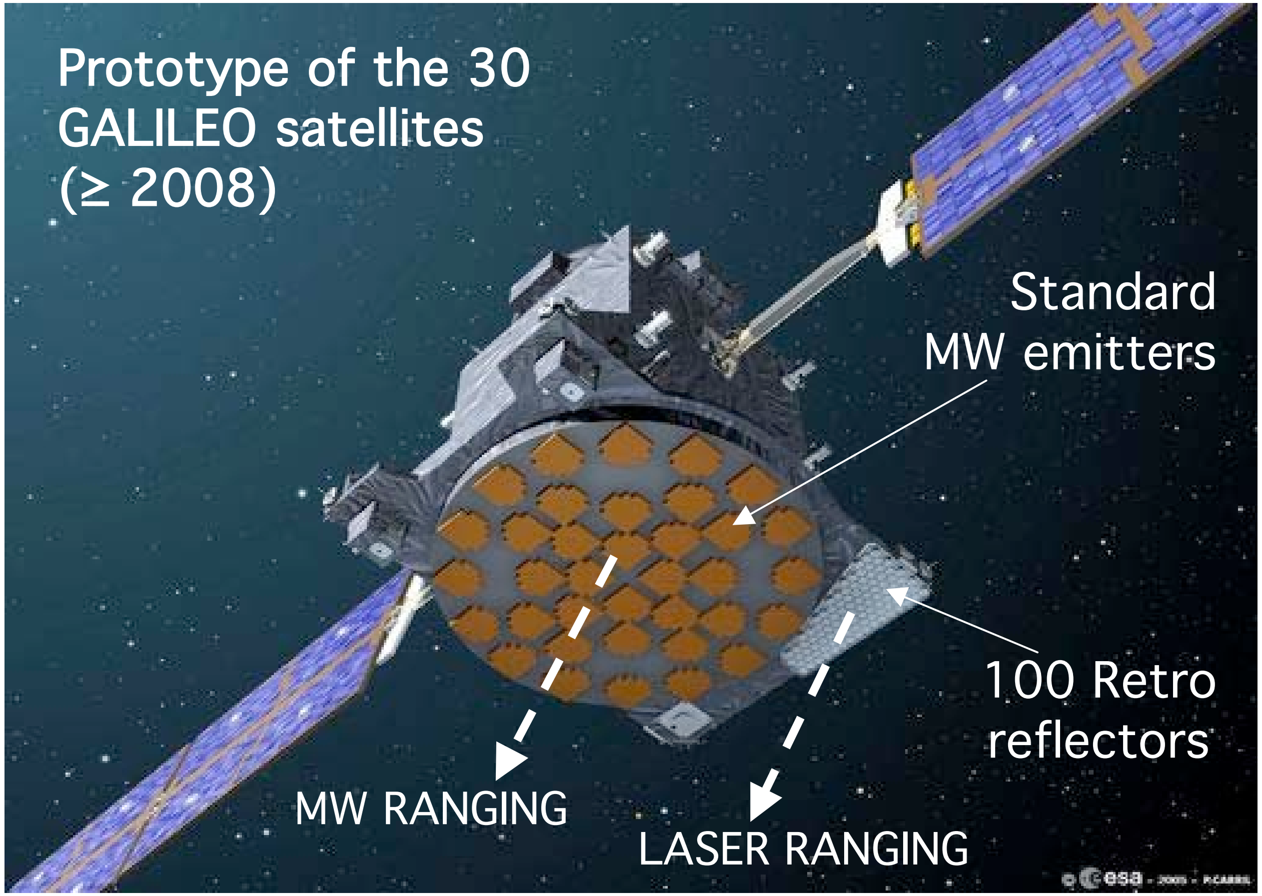
ETRUSCO projects

- Improving future GNSS in Near Earth Orbits
  - Integration of laser and MW ranging on GALILEO (EU)
  - Better understand laser ranging on GALILEO and GPS-2, then push for its integration on GPS-3 (US)
  - Map NEO space-time with 30 satellites to test accurately GR corrections
- Proposed Deep Space Gravity Probe mission
  - Develop test-masses to study $1/r^2$ in the outer solar system (the "Pioneer anomaly") and test them in the SCF
    - Largest thermal accelerations for NEO test masses (LAGEOS and LARES) are 10 times smaller than the Pioneer anomalous deceleration

GNSS Unified Constellation

MW Ranging: standard measurement of (space-)time coordinates of the "GPS" satellite with microwaves. **σ ~ 10-20 cm.** No long term memory (periodic clock re-synchronization), but great for real-time navigation

LASER Ranging**: σ ~ few mm (with complete climatic & optical characterization), absolute position wrt ITRF, long term stability (tens of yrs)**



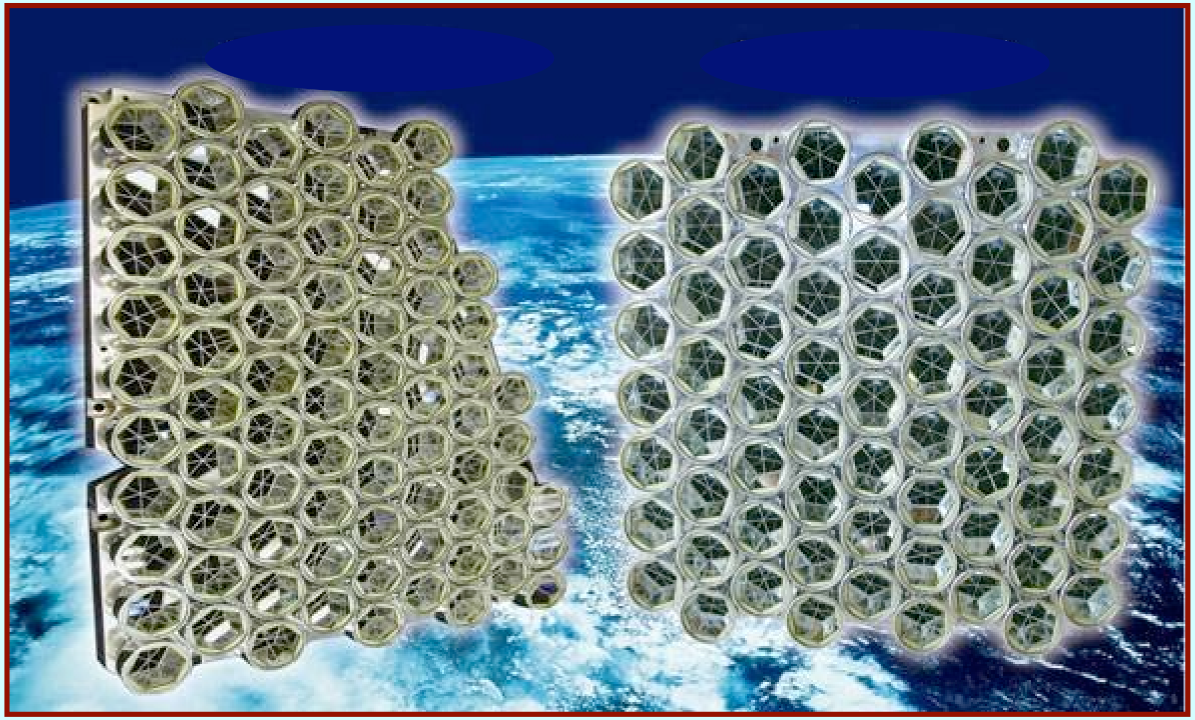
Current GNSS solid retroreflector arrays

V. Vasiliev, IPIE-Moscow; talk at FPS-06, Frascati, March 06
(see http://www.lnf.infn.it/conference/fps06/)

GALILEO TEST satellites
Orbit: h = 23200 km, i = 56°

GPS-35 } ***Orbit: h = 20200 km, i = 54°***
GPS-36 } ***Number of CCR's: 32***

GIOVE-A (76 CCRs)   GIOVE-B (67 CCRs)



“GPS3” CCR array sent by UMCP to LNF

To be launched with one of the next GPS-2 satellites

Property of Univ. of Maryland at College Park at LNF for test in the SCF

THERMAL measurements

-IR thermo-optical parameters with Earth IR simulator in the SCF/room-T

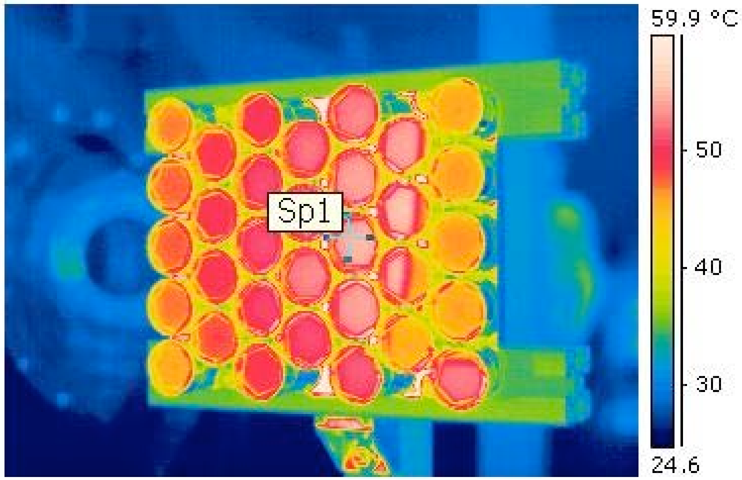
- Solar thermo-optical parameters with solar simulator in the SCF

