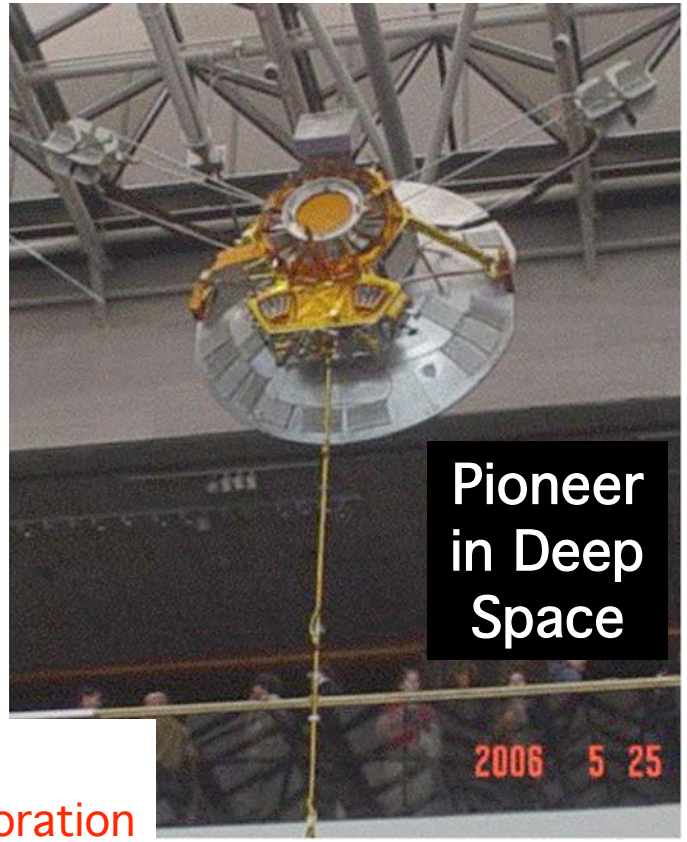
Probing Gravity in the Solar System with ETRUSCO

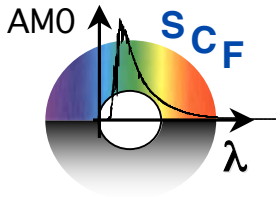
Extra Terrestrial Ranging to Unified Satellite COnstellations

S. Dell'Agnello, INFN-LNF
(Resp., 30%)
G. Delle Monache, INFN-LNF
(30%)
C. Cantone, INFN-LNF
(Bors. INFN, 30%)
M. Garattini, INFN-LNF
(Bors. INFN, 30%)
G. Bellettini, Roma2
(PO, 30%)
TOTAL = 1.5 FTE



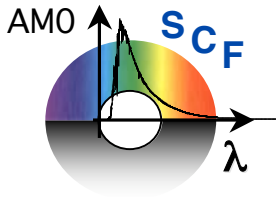
Slava Turyshev, NASA-JPL, Spokesman of the
"Pioneer Explorer and Deep Space Gravity Probe" Collaboration

Outline



- Probing gravity in the Solar System
- ETRUSCO concept and goals, in brief (slides 5-9)
- “Unified” GNSS constellations
- The existing INFN-LNF Space Climatic Facility (SCF)
- Analysis of PIONEER data and the new proposed “Unified” satellite formation, DSGP
- Conclusions (slide 41)
- Group and financial requests (slides 42-45)

Experimental tests of General Relativity



Space-time curvature in GR, Cassini probe:

$\gamma = 1 \pm 2 \times 10^{-5}$

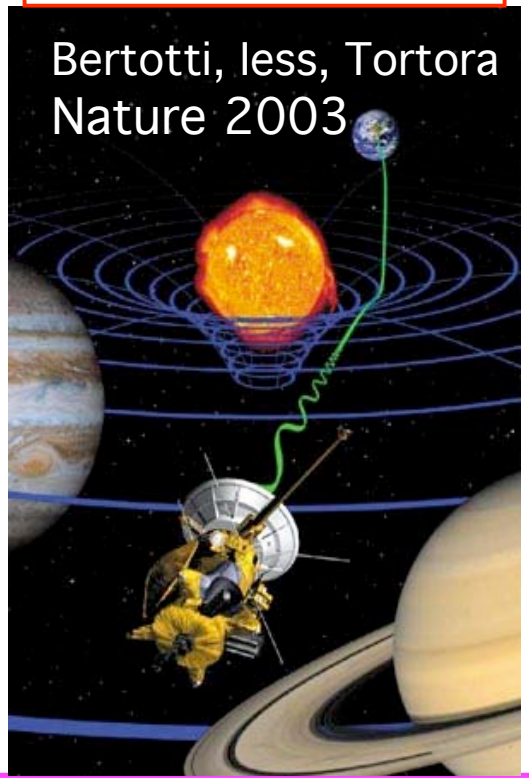
γ(GR) =1

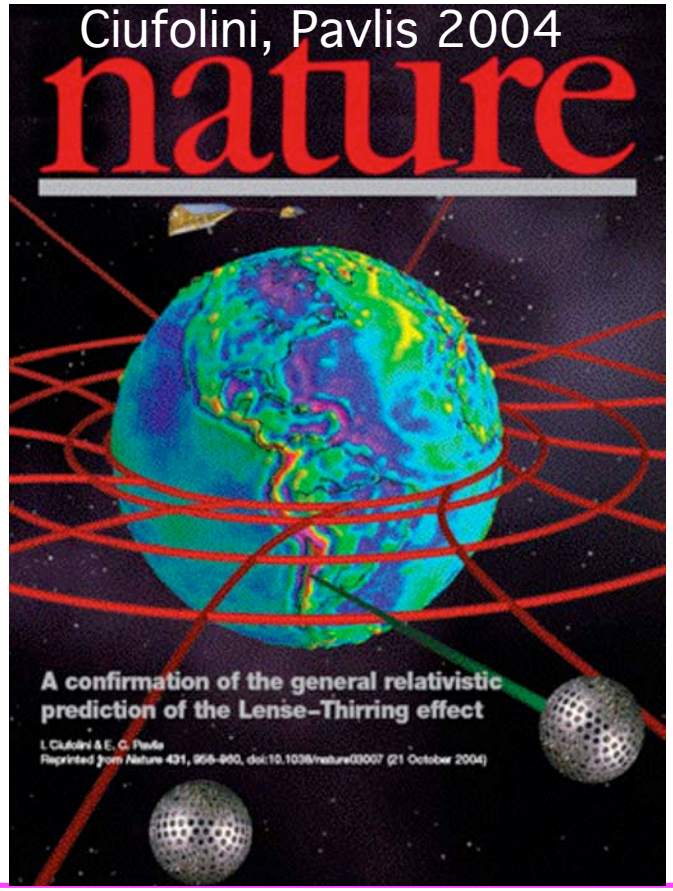
γ (Newton) =1/2

Dragging of space-time in GR, LAGEOS satellites

$\dot{\Omega}^{L-T}$ = 99% x GR value (± 5-10% error)

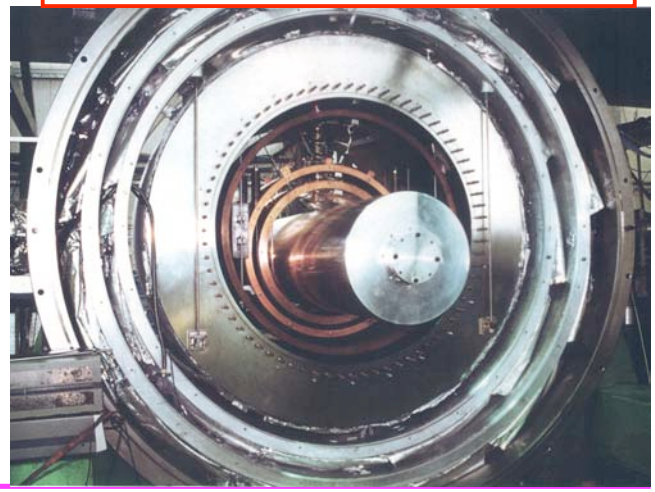
LARES satellite (INFN-GR2) to get ≤ 1% error



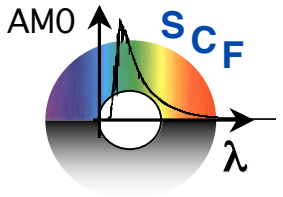


Gravitational waves of space-time:
'the' most important dynamical test of GR

NAUTILUS @ LNF

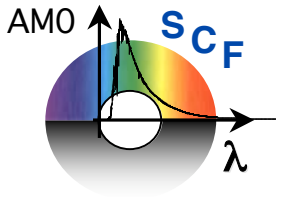


Laboratory physics of General Relativity



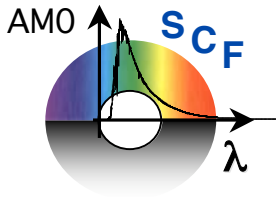
- The Solar System is our laboratory
- Near Earth Orbits (NEO)
  - Accurate measurement of space-time coordinates of "Global Positioning" satellite constellations
    - **GPS-3** (USA), **GALILEO** (Europe)
- Deep Space
  - Study of the anomalous deceleration of the **PIONEER**s (72-02). Test of $1/r^2$ law in Deep Space
    - Publish a technology paper on thermal re-analysis of the Pioneers
    - Publish a physics measurement on the $1/r^2$ test
  - In parallel, by the end of 2006, propose the new mission: **Deep Space Gravity Probe**, for the ESA Cosmic Vision Program

The ETRUSCO concept



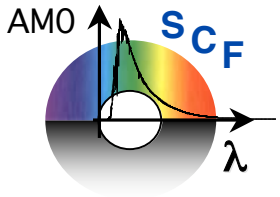
- "Extra Terrestrial Ranging": measurement of space-time positions of active satellites or passive test-masses in space with electromagnetic waves (ranging)
- Use two "Unified Satellite COnstellations" to probe gravity in the solar system
  - GNSS (Global Navigation Satellite System) in NEO
    - GALILEO (30 active satellites, 29601 Km altitude)
    - GPS-3 (30 active satellites, 20195 Km altitude)
    - ITRF: International Terrestrial Reference Frame
  - Deep Space Gravity Probe (DSGP)
    - Satellite formation of 1 active spacecraft + a few passive test masses
    - Outbound orbit, spanning the whole solar system
    - ICRF: International Celestial Reference Frame
- "Unification": addition of LASER ranging to MICROWAVE ranging

Goals of ETRUSCO for GNSS



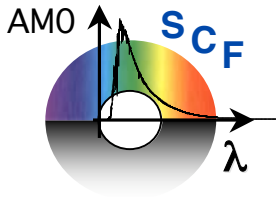
- Physics goals
  - high-accuracy experimental map of space-time with a high-multiplicity satellite constellation
  - Excellent data set for rigorous and non trivial definition of the most-general non-inertial reference frames in GR
- Technological goals
  - GALILEO is “unified” (laser ranging included in the design)
    - So far, traditional retro-reflectors are foreseen : solid, fused-silica CCRs
  - GPS-3 is to be “unified” (ie to convince US agencies to add laser ranging)
  - Upgrade the LNF Space Climatic Facility (SCF) to perform a dedicated climatic and optical characterization of retro-reflectors arrays for GNSS conditions (20000-29000 Km altitude)
  - Develop new, state-of-art retroreflectors
    - Hollow, metallic CCRs (Be or Al). Lighter and smaller than solid CCRs

Goals of ETRUSCO for DSGP



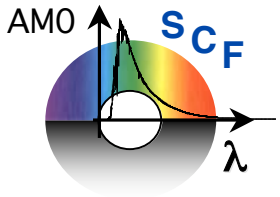
- Physics goals
  - Test of 1/r2 law in deep space. Unique to Pioneers/DSGP
- Technological goals:
  - Use our expertise for a critical thermal analysis of Pioneer data to find out if anomalous deceleration is due to an instrumental effect. Never done before. Radioactivity on board is the suspect
  - Test small samples and components of the Pioneers at the LNF SCF
  - Design laser-ranged spherical test masses for DSGP, the first-ever unified satellite formation in deep space. Here our expertise with the design and test of LARES is crucial
    - LARES designed to be the most accurate laser-ranged test mass ever
    - LARES typical thermal accelerations in NEO are 1/10th of Pioneer anomalous decelerations: so we are already dealing with fractions of the effect of interest
    - If LARES, as designed for NEO, were to be sent to Saturn and beyond, thermal accelerations on it would be 1/100th than in NEO, because the solar constant $\propto 1/r^2$ => so known thermal effects on a LARES in deep space would be 1/1000th of the Pioneer anomalous deceleration

Truly international, inter-agency effort



- Overall study proposed to ASI for 2006-2008 by this LNF group
- International collaboration with:
  - International Laser Ranging Service (ILRS): E. C. Pavlis et al
  - Univ. of Maryland at College Park (UMCP): D. Currie et al
  - NASA-Goddard Space Flight Center (GSFC): J. McGarry et al
  - NASA-Jet Propulsion Laboratory (JPL): S. Turyshev et al
- GNSS
  - GPS-3: formal collaboration with ILRS, NASA-GSFC, UMCP
  - GALILEO: we did not contact the GALILEO consortium, yet ! We'd like to do it with ETRUSCO. If we succeed in performing the climatic/optical characterization of their retro-reflectors, it would also be a major, winning, high-profile technological application of INFN research. GALILEO is worth billion €'s
- Pioneer/DSGP
  - Collaboration with NASA-JPL, Germany, France, ASI
  - DSGP mission to be proposed to ESA by Jan 2007

Truly interdisciplinary effort



- The ETRUSCO project requires knowledge of:
  - General relativity
  - Space navigation
  - Space geodesy
  - Cryogenics and vacuum
  - Space climate
  - Thermography with IR camera and probes
  - Lasers and optics analysis
  - Precision mechanics and mounting
  - Finite element, finite difference modeling
  - Thermal analysis for satellites
  - Physics data analysis

LNF SCF & Cryo service

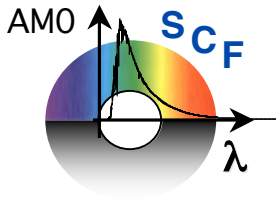
LNF ex-Virgo optical bench

LNF Mech. service

LARES expertise

- With the SCF, our professional international collaborators, plus some extra support from INFN-GR5 … we can do it !