OPTICAL measurements:

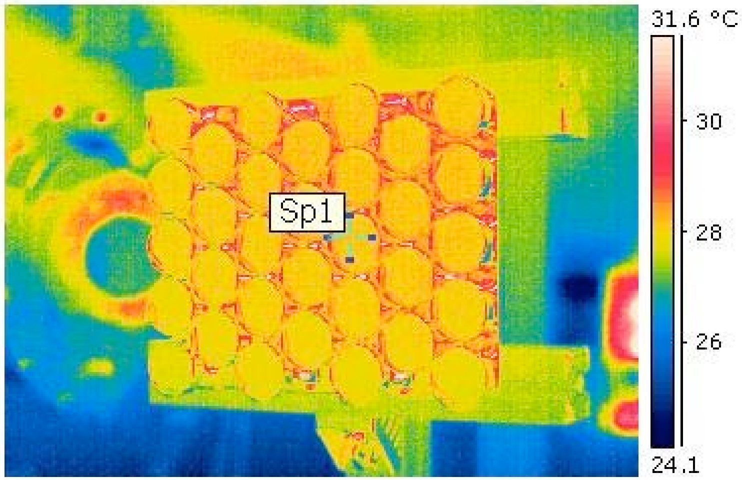
- FFDP
- Range correction

Preliminary test of UMCP GPS array at LNF

HOT
Sun on

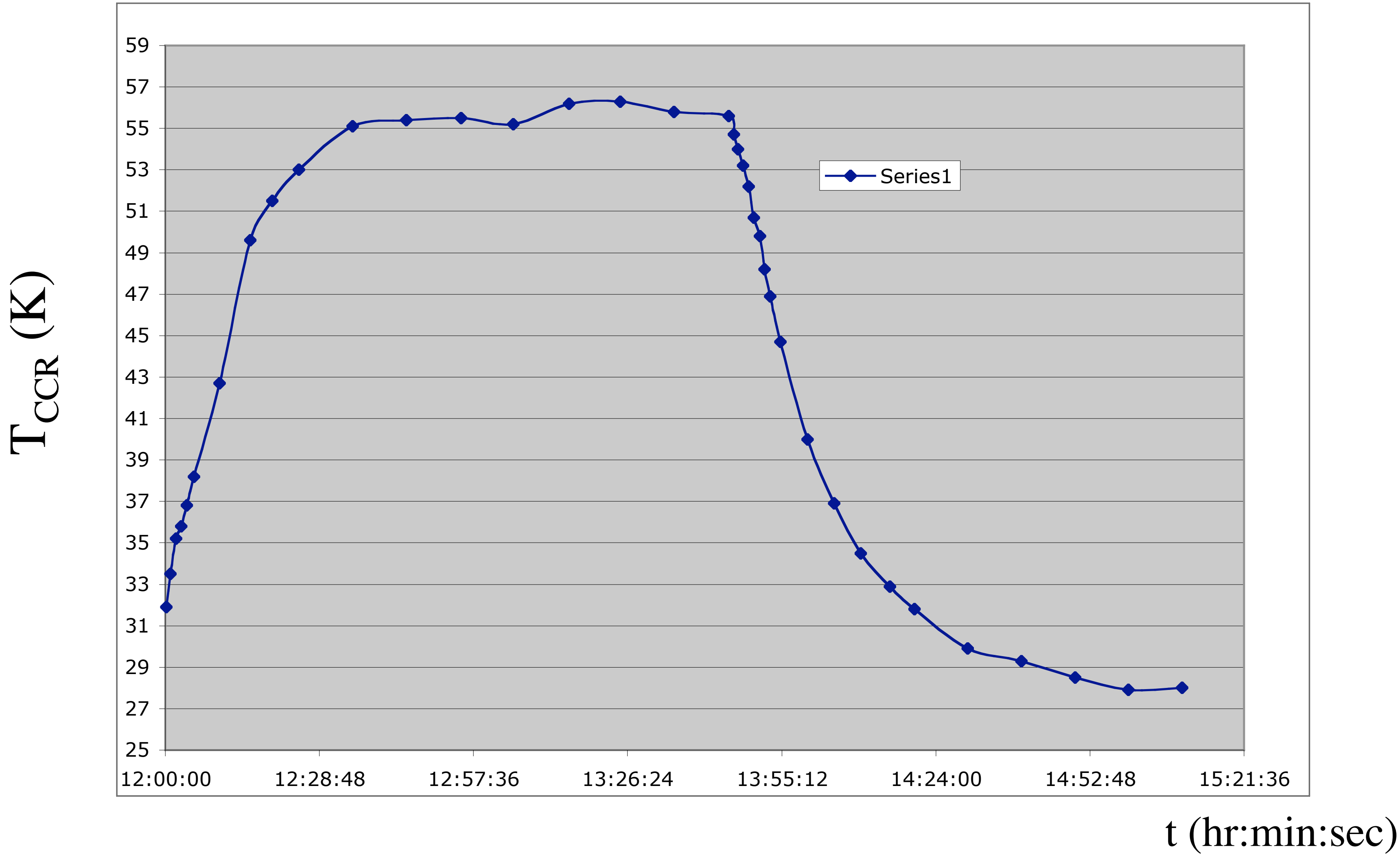


COLD
Sun off



“GPS3” cooling time constant

- Preliminary test, in air at room temperature
- 3/4 of the NEO solar constant. T vs time



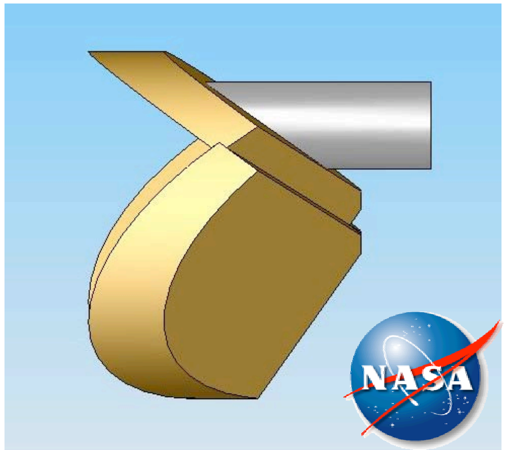
GALILEO (≥ 2008) and GPS-3 (≥ 2011)

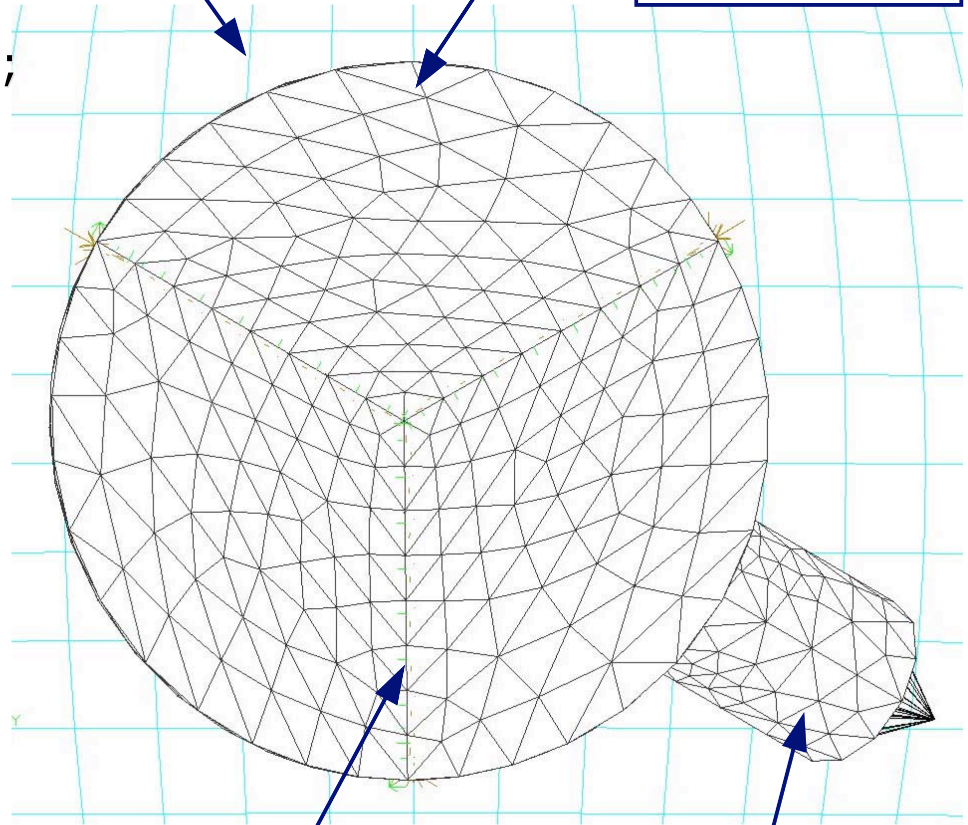
- GALILEO
  - Commercial and scientific, civilian use
  - “Unified”: 100 CCRs on each satellite
- Addition of quartz solid CCRs
  - improves performance for space geodesy and for commercial services of enormous €-value
- GALILEO puts pressure on US for GPS-3
- ILRS wants to equip GPS-3 with hollow metal CCRs
  - Develop new, state-of-art retroreflectors for GPS-3. Hollow, metallic CCRs (Be or Al)
  - Lighter and smaller than solid CCRs

Beryllium hollow CCR candidate for GPS-3

CCR modeled with ThermalDesktop sw; bonding effects between the 3 planes and the post modeled

Very crude spacecraft model: an Al sphere surrounding the CCR

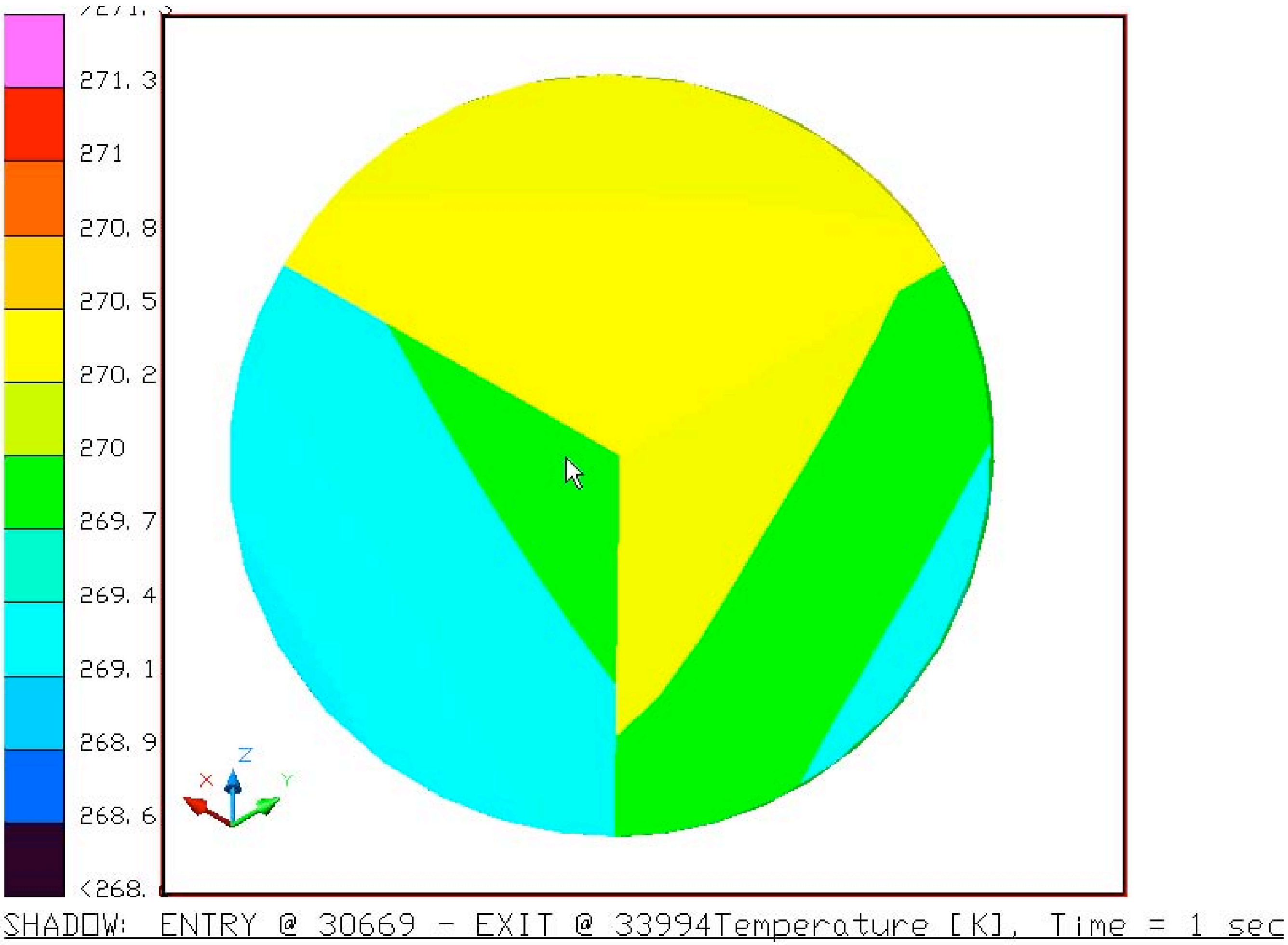




Climatic simulation of GPS-3 hollow CCR

T variation of CCR (thermally linked). Agreed plan: structural analysis by NASA-GSFC, climatic test by LNF SCF required by NASA

Delle Monache
Preliminary

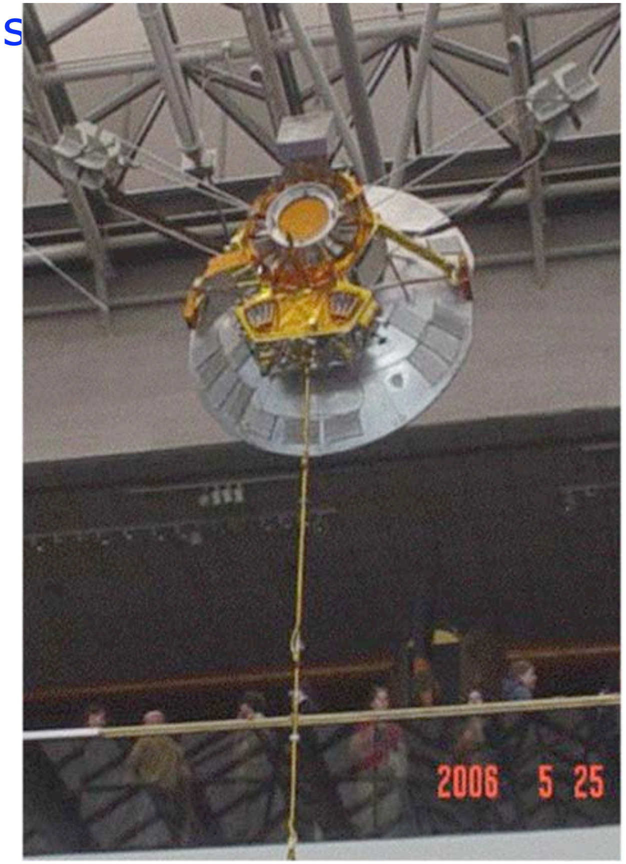


Conclusions

- The SCF built at INFN-LNF fills a research "niche" in the field of experimental tests of General Relativity, space geodesy and satellite navigation
- LARES is a very inexpensive, 2nd generation mission, based on the consolidated SLR technique. The SCF will reduce the few % error due to thermal perturbations on the Lense-Thirring measurement down to permill level
- ETRUSCO is an international, interdisciplinary project of space research. Goals:
  - GNSS: enhance performance with SLR; good potential for high-tech applied research
  - DSGP: develop SLR masses for deep space

The mistery of Pioneer deceleration

- $a_{PIO} = (8.74 \pm 1.33) \times 10^{-10}\ m/s^2$
  - ~ 10 x maximum LAGEOS thermal accelerations that we are studying with great care
- Effect of asymmetric thermal forces ?
  - forward-backward asymmetry in thermo-optical parameters ?