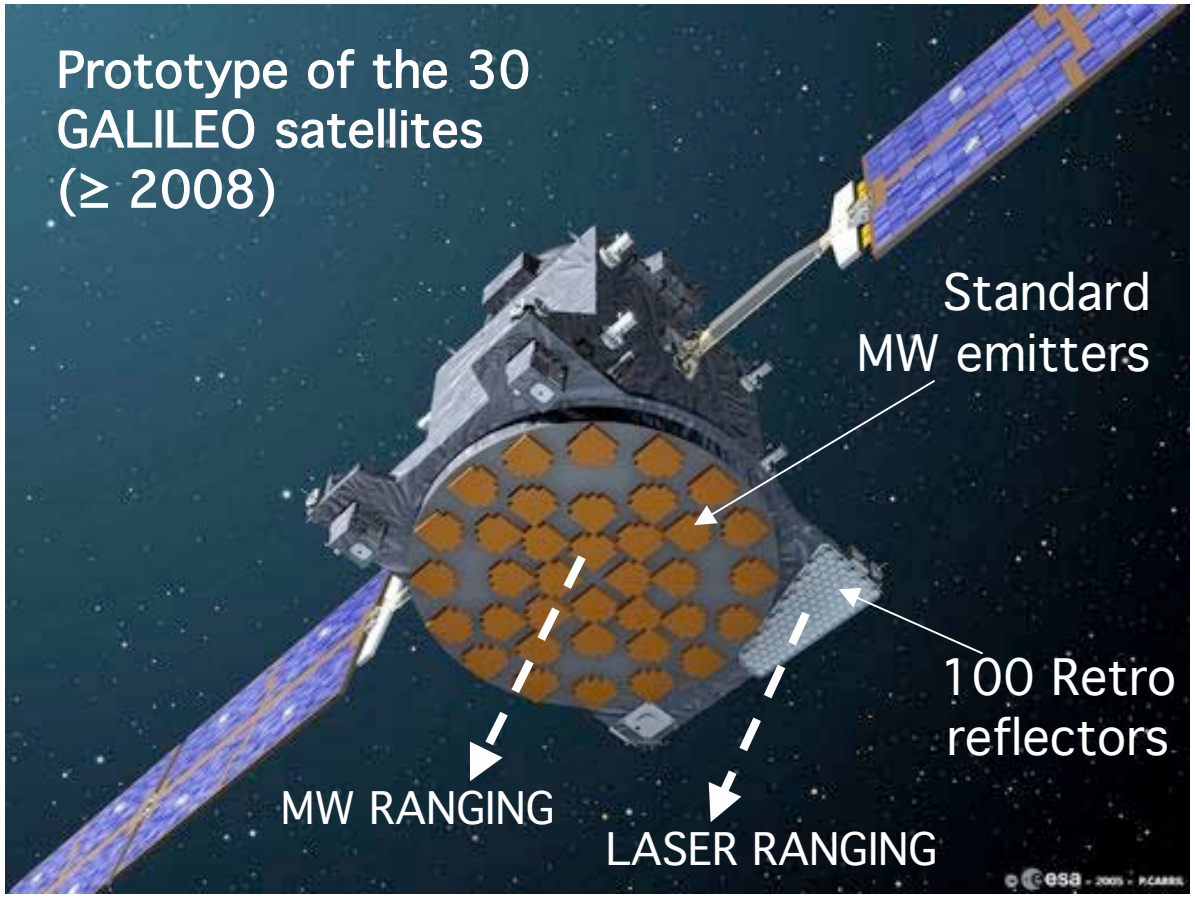
A Global Positioning Unified Constellation



MW Ranging: standard measurement of space-time coordinates of a test mass (the "GPS" satellite) with microwaves. σ ~ 10-20 cm

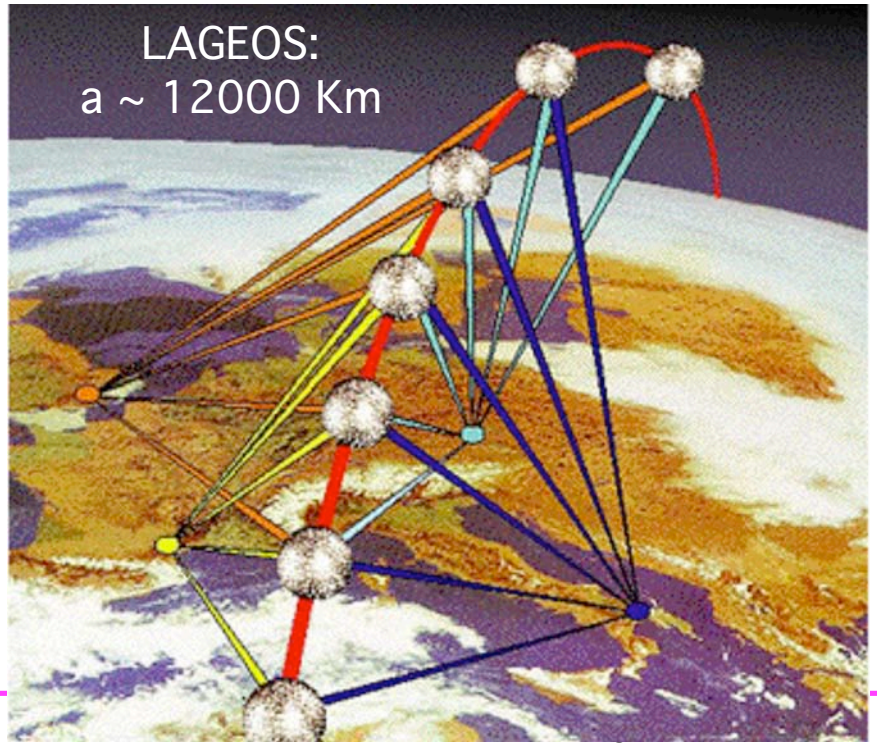
No long term memory (clock re-calibration) but great for real-time navigation

LASER Ranging: retro-reflectors (CCR) and optical waves. σ ~ few mm, absolute position standard, long term stability (tens of yrs)

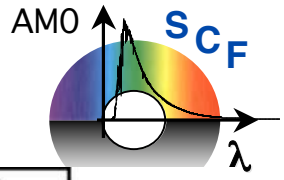


Satellite Laser Ranging (SLR)

- Orbit accuracy < 1 cm
- Orbits used to define the International Terrestrial Reference Frame (ITRF)
  - Issued by IERS = International Earth Reference Service
  - "The" stardard for all civilian, commercial and scientific activities

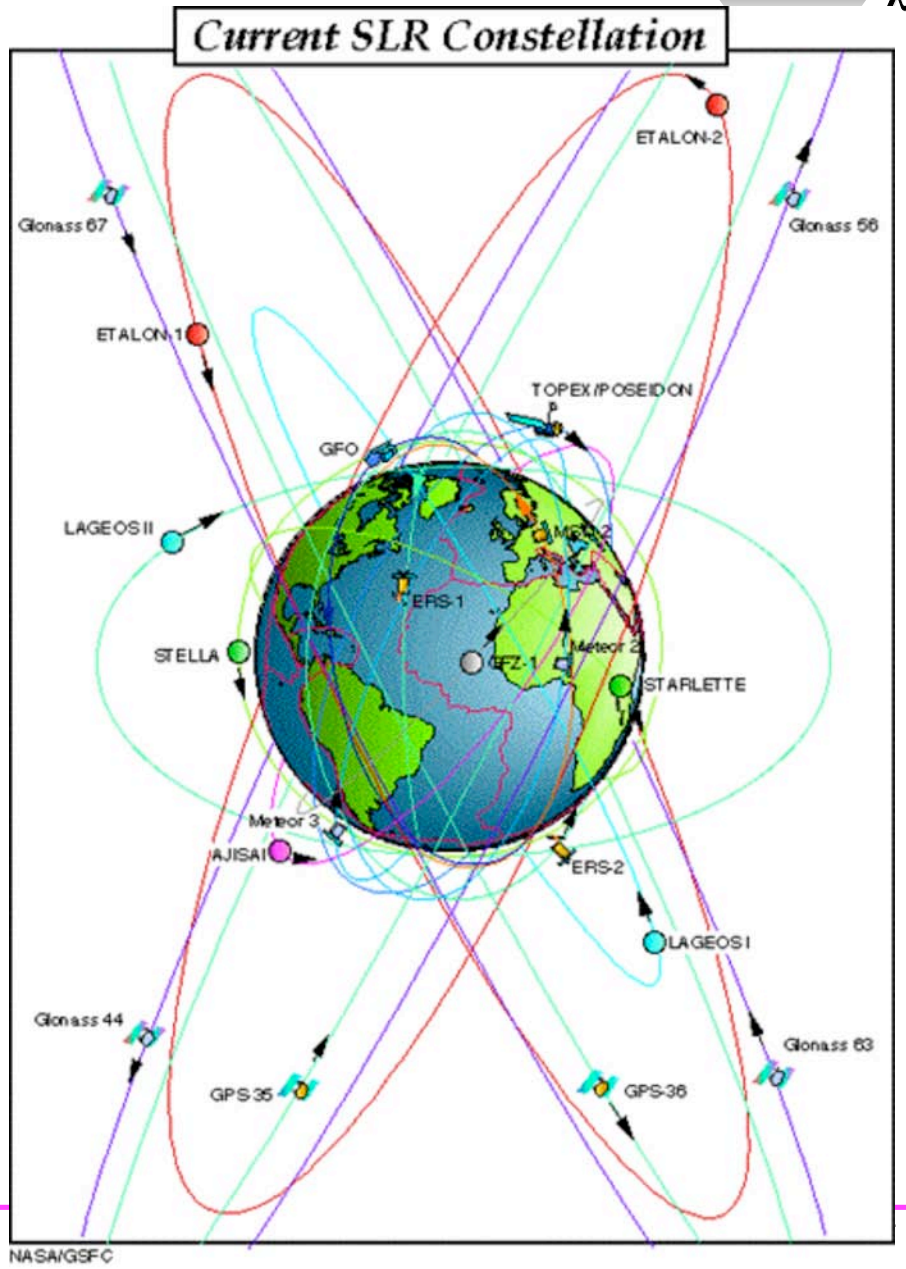


Current laser ranging constellation



Satellite distances:
400 Km to > 20000 Km
for GPS/GLONASS

Now only 2 GPS-2 (USA) and 4 GLONASS (Russia) satellites have retro-reflectors (traditional solid CCRs made of fused silica)



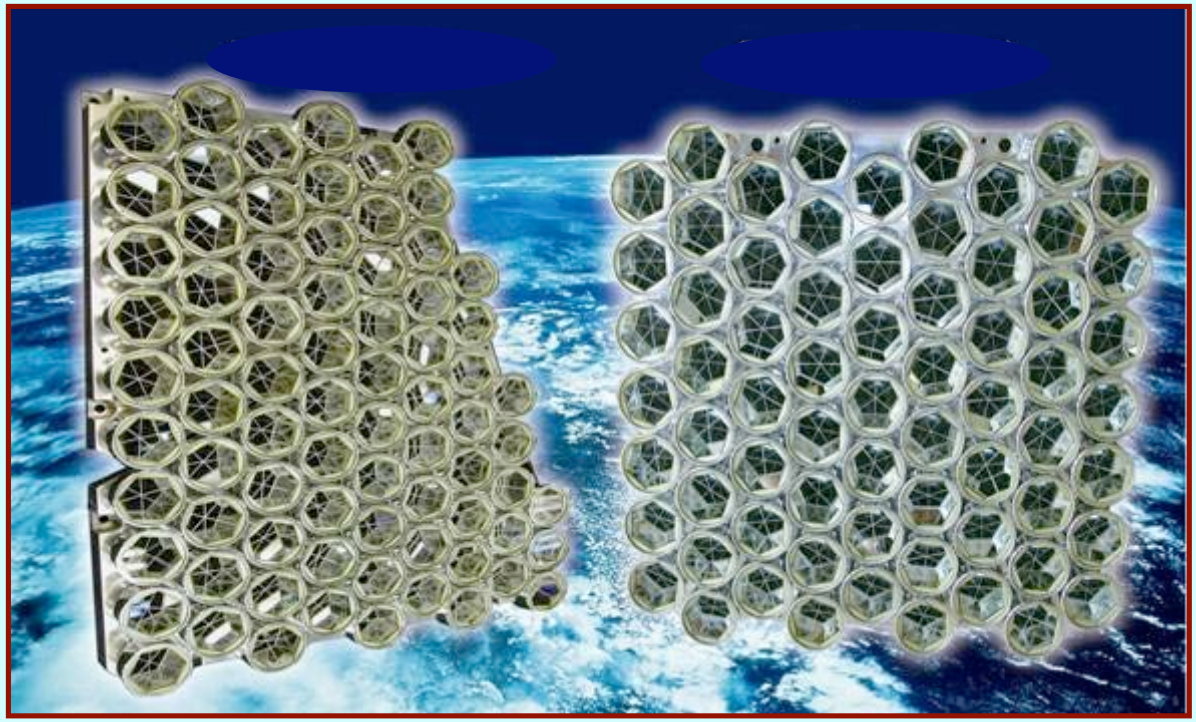
GNSS solid retroreflector arrays

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

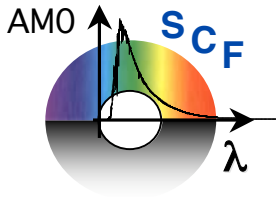
GALILEO TEST satellites
Orbit: h = 23200 km, i = 56°

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

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

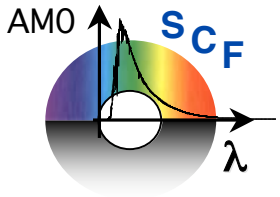


GNSS = Global Navigation Satellite System



- MW ranging among
  - the constellation (27 satellites + 3 spares), the fixed ground stations (over 250) and you, the final end user
- GNSS = 3 constellations of 30 satellites each
  - GPS (USA), GLONASS (Russia), GALILEO (Europe)
- Enormous impact in many fields
- IGS (International GNSS Service)
- GPS/GLONASS are proprietary/military at heart

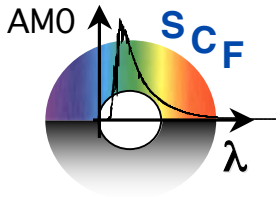
GALILEO (≥ 2008) and GPS-3 (≥ 2011)