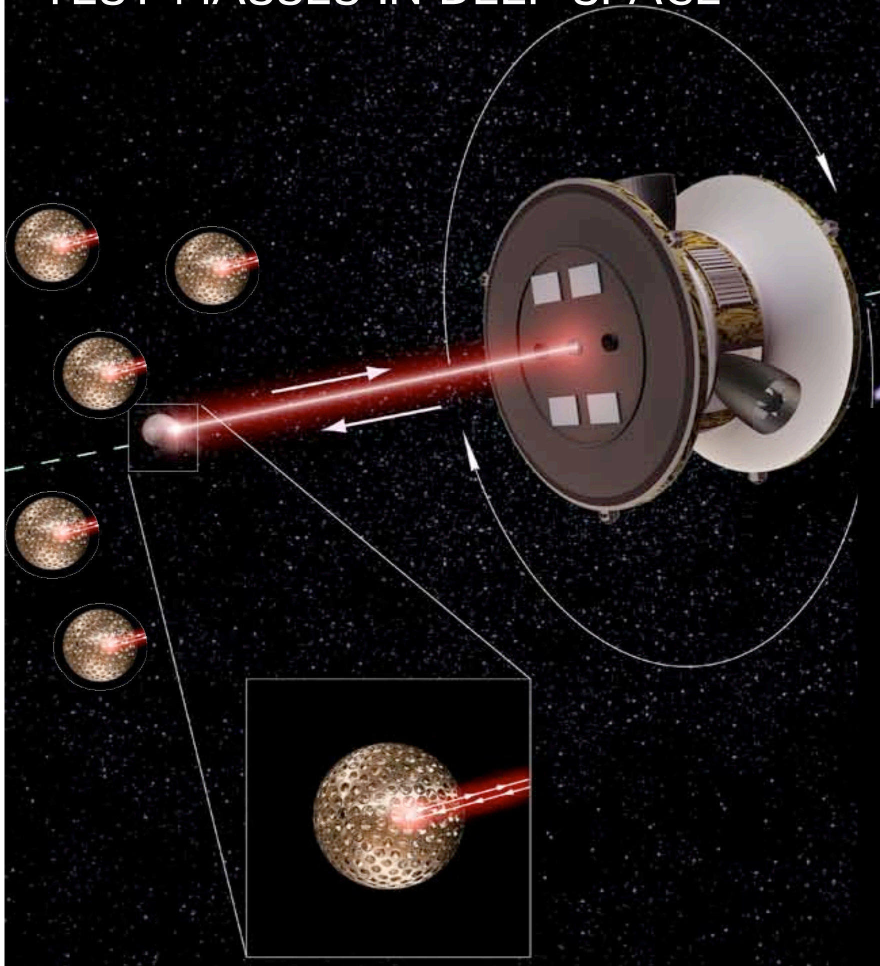


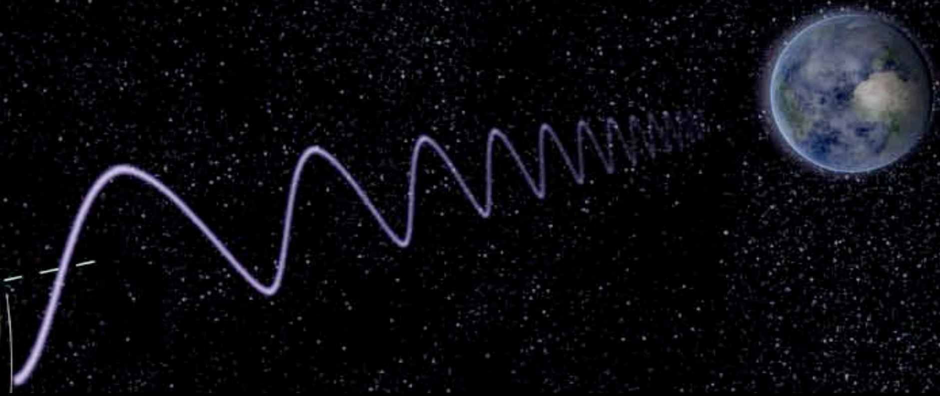
Radioisotope Thermoelectric Generators (RTGs)

Measurement Concept: Formation-flying

A CONSTELLATION OF SLR
TEST MASSES IN DEEP SPACE

Courtesy of
S. Turyshev (JPL)



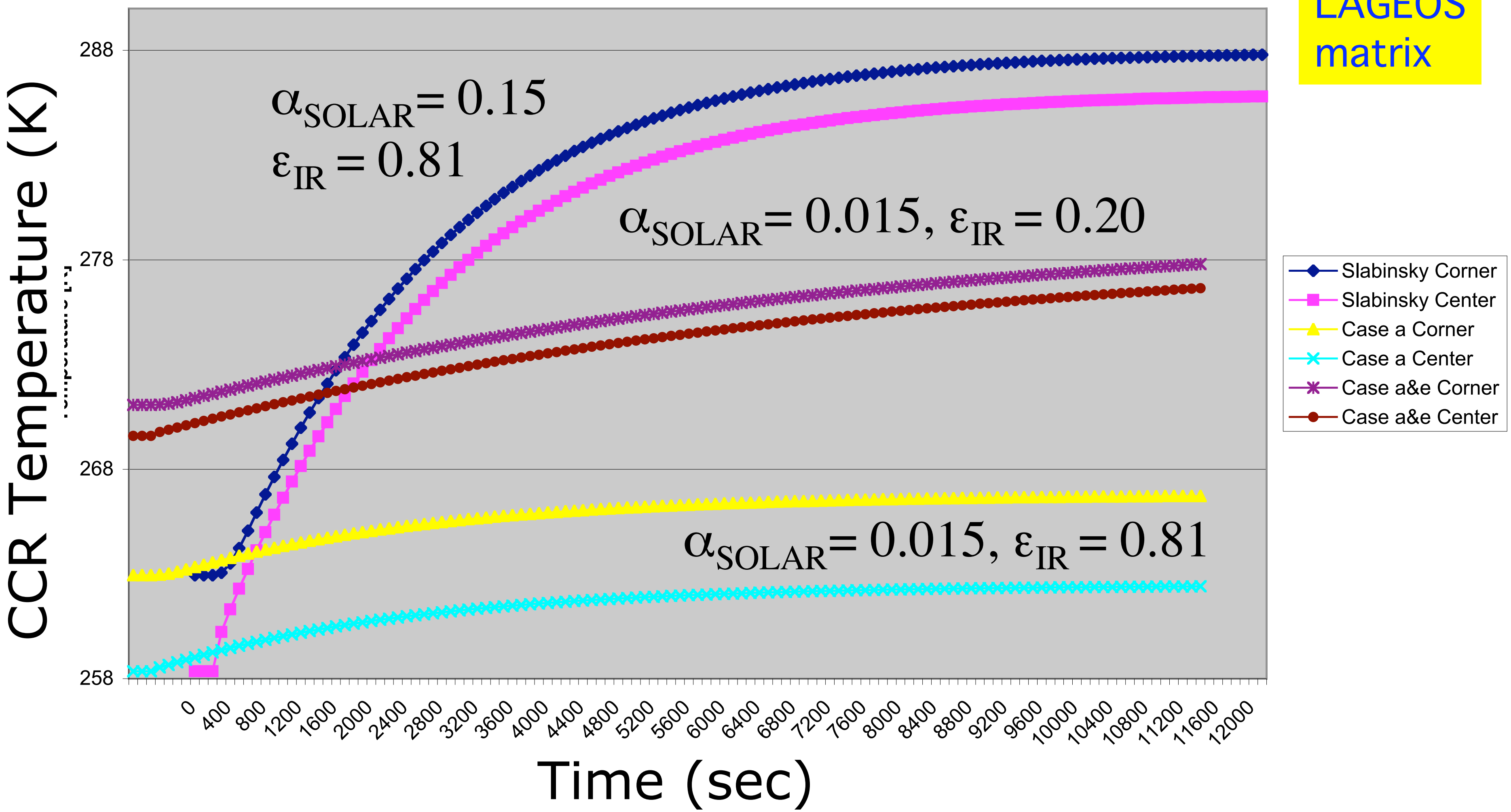


- Active spacecraft and passive test-mass
- Objective: accurate tracking of test-masses
- 2-step tracking: common-mode noise rejection
  - Radio: Earth → spacecraft
  - Laser: spacecraft → test-mass
- Flexible formation: distance may vary
- The test mass is at an environmentally quiet distance from the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