- European GALILEO (E.U. + ESA) changes whole picture
  - Atomic clocks better than GPS ones, commercial constellation, civilian use only. "Unified":
    - 100 CCRs on each and every one of the 30 satellites !
    - CCR approximate cost (my estimate): 5K€/CCR ⇒ 15 M€
- Addition of CCRs
  - improves space accuracy by factor ~20; 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 CCRs
  - Lighter and smaller

PLX

GNSS observation with laser ranging

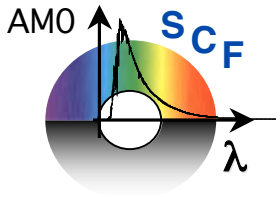


- HOLLOW CCRs: long term stability and performance in space environment to be proven
  - Agreed plan: structural analysis by NASA-GSFC, climatic test by LNF
- SLR+MW: the best of both worlds to map the NEO space-time

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

Beryllium Hollow CCR candidate for GPS3

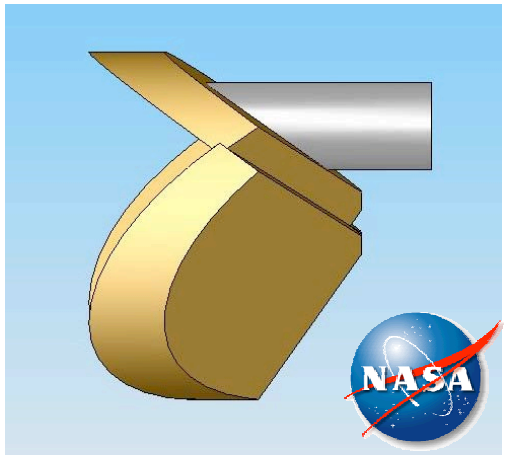


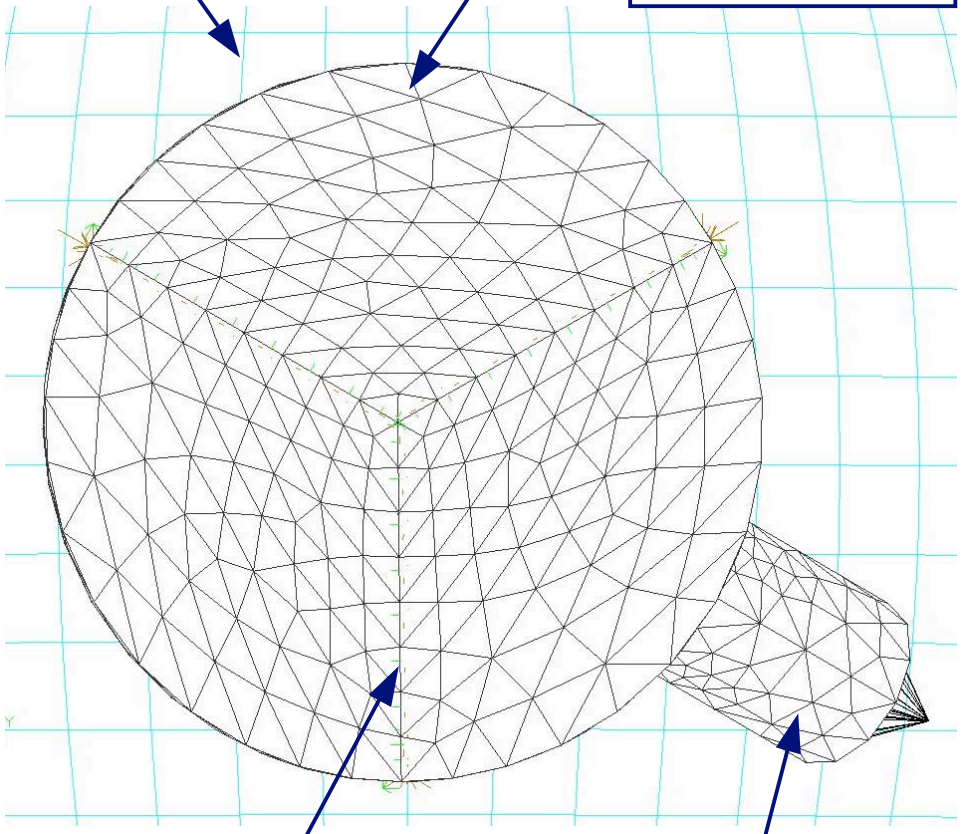
"Fake" spacecraft

3 Be planes

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

Very crude spacecraft model: an Al sphere surrounding the CCR





Stycast bonding (10W/K)

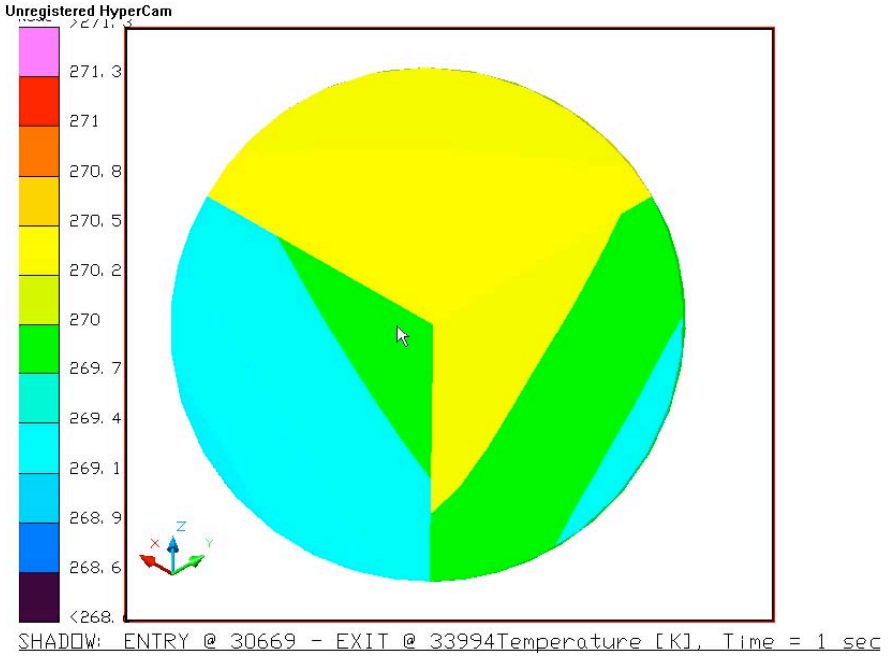
Post

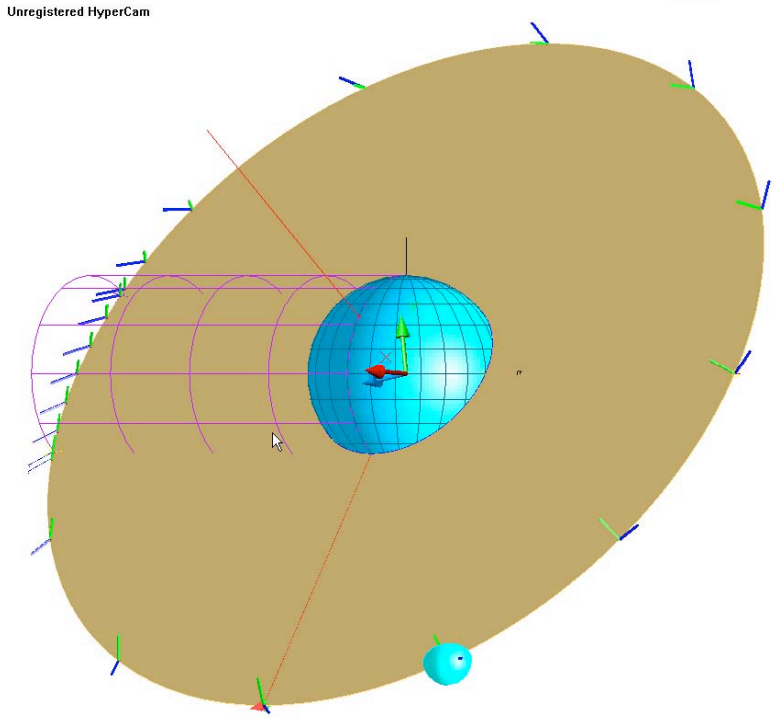
Climatic simulation of GPS-3 hollow CCR

Hollow CCRs made of 3 pieces, glued (Be) or bolted (Al).

Most severe problem is CCR warping in space climate, which could prevent laser light return. T variation of CCR:

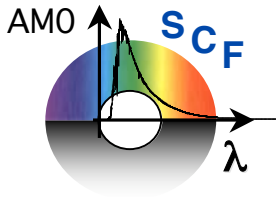
- 300-400 K if CCR thermally isolated from spacecraft
- Much smaller gradient if CCR thermally linked to spacecraft.



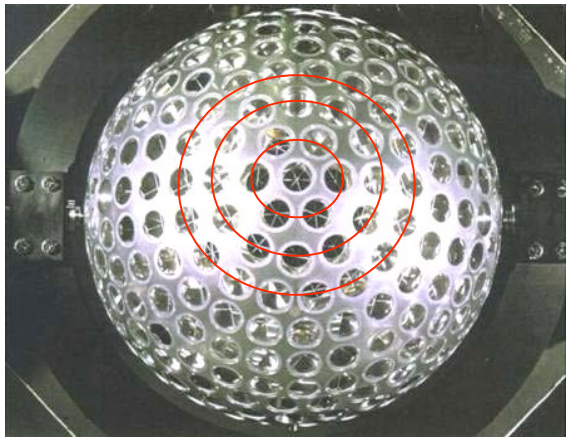


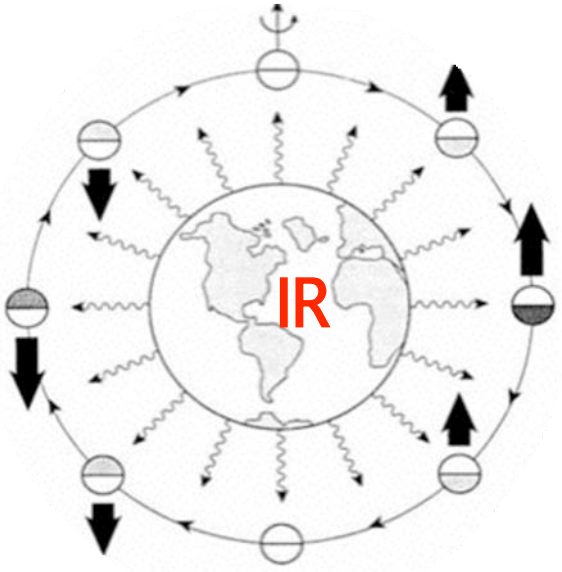
G. Delle Monache. Preliminary.

The (existing) LNF Space Climatic Facility

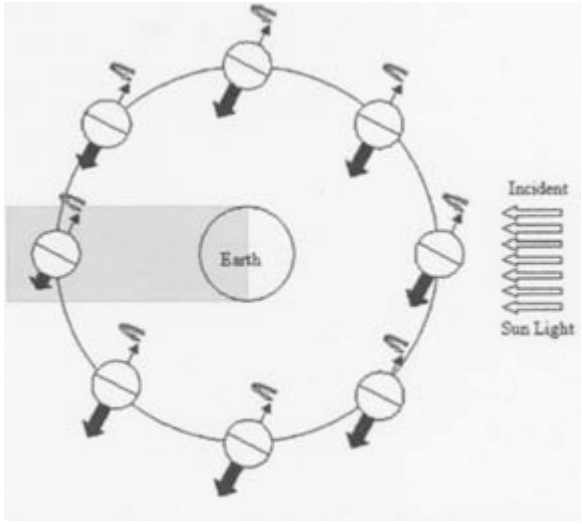


- We do have a climatic facility, built for thermal test of LAGEOS/LARES prototypes of INFN-GR2
- Measurement of optical properties with lasers on a separate optical bench
- Merge of climatic and optical test TO BE DONE





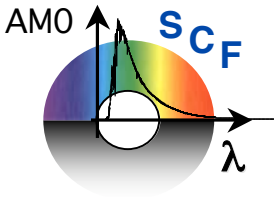
Earth Infrared Yarkovsky effect



SUN

Solar Yarkovsky effect

The LNF Space Climatic Facility (SCF)



Vac. shell
~10^{-5} mbar

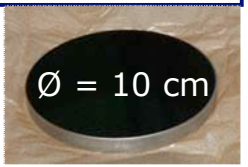
Thermal shield (Cu)
T = 77 K

L~2 m, ∅ ~1 m

Service turret

Side tunnel

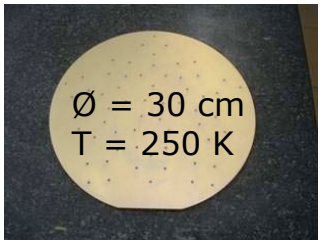
IR camera
Ge window



Prototype

Ø = 30 cm

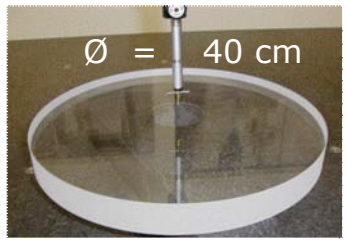
Earth IR simulator
(Z306 paint)



(alodized back)

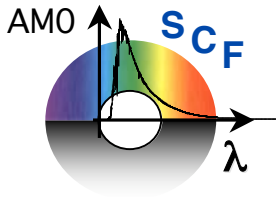
Solar NEO simulator

Quartz window

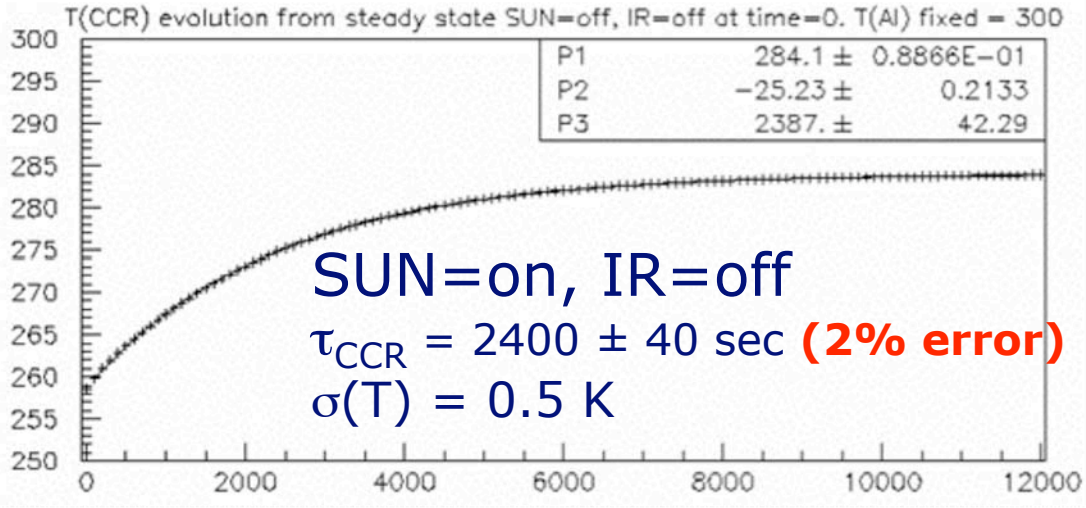


Solar beam shroud

Simulation of CCR warm-up/cool-down times



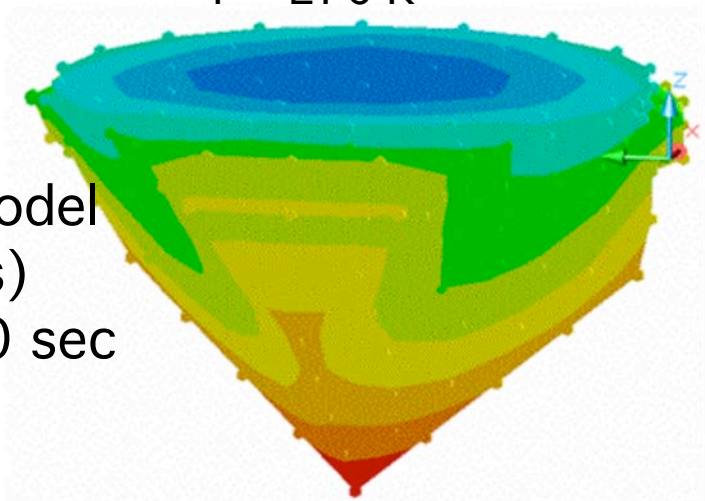
CCR T(K)



t(sec)

Goal: measure unknown τ_{CCR} at ≤**10% accuracy**. With a 0.5 K accuracy on temperat. this is well within statistical reach

T = 276 K

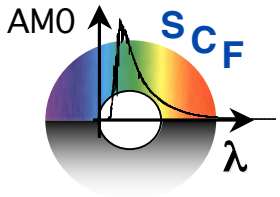


T = 278 K

CCR FEM model (250 nodes) at t = 2800 sec

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

Thermometry measurements with IR camera



- Indoor, in-air test at room temperature to measure emissivity (ε) and reflectivity (ρ) of Al and retro-reflectors
- $Q_{camera} = Q_{emission} + Q_{reflected}$
- T_x w/thermocouple
- T_{bkg}: black disk with controlled temperature = 10 °C or 50°C

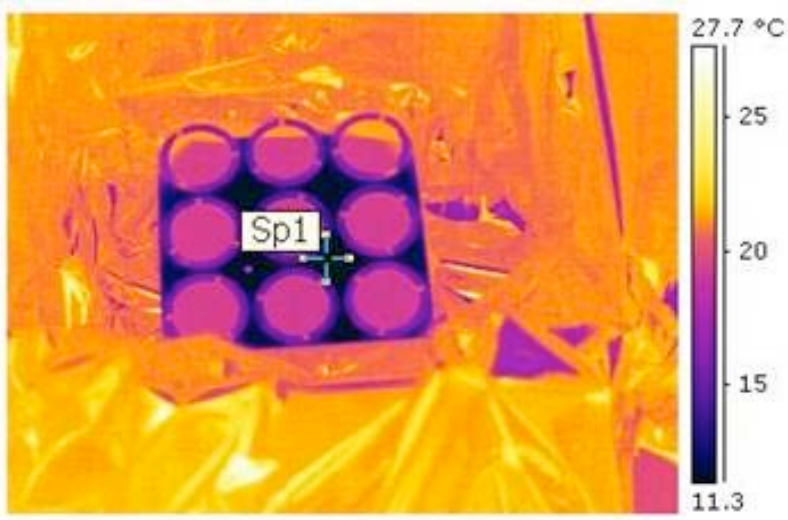
$\varepsilon_{IR}(CCR) \sim 0.82$

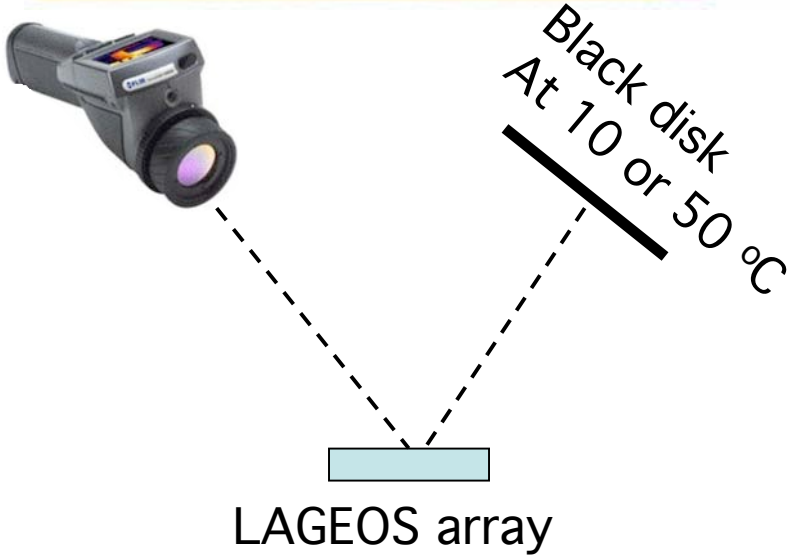
$\rho_{IR}(CCR) \sim 0.18$

$\varepsilon_{IR}(Al) \sim 0.15$

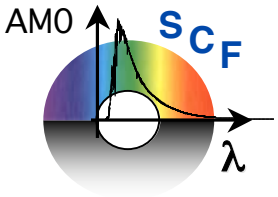
$\rho_{IR}(Al) \sim 0.85$

IR pictures of the LAGEOS array

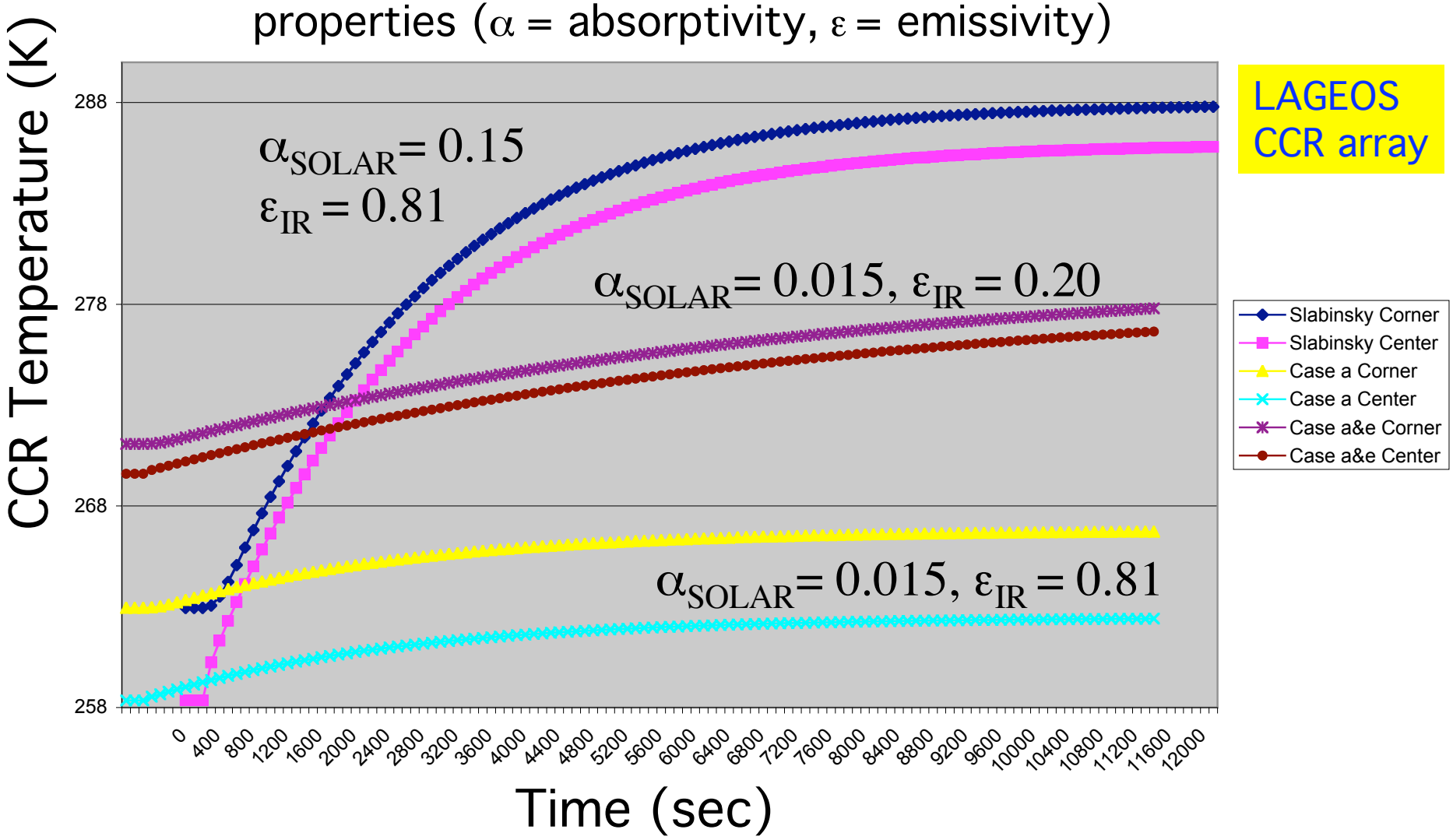




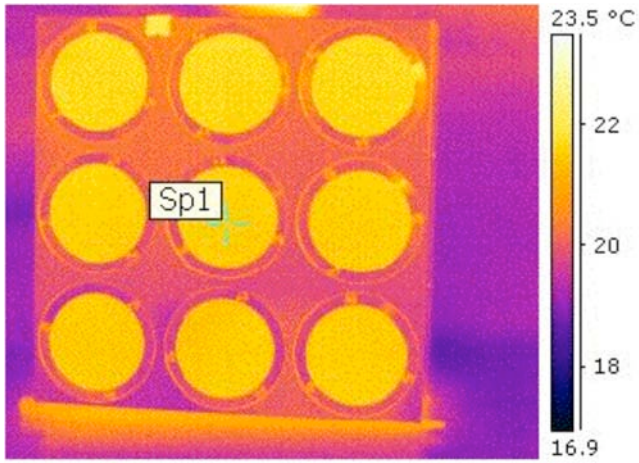
Warm-up time vs thermo-optical properties

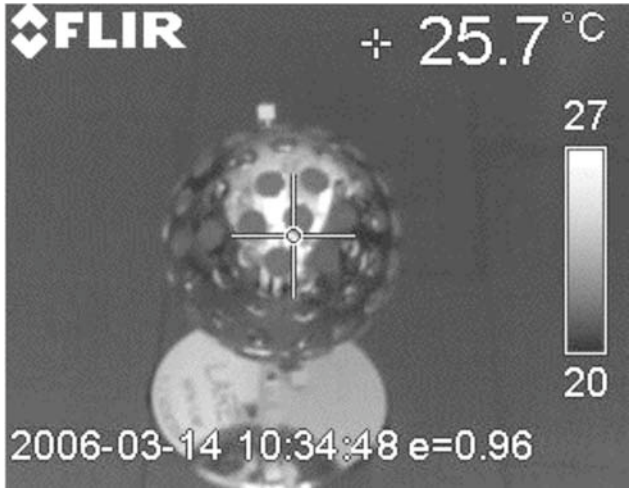


Simulation for different suprasil (CCR) thermo-optical properties (α = absorptivity, ε = emissivity)