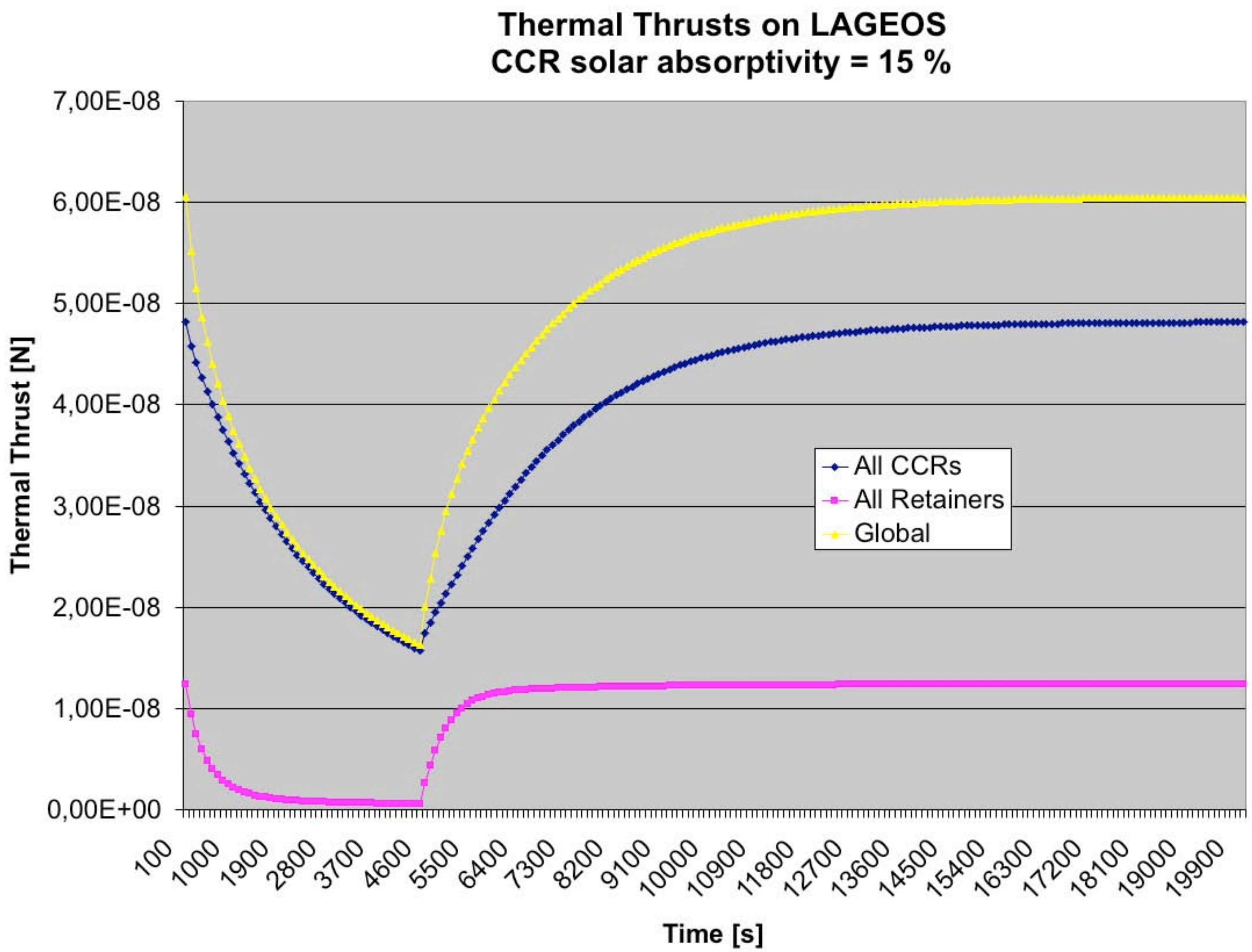
Thermal model to be tuned to SCF data

Different suprasil (CCR) thermo-optical properties
(α = absorptivity, ε = emissivity)

LAGEOS matrix



LAGEOS model of thermal thrusts for α_{SUN}=15 %



Steady state:
t=0 sec
SUN=ON

SUN=OFF for
4500 s

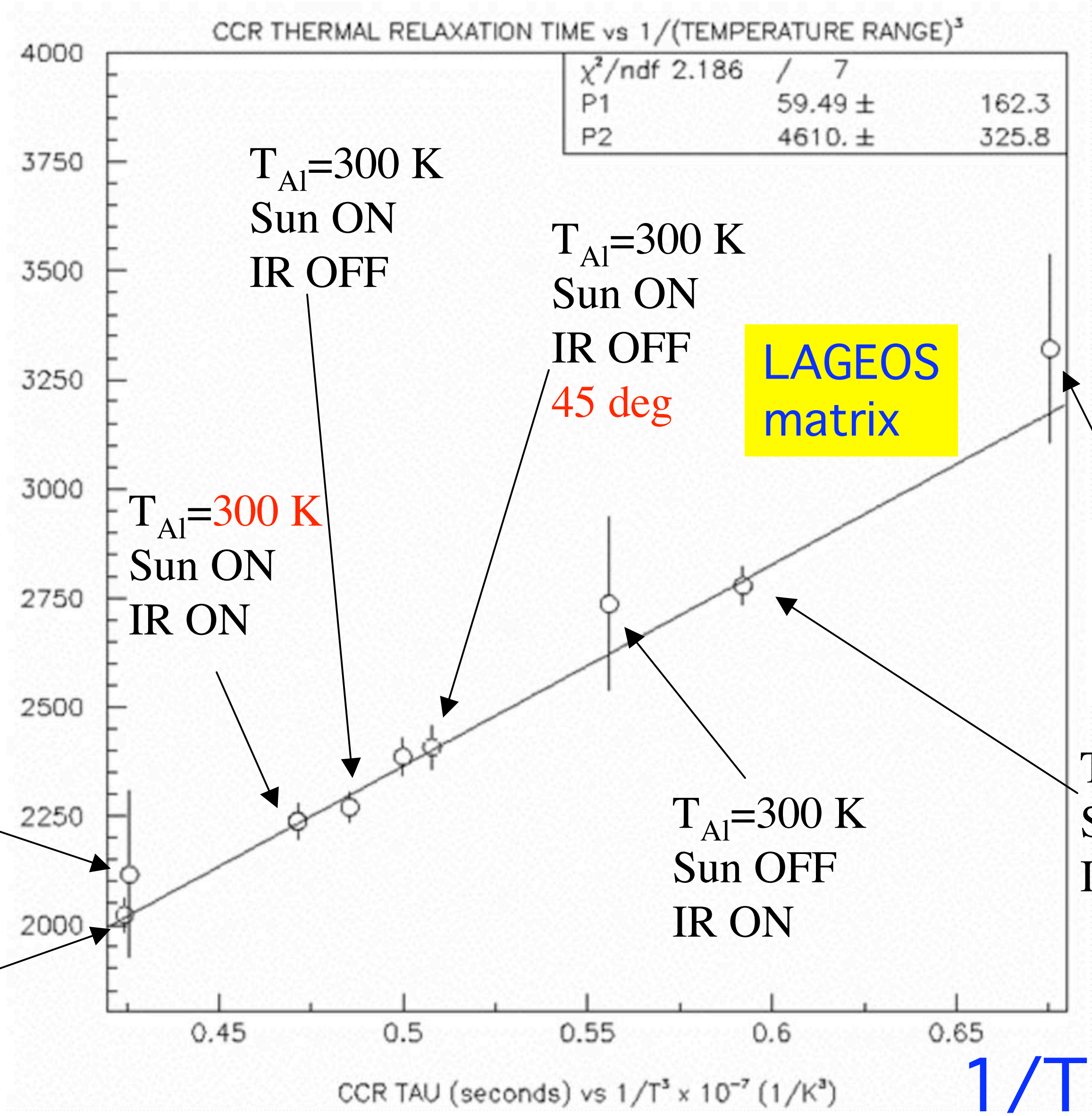
then SUN=ON.

IR always ON

Simulation results on τ_{CCR} vs Temperature

τ_{CCR} (sec) retroreflectors

Different Sun and IR conditions, incidence angle and temperature of the Al

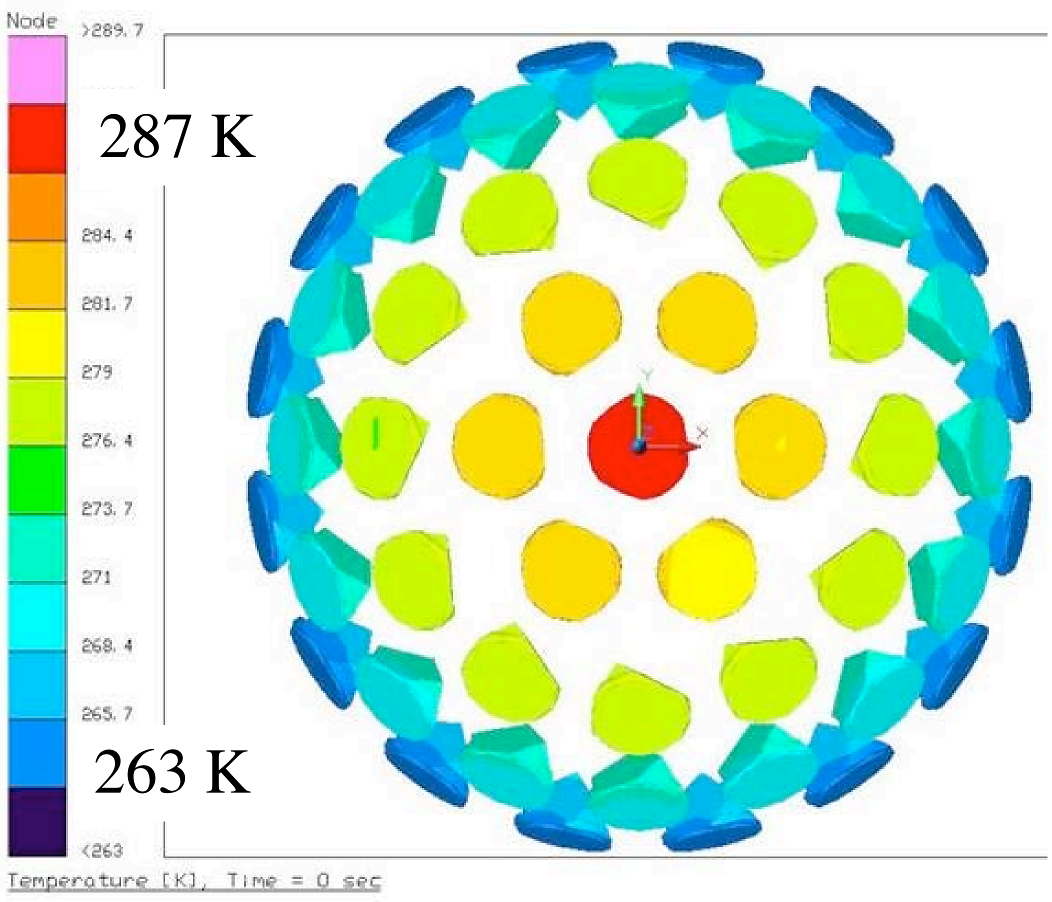


$1/T^3$ (K^{-3})