LAGEOS matrix, LARES 1:2 proto built at LNF



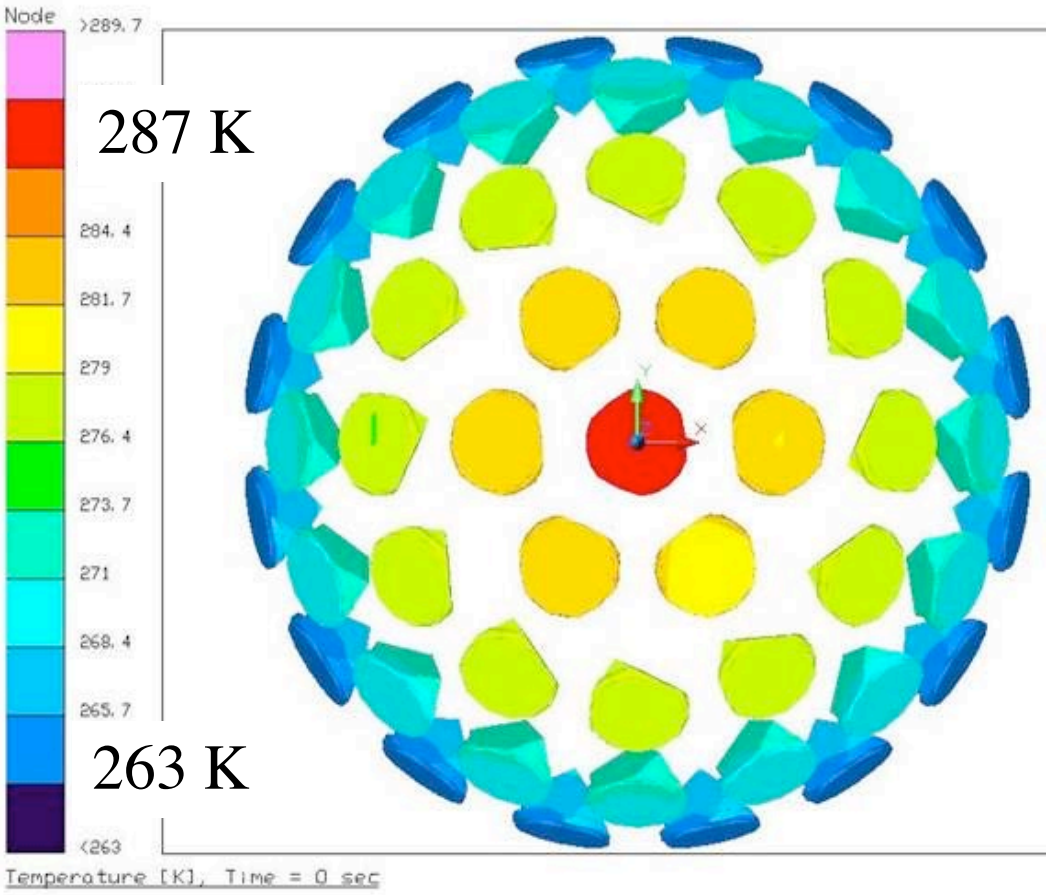


IR images

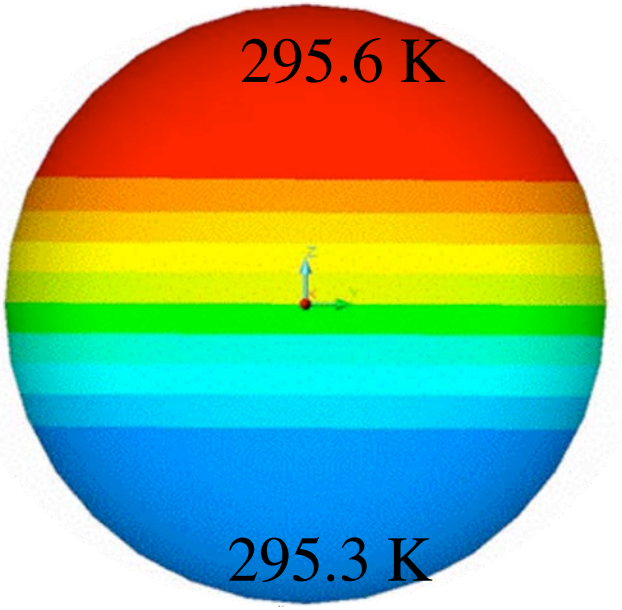
FE model & thermal simulation of LARES

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

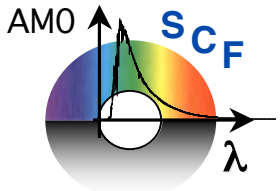
CCRs, front view



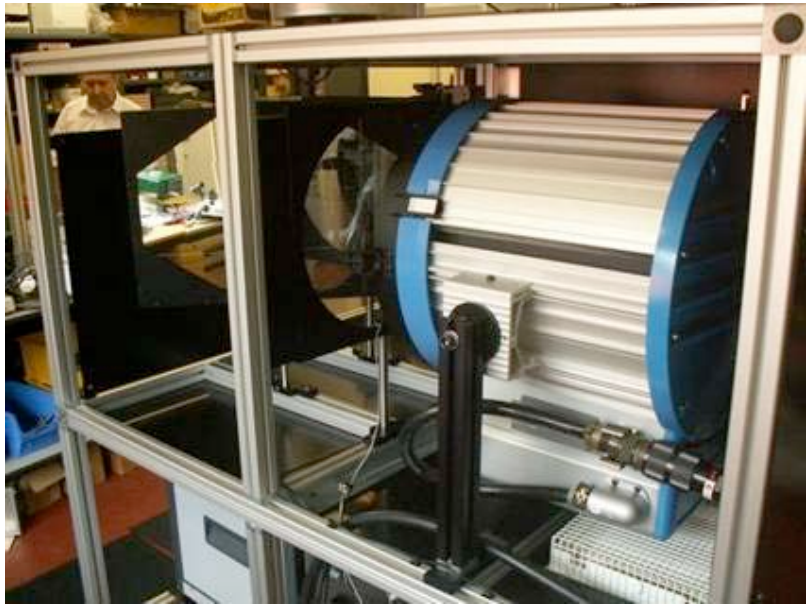
Core, side view

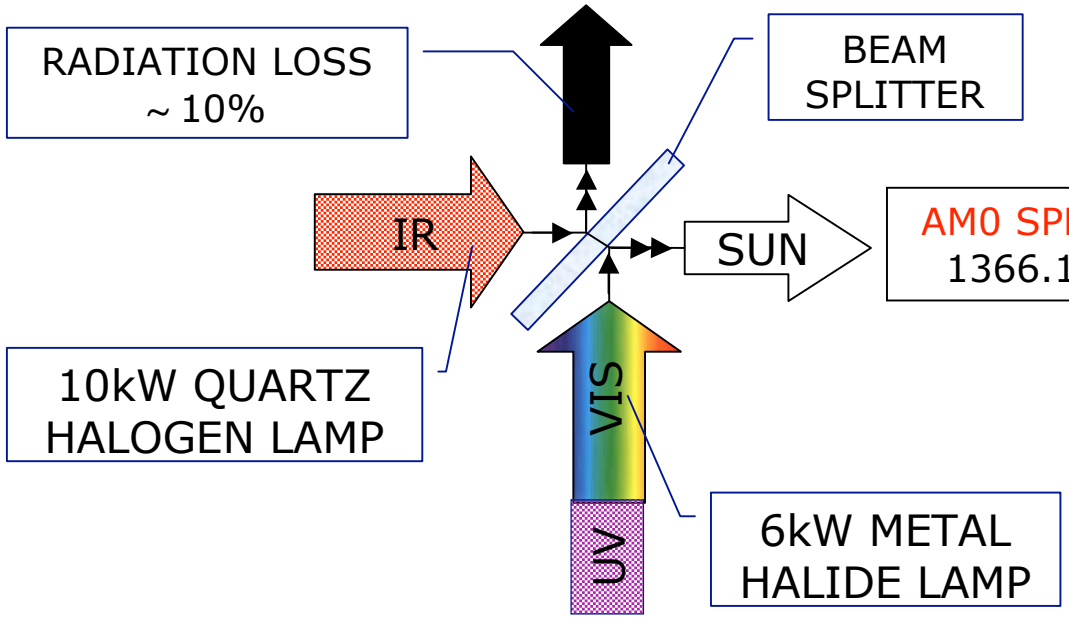


Status of the SCF



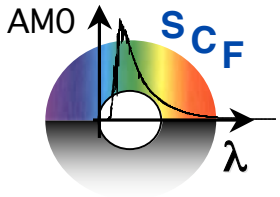
- Solar simulator acceptance test at TS-Space (UK) successful; being shipped to LNF
- Outgassing performed, Nitrogen transfer line installed





We deeply thank M. Calvetti, C. Sanelli, M. Curatolo of LNF for their support to the SCF !

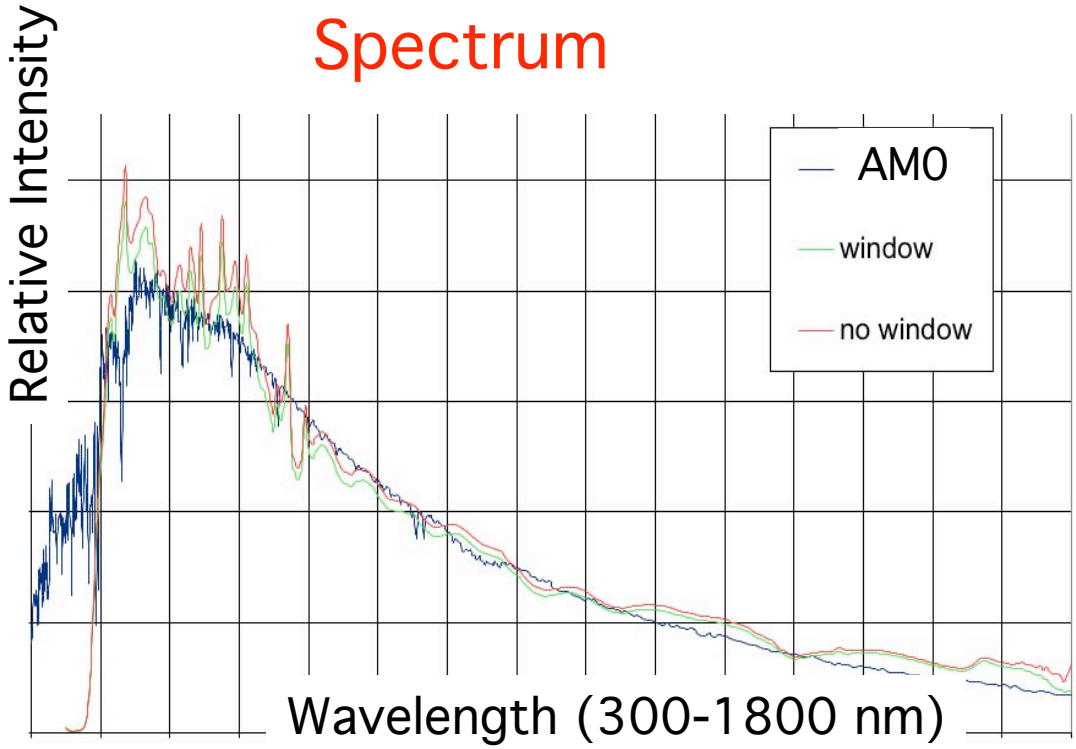
Measured Solar Simulator spectrum & uniformity



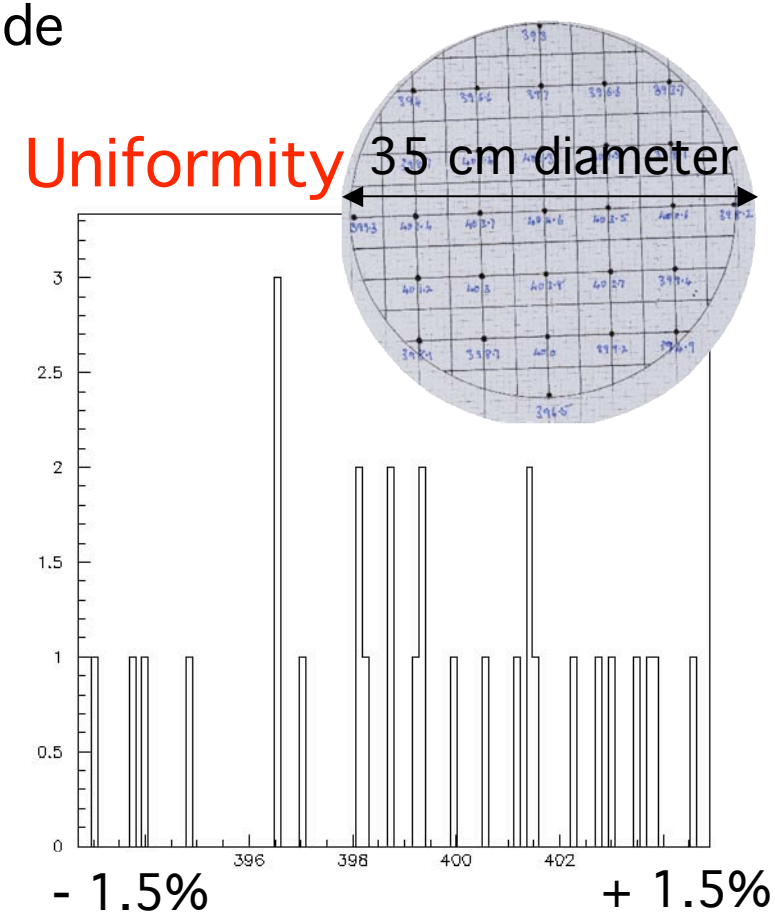
- "AM0" standard spectrum (400-3000 nm)
- Absolute calibration @1% w/Solarimeter
- HV adjusted for lamp ageing w/PIN diode

ACCEPTANCE TEST
MAY 29, 2006 OK.
Being shipped to LNF

Spectrum

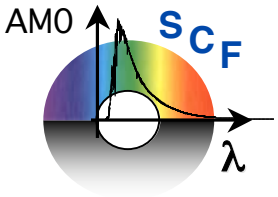


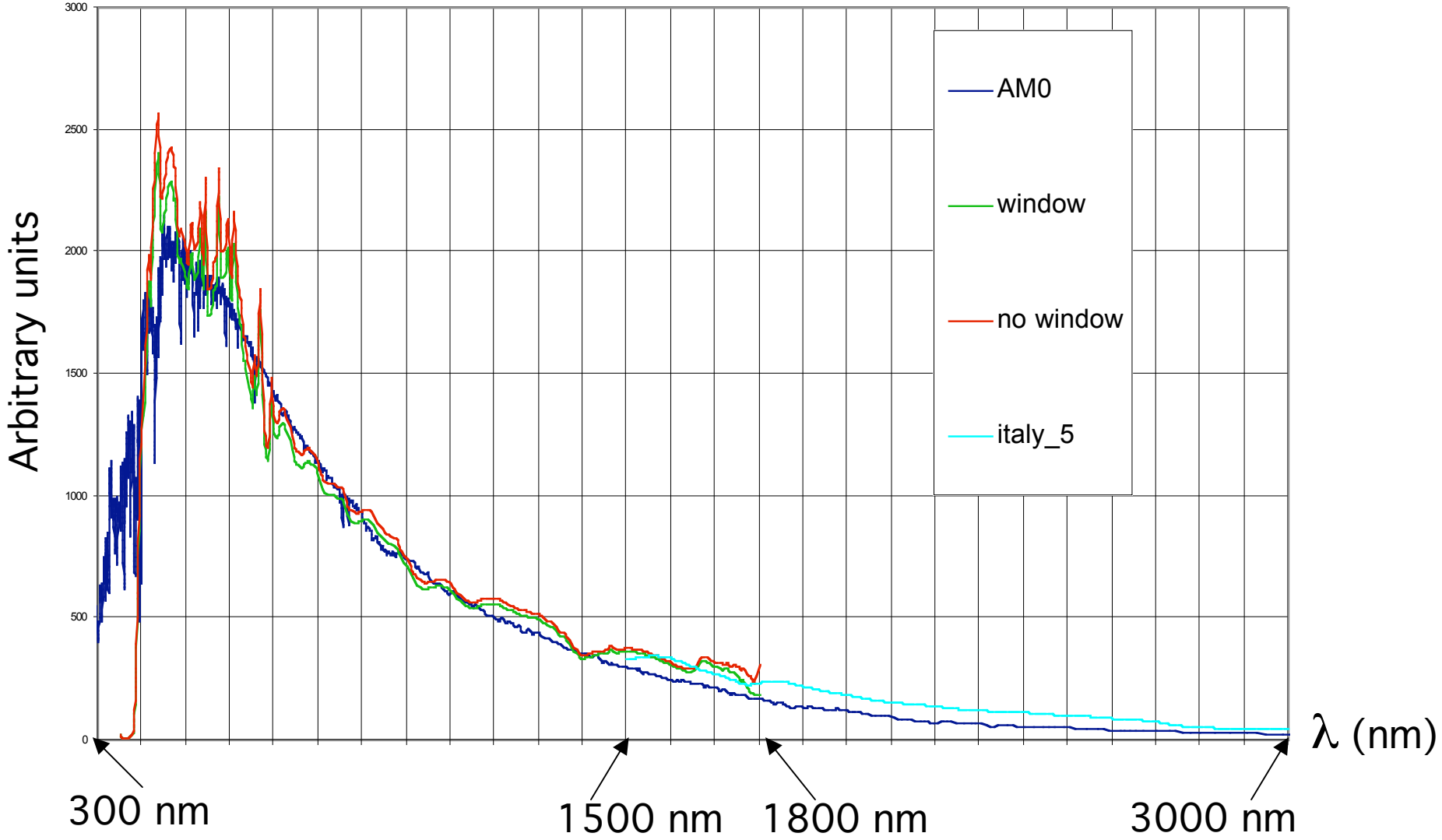
Uniformity



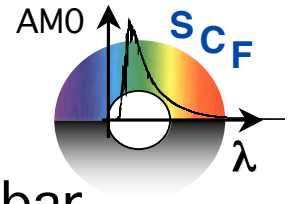
- 1.5% + 1.5%

Extended AM0 spectrum (300 - 3000 nm)

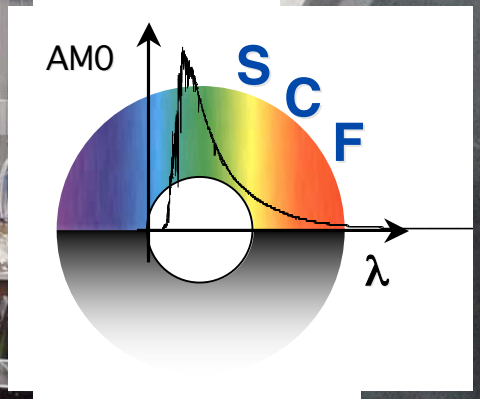




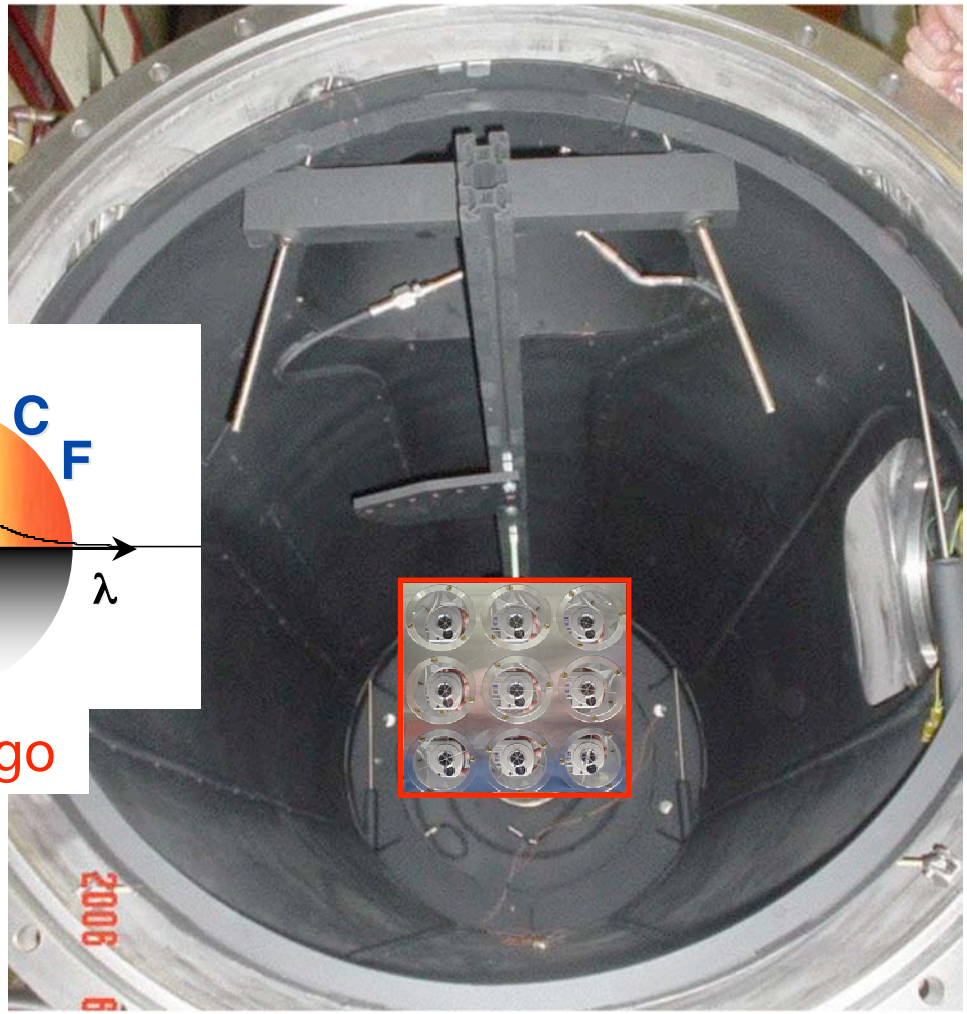
LNF SCF commissioning well underway



T probes installed, outgassing performed, vacuum @ 10^{-5} mbar.
Liquid N_2 TL connected this week, then real MEASUREMENTS !!!



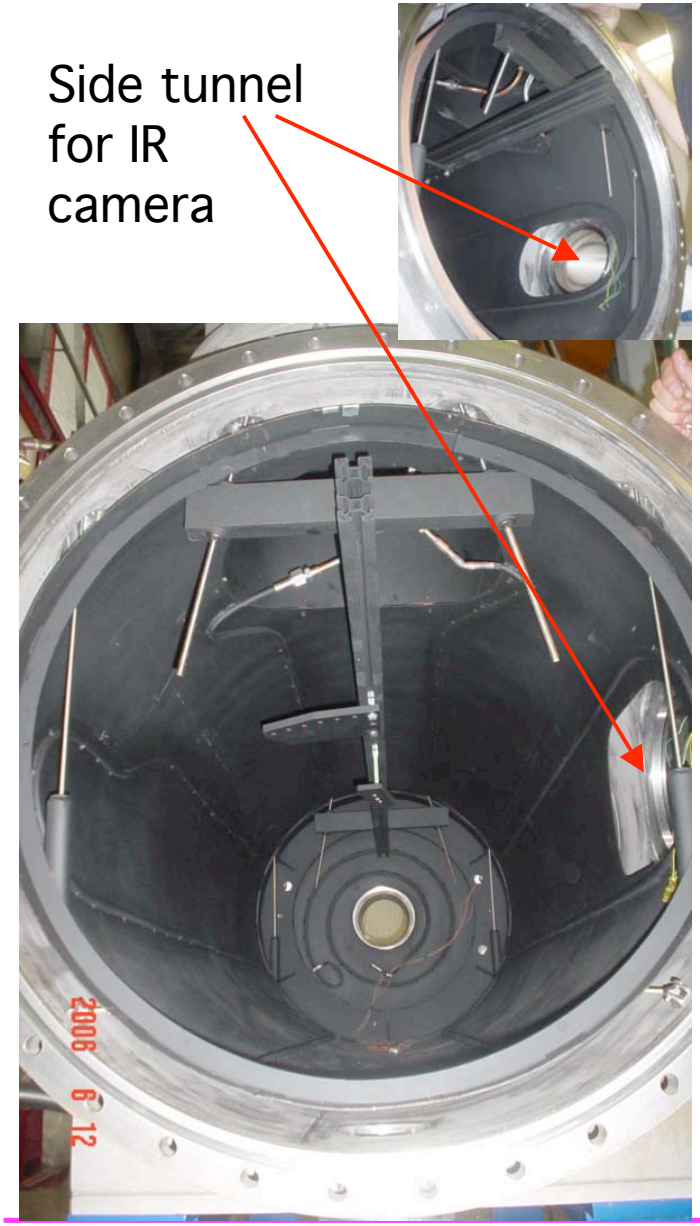
SCF logo

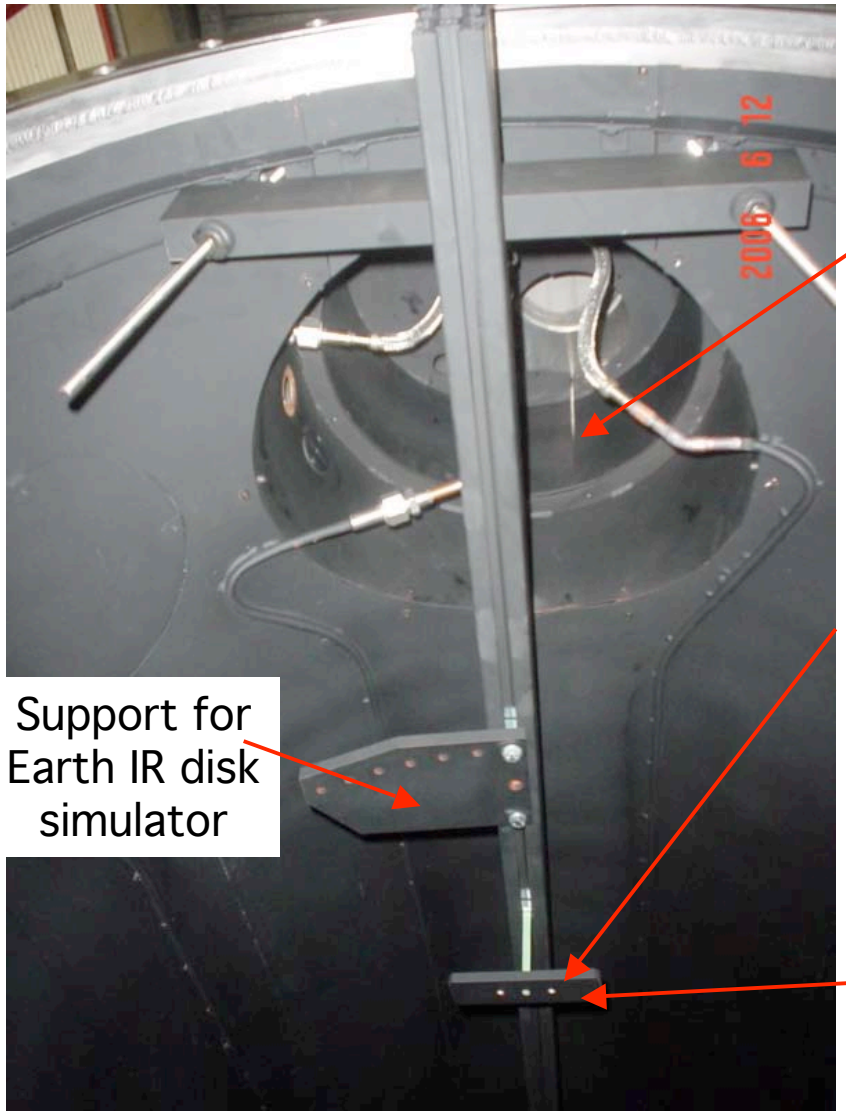


LNF SCF commissioning

Liquid N_2 TL connected

Inside the LNF SCF

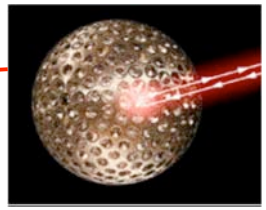




Service turret

Support for GNSS array...

... or DSGP spherical test-mass

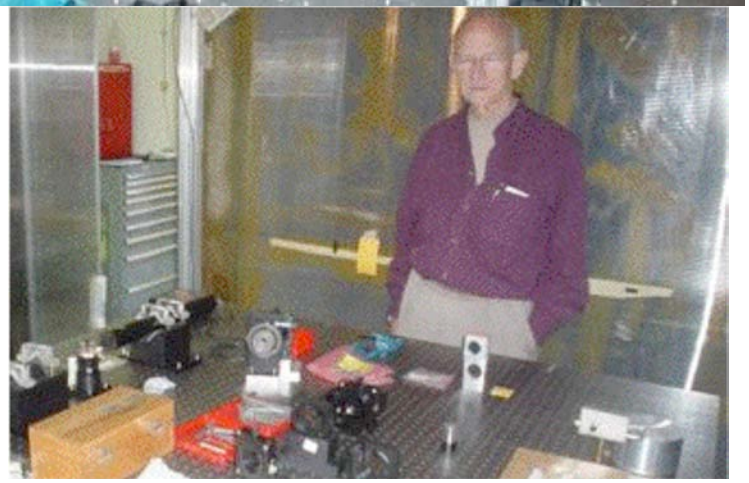


Optical characterization of retro-reflectors

Test 1: Far-Field Diffraction Pattern (FFDP)