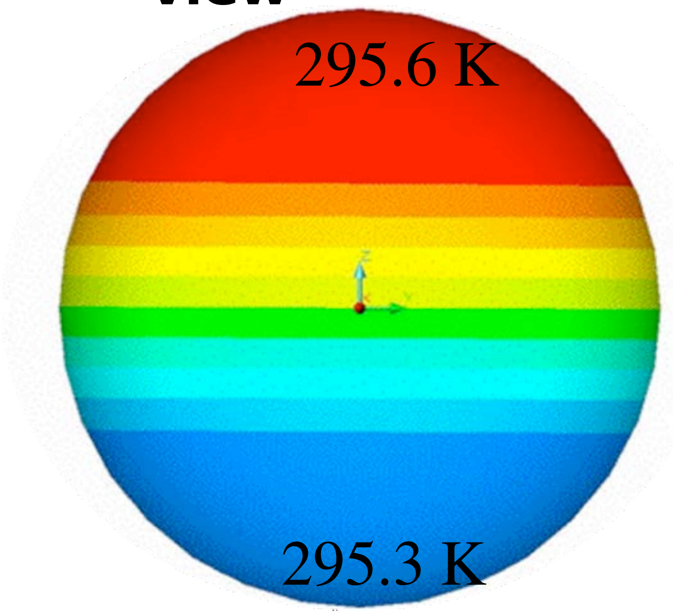
FE model and thermal simulation of LARES

- New shell-over-the-core design
- Model with15000 nodes. Being optimized
- Steady steady with LARES in front of a solar lamp

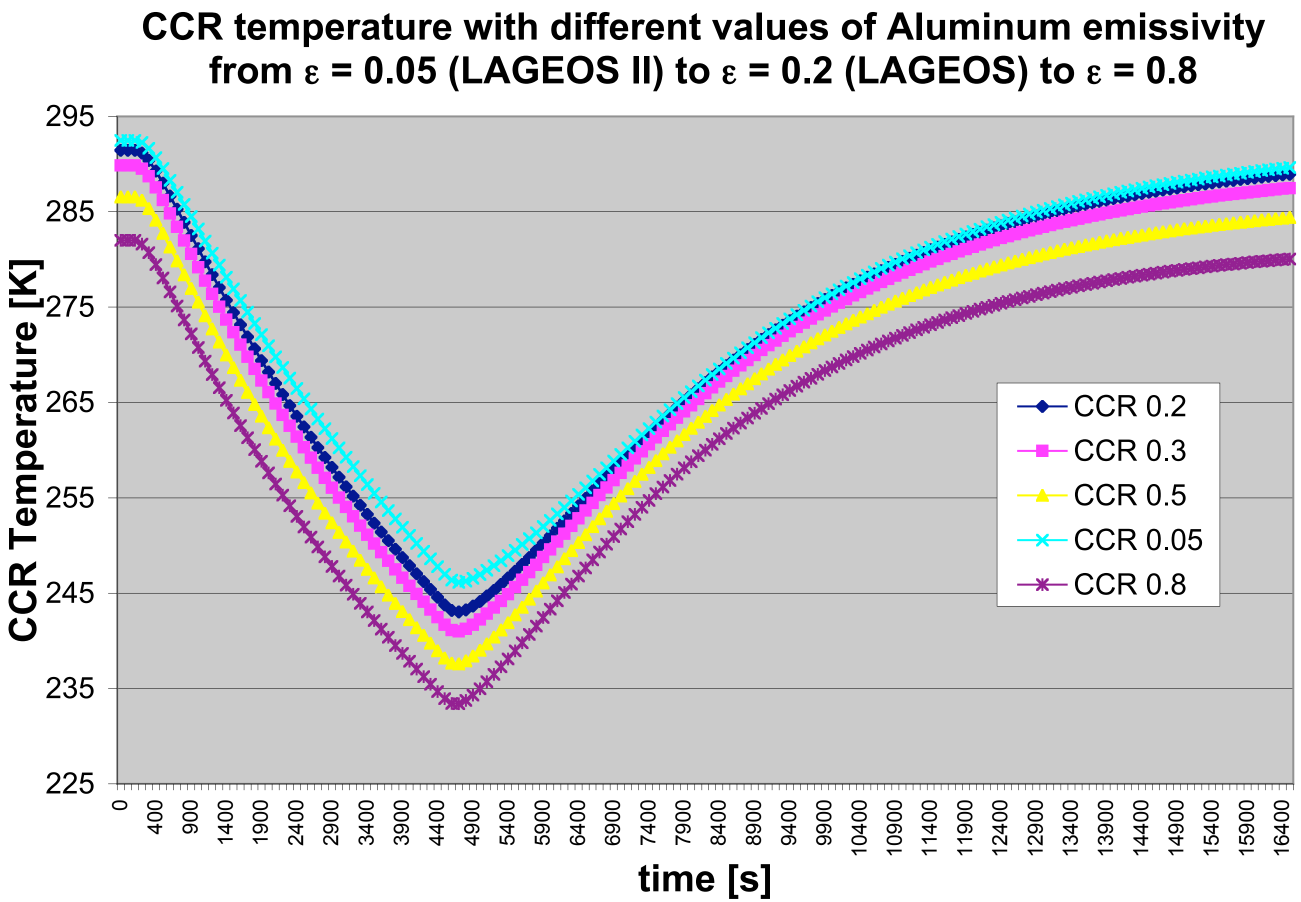
CCRs, front view



Core, side view



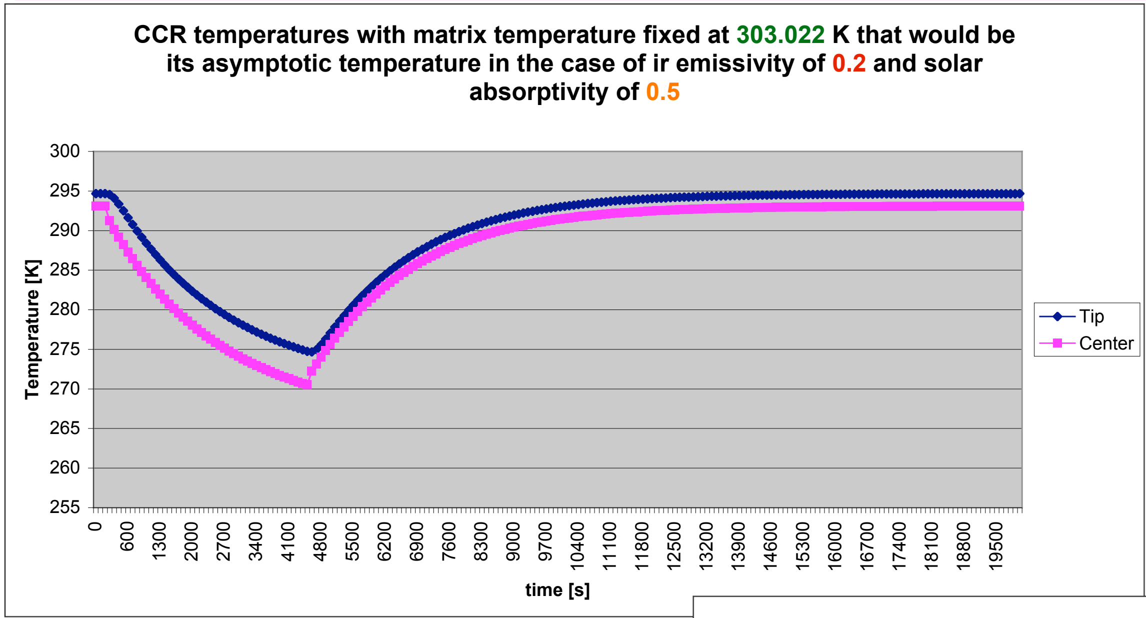
Simulation result on “ageing” of Al (IR emissivity)