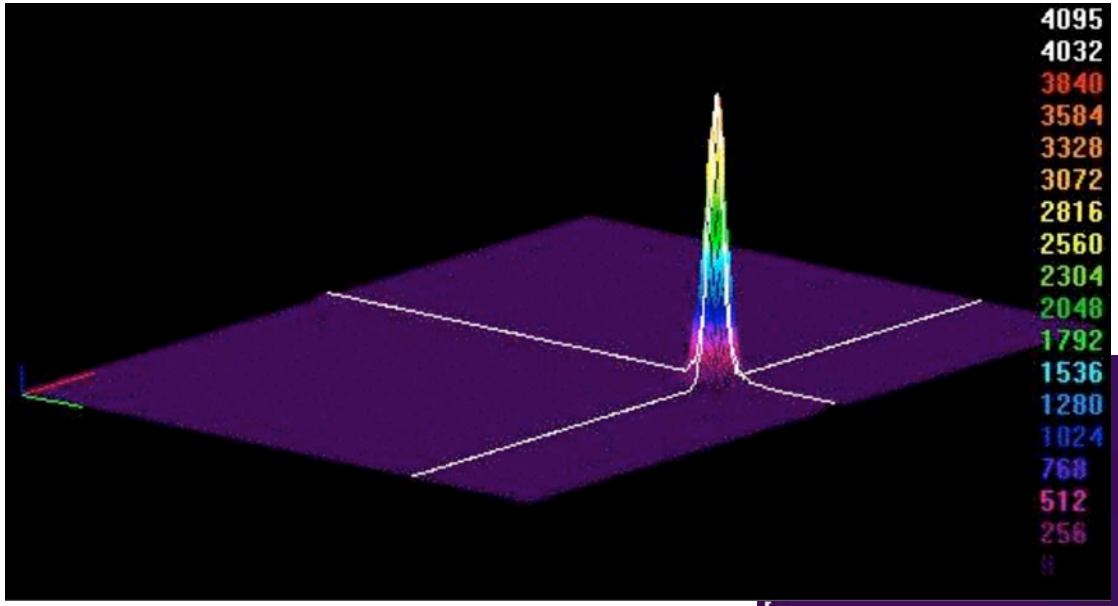
- "Optical FLAT" (mirror) for normalization
- CCDs as laser beam profilers

Repeat test inside the SCF

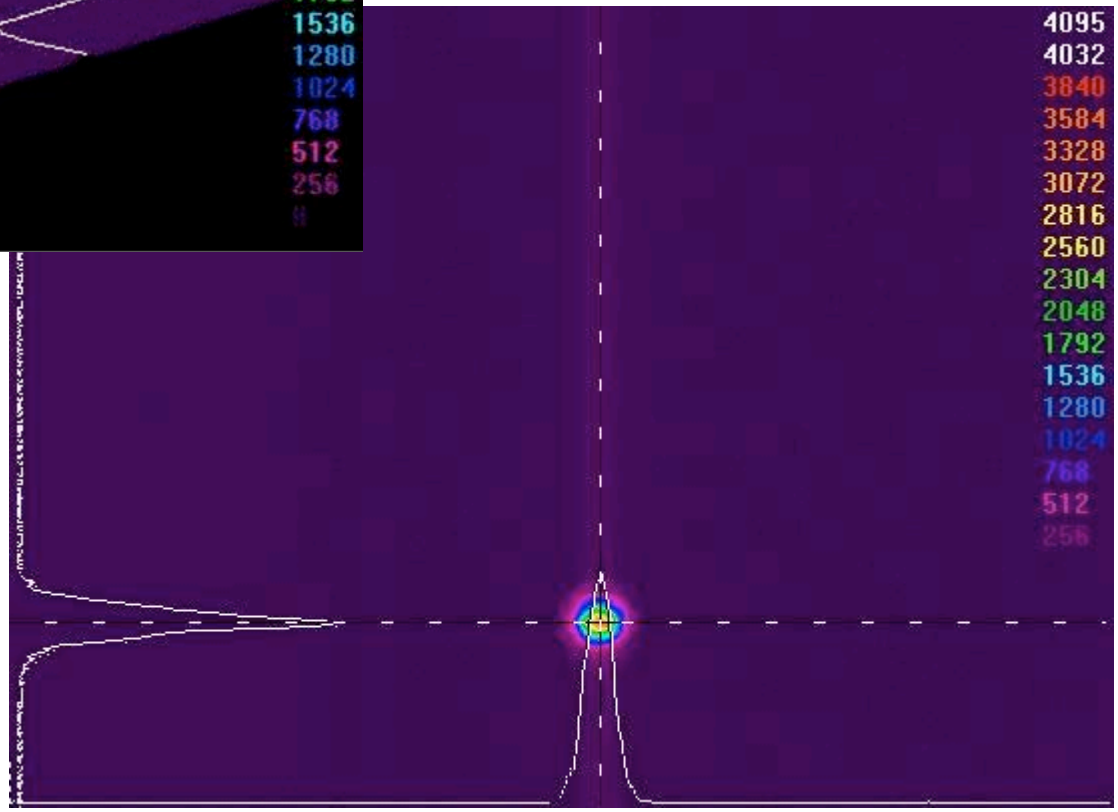


Thanks to John Degnan, Dave Arnold, Erricos Pavlis, Jan McGarry for advise and to Doug Currie (in photo) for help on setting up the optical tests at LNF

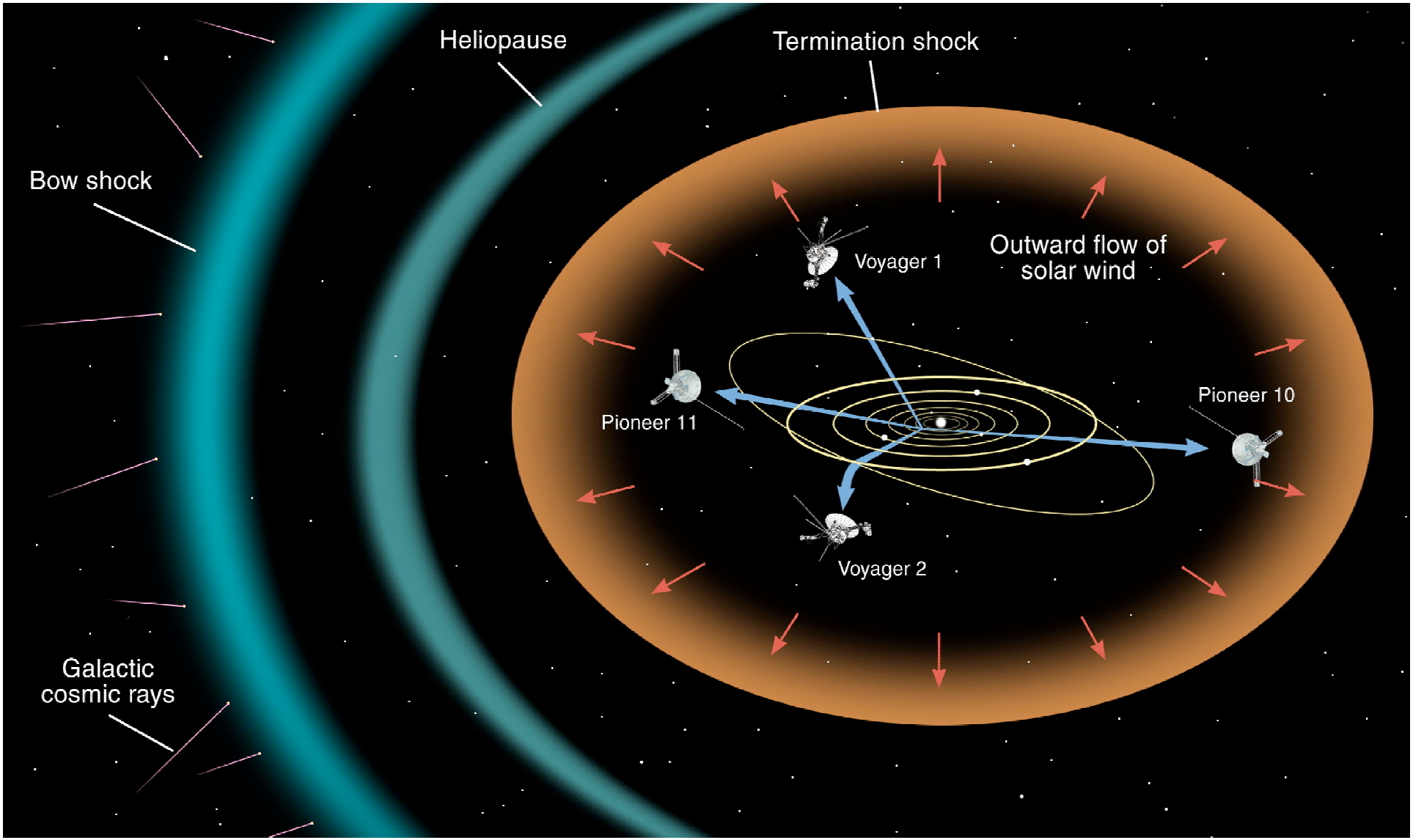
He-Ne laser beam readout by CCD



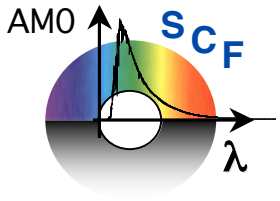
A. Lucantoni, Rome I Univ.
(LARES student of A. Paolozzi)



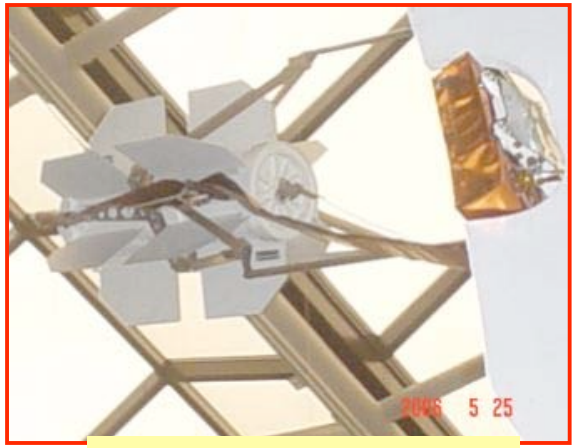
Enough with NEO. Let's go to Deep Space



Probing Gravity in Deep Space: the Mistery of Pioneer Deceleration



- In the outer SS the probes with the most accurate and robust navigation capabilities are the PIONEERS. Why ? Because:
  - Pioneers were spin-stabilized => months without firing thrusters
  - VOYAGERS: factor 50 less accurate, because 3-axis stabilized
  - GALILEO: less accurate and up to Jupiter only
  - CASSINI: analysis not accurate enough
  - Outer planets: less accurate than Pioneers
- Pioneer doppler data ('87-'98, 40-70.5 AU) provide clear anomalous deceleration



Radioisotope Thermoelectric Generators (RTGs)

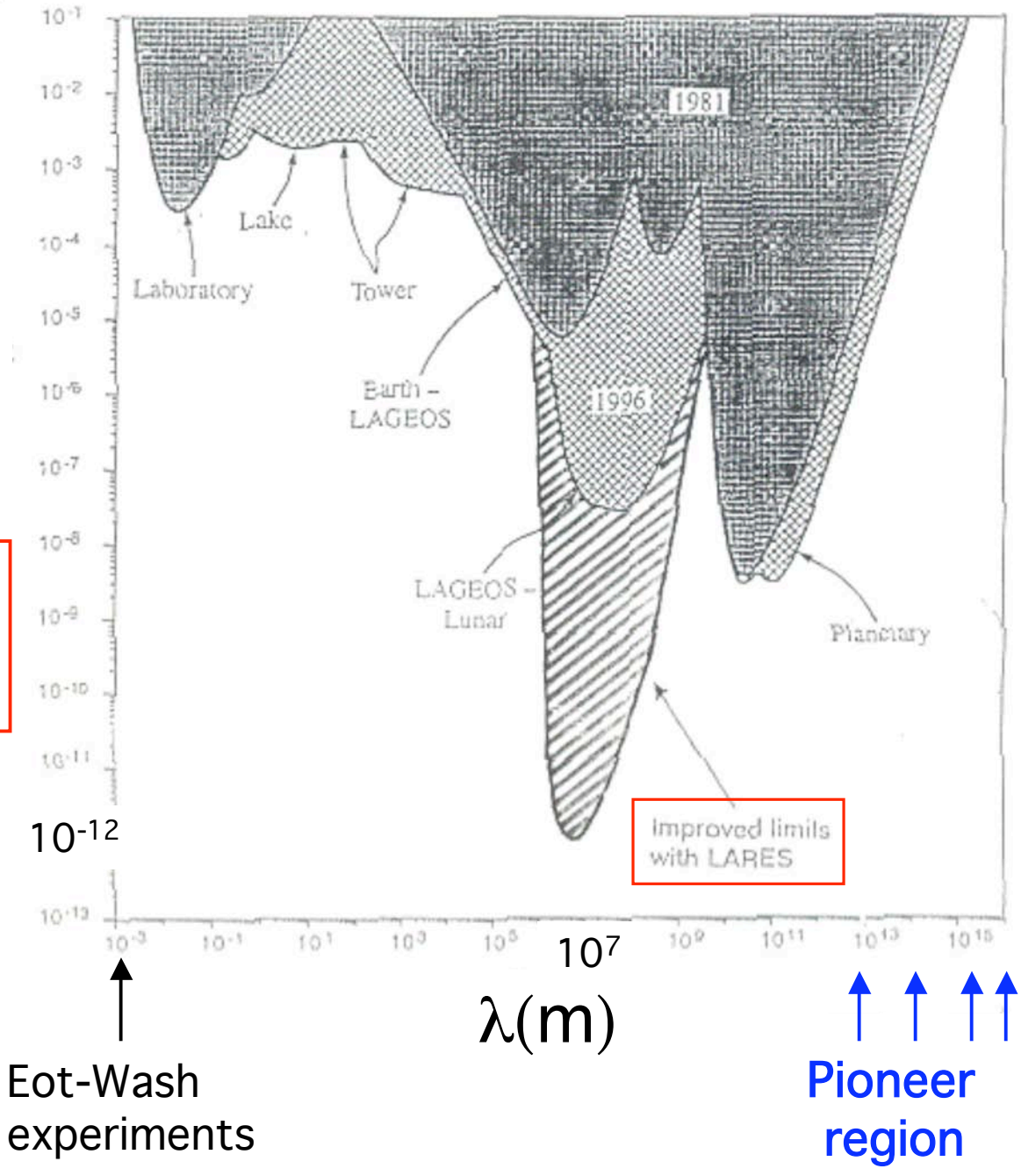
$$a_{PIO} = (8.74 \pm 1.33) \times 10^{-10}\ m/s^2$$

~10 x maximum LAGEOS thermal accelerations !!