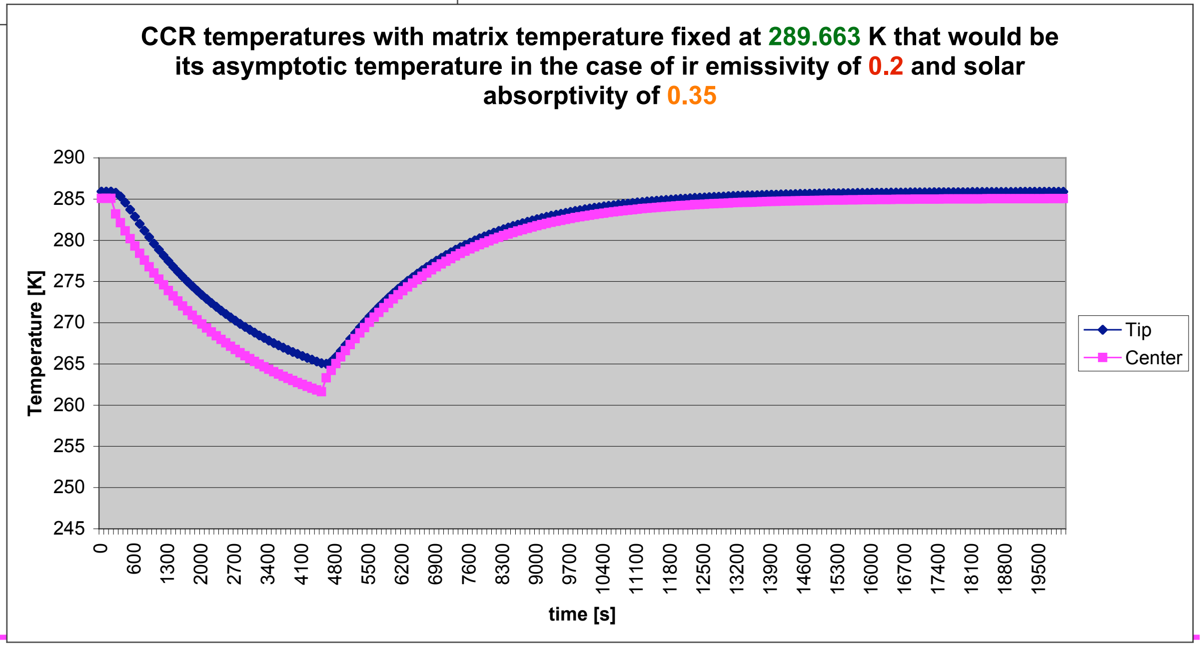


LAGEOS matrix

Temperature shifts, but shape stays about the same:
τ_{CCR} insensitive, at ≤10%, to this large variation of ε(Al)

Simulation result on "ageing" of Al (Sun absorptivity)





Misura/predizione dello spin di LAGEOS

Obiettivo: determinazione dello spin di Lageos 1 e 2 per poter calcolare le perturbazioni delle loro orbite dovute agli effetti termici

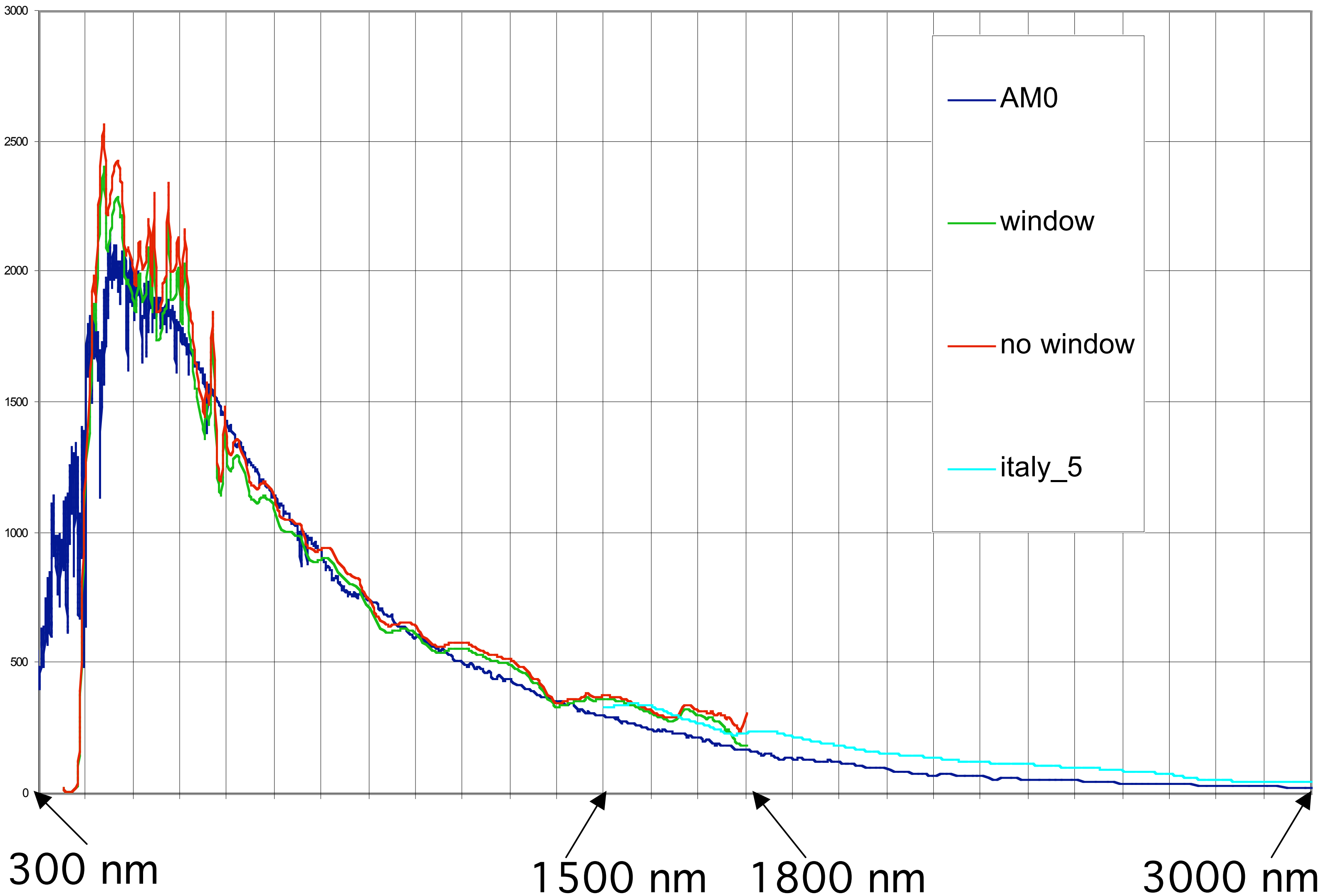
Idea:la stazione a terra traccia il satellite e registra su video le informazioni fotometriche. Quando la posizione reciproca stazione-satellite-sole lo consente vengono registrati dei rapidi **impulsi luminosi dovuti alla riflessione dei raggi solari sui CCR del satellite**. Confrontando il rapporto tra le frequenze di questi treni di impulsi e la distribuzione dei retro-riflettori sulla superficie del satellite (latitudine delle fasce di CCR rispetto all'asse del satellite e il numero di CCR per fascia) si risale all'orientazione dello spin e alla sua velocita' angolare (tesi di Ph.D. di Petras Avizonis, Relatore Douglas Currie, University of Maryland at College Park - UMCP)

Problemi: le posizione geometriche stazione-satellite-sole (e le condizioni meteo) propizie per una misura efficace durano pochi secondi quindi per ottimizzare l'impiego di una stazione nell'osservazione **bisogna prevedere delle accurate finestre-temporali**. Inoltre ci sono diverse ore di registrazione non ancora visionate dalla cui analisi potrebbe emergere un interessante confronto con i dati prodotti dal programma LOSSAM sviluppato da Nacho Andres (DELFT Technical University).

Realizzazione: sviluppo di un pacchetto Mathlab per:

- calcolo per un certo istante (UT) della posizione nel sistema di riferimento J2000 del sole, della stazione e del satellite (TLE+ propagatore SGP4)
- **analisi video**: dati gli istanti degli impulsi riflessi in un intervallo di tempo, calcolo dello spin
- **previsioni**: dato lo spin, calcolo per una certa finestra temporale di azimuth e altezza del satellite nel cielo della stazione e degli istanti degli eventuali impulsi riflessi.

Extended AM0 spectrum (400 - 3000 nm)



Simulation of the optical performance of baseline LARES

Simulation by Dave Arnold
(designed LAGEOS optical configuration)

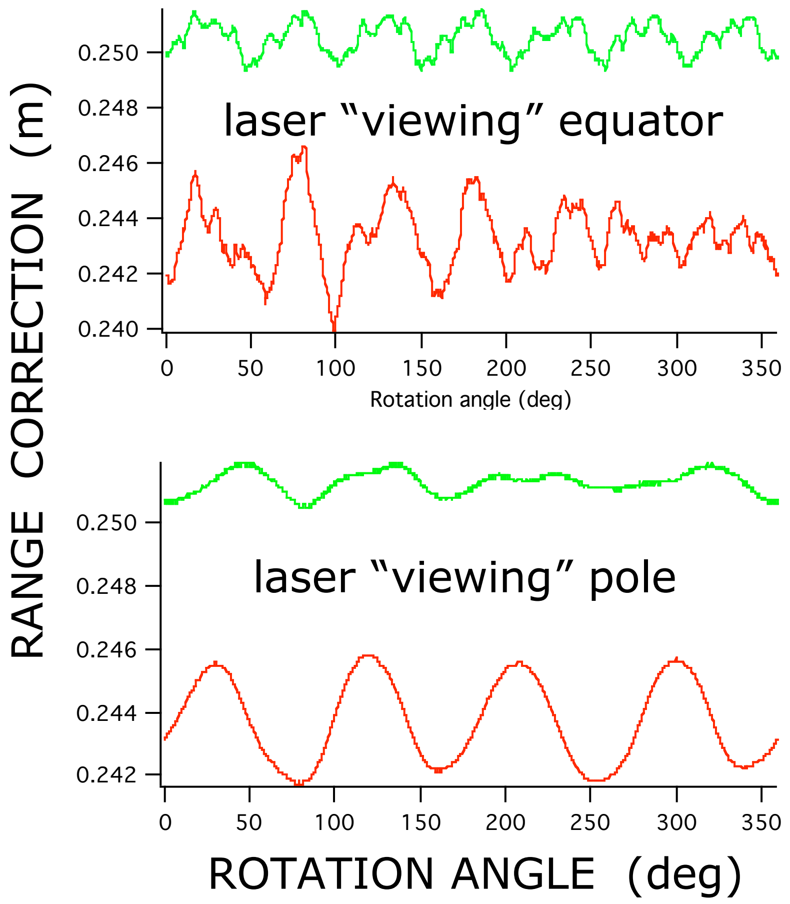
LAGEOS & LARES have same CCRs.

LAGEOS has ~4 times as many cubes: ranging better by ~ 2.

LARES is half the size: range variations smaller by ~ 2 if there were the same number of cubes.

Since LARES has fewer cubes the two effects cancel each other so that the variation in the range correction is **about the same as LAGEOS**

LAGEOS range correction~ ∅/2



The top curve (green) in each plot is the half-max range correction.
The bottom curve (red) is the centroid range correction.

Optical characterization: the “range” correction

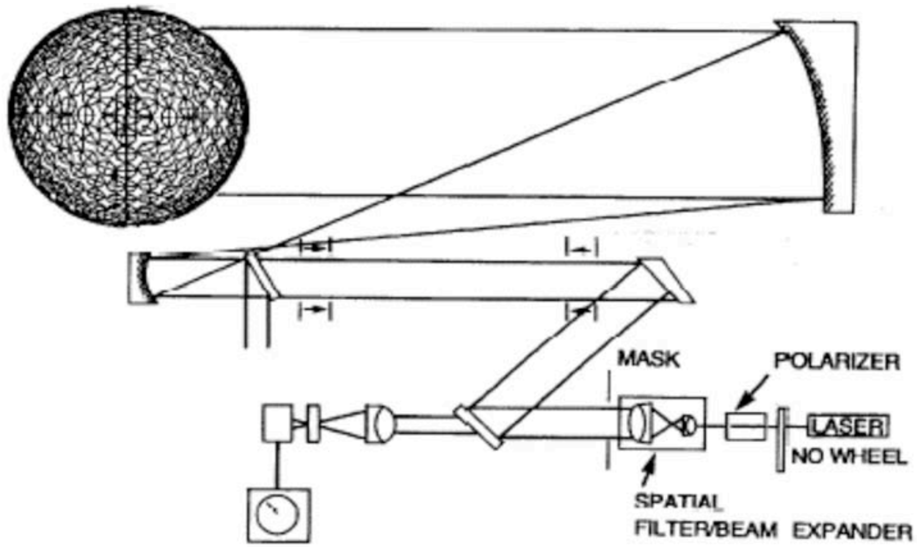
Test 2: Ranging test (array or sphere)

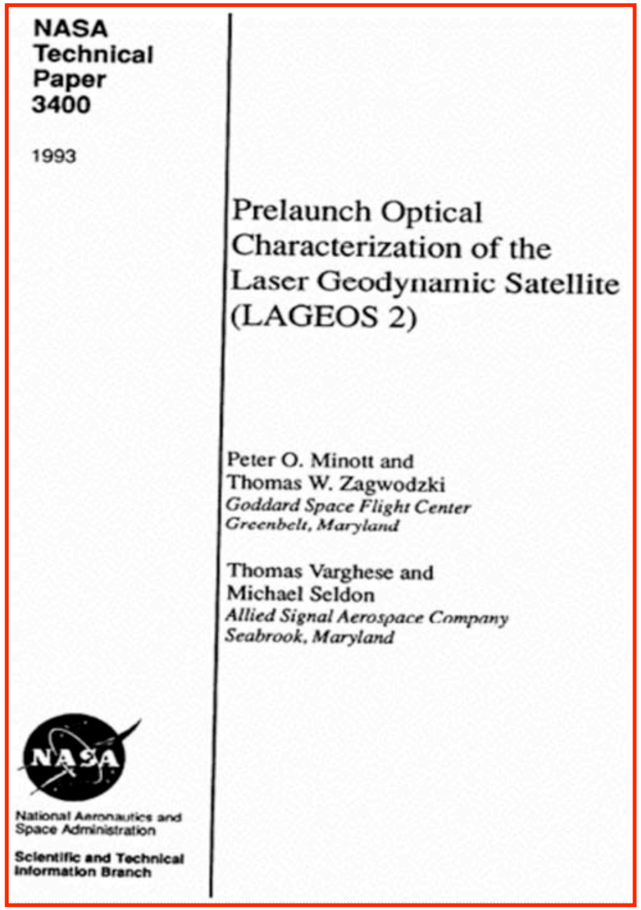
Collaboration w/ILRS, GSFC, ASI-MLRO

- Pulsed laser timing unit (start time)
- Microchannel Plate Photomultiplier or Streak Camera (stop time)
- Mirror to expand the laser beam - ***need to buy it***
- Test to be done at the Matera ASI laser-ranging station (ASI-MLRO). Streak camera from LNF/ENEA.

Repeat test inside the SCF

Test the actual measurement of Δt = (t_arrival - t_start) after retro-reflection from satellite. Satellite distance = Δt x c.





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

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Greenbelt, Maryland

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

National Aeronautics and Space Administration

Scientific and Technical Information Branch

LAGEOS I prototype sent by NASA-GSFC to LNF

LAGEOS I sand-blasted Al: ε(IR)=20%

LAGEOS II, instead, had ε(IR) = 5%

We are getting the LAGEOS II eng. model

GNSS observation with laser ranging

- HOLLOW CCRs: long term stability and performance in space environment to be proven

Calculations by D. Arnold, ILRS meeting at EGU, April 06, Vienna

Simulations at Galileo altitude for Effective Cross Section of 100 million sq. meters.				
Design	# of cubes	Diam. (inch)	Approx. Area of the cornercubes (sq cm)	Approx Mass of the cornercubes (gm)
uncoated	50	1.3	428	1000
coated	400	0.5	508	460
hollow	400	0.5	508	201
hollow	36	1.4	356	400
Present GPS cubes	160	1.06	1008	1760

Important acronyms

- GNSS = Global Navigation Satellite System
- IGS = International GNSS Service
- GPS = Global Positioning System; american GNSS constellation
- GLONASS = current russian GNSS
- GALILEO = *new* European GNSS from 2008
- NEO = Near Earth Orbits
- DSGP = Deep Space Gravity Probe; proposed mission
- GR = General Relativity
- ILRS = International Laser Ranging Service
- LAGEOS I, II = Laser Geodynamics Satellites (launch: ‘76, ‘92)
- LARES = Laser Relativity Satellite; proposed to INFN-GR2
- SCF = Space Climatic Facility; built at LNF for LARES & ETRUSCO

Simplified view of ITRF and GNSS

- ITRF = absolute cartesian International Terrestrial Reference Frame; ORIGIN = Geocenter = Earth Center of Mass. This is the basis of any local/national geodetic network
- Satellite Laser Ranging defines Geocenter and SCALE of length
- VLBI (Very Long Baseline Interferometry to distant quasars with radio-telescopes) defines ORIENTATION
- GNSS provides real-time navigation on Earth and in NEO with respect to ITRF