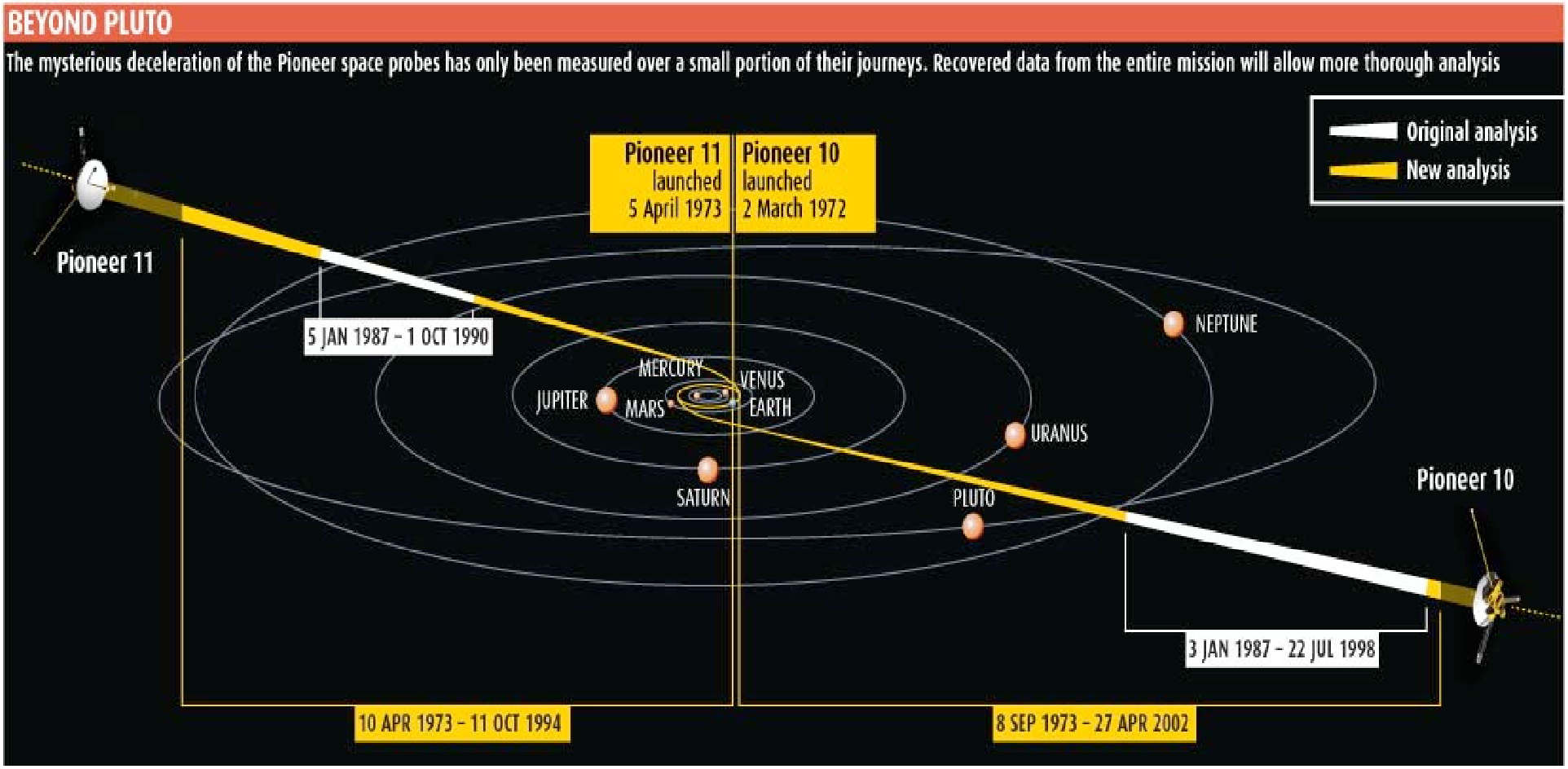
- Effect of asymmetric thermal forces ?
  - forward-backward asymmetry in thermo-optical parameters ?
- Was it the RTGs ? Or is $1/r^2$ violated by New Physics ?

Test of $1/r^2$ law and of new long range interactions, ie, a Yukawa Potential

$$V_{YUK} = -\alpha \frac{GM_{earth}}{r} e^{-\frac{r}{\lambda}}$$

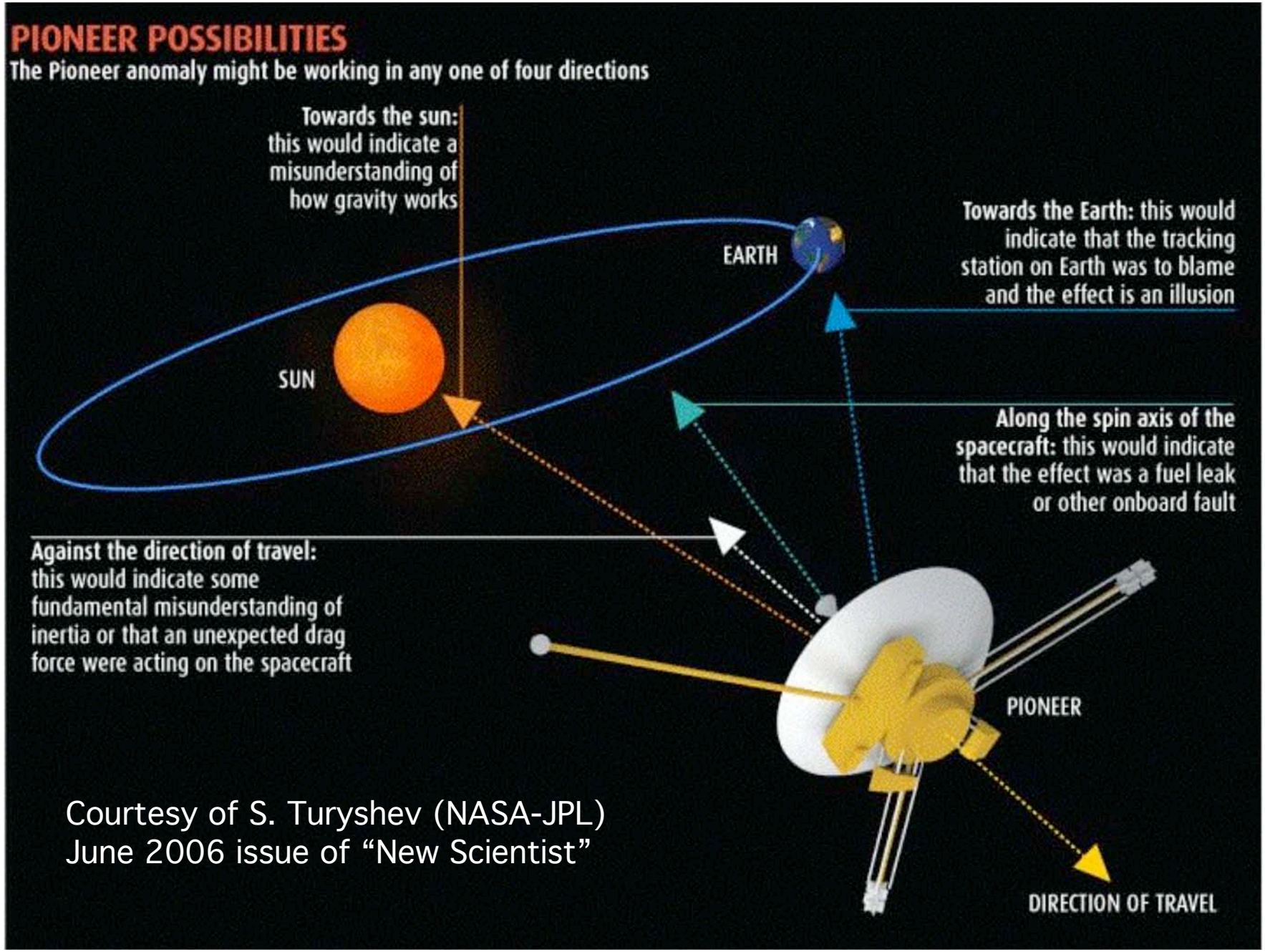


Status of the analysis of Pioneer data



Courtesy of S. Turyshev (NASA-JPL) - June 2006 issue of “New Scientist”

Status of the analysis of Pioneer data

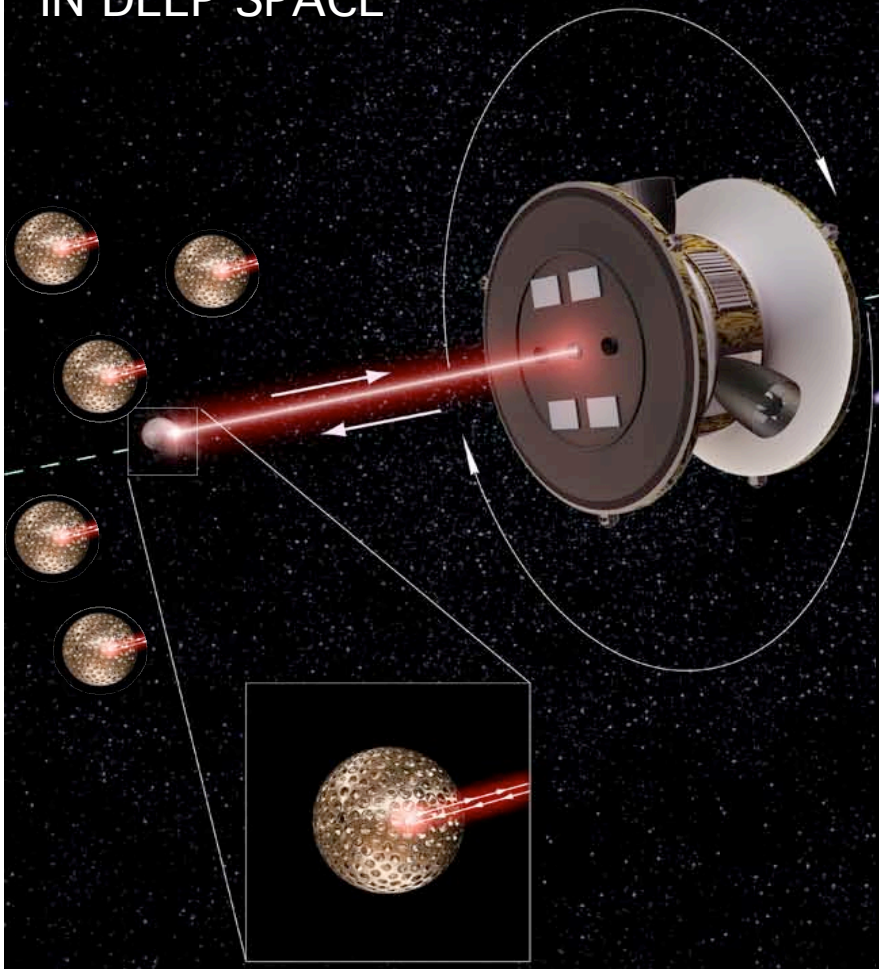


Courtesy of S. Turyshev (NASA-JPL)
June 2006 issue of “New Scientist”

Measurement Concept: Formation-flying

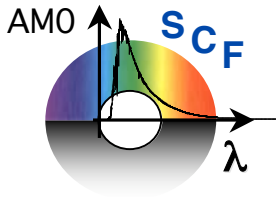
A CONSTELLATION OF SMALLER “LARES” IN DEEP SPACE

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

The Deep Space Gravity Probe mission

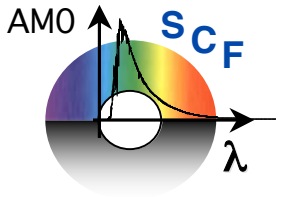


- Study of the Pioneer anomaly with a few lighter "LARES"
- Different masses/materials to test Equivalence Principle
- Planet flybys for planetary science

- Thermal forces; here we can contribute
  - Solar constants beyond Saturn ≤ 10^{-2} × NEO-AM0.
  - IR radiation by planets. Disks with varying ∅ and Temperature
  - Measure thermal properties in SCF, then use orbital simular and thermal sw for full 10-80+ AU orbit

- LAGEOS thermal accelerations ≤ 1/10 × a_{PIO} ! Our expertise with the high-accuracy thermal characterization of LARES at the SCF will be extremely useful for the design of DSGP

Conclusions



- ETRUSCO is a truly international, inter-agency, interdisciplinary project of space research, in NEO and Deep Space
- ETRUSCO builds upon the LNF SCF, which has been funded for the LARES space mission by INFN-GR2 + LNF
- The LNF SCF fills a research "niche" in the field of experimental tests of General Relativity
- GNSS project: good potential for high-tech applied research. GALILEO is maybe the most important EU/ESA enterprise
- We propose to INFN-GR5 this program and requests funding for:
  - Dedicated software license for thermal analysis
  - GNSS: innovative hollow retro-reflector prototypes
  - Pioneer/DSGP: modest upgrade of SCF for Deep Space conditions (liquid Nitrogen not enough, since at Saturn distances, T(test mass) < 77 K)
  - Pioneer/DSGP: construction of prototype test mass

Summary of ETRUSCO LNF resources

GROUP (all "associated" to INFN-LNF)

- S. Dell'Agnello, INFN-LNF

(30%, responsabile)

- G. Delle Monache, INFN-LNF

(30%, head Cryogenics Service)

- C. Cantone, INFN-LNF

(30%, borsista INFN)

- M. Garattini, INFN-LNF

(30%, borsista INFN)

- G. Bellettini, Roma2

(30%, Prof. Ord.)

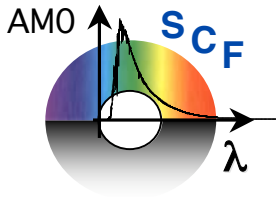
TOTAL = 1.5 FTE

Requests to LNF (per year)

- Cryogenics Service: 3 mesi uomo
- Mechanics Service: 3 mesi uomo

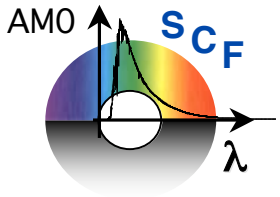
Picture from www.apollodiveio.it

Financial request to INFN-GR5



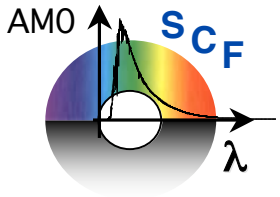
- Dedicated license of software for thermal analysis
  (SINDA-Fluint/RadCad/ThermalDesktop by C&R Tech) 15 K€
- GNSS: innovative hollow retro-reflector prototypes
  (bolted Al and glued types by PLXinc, PROSystems) 15 K€
- Upgrade of NEO SCF for Deep Space
  - T(test-mass) < 77 K, the limit of the current liquid nitrogen system; need to get towards 10 K;
    SHI Cryocooler SRDK-408D2-W71D by TECO 25 K€
- Deep space test masses prototypes
  - DSGP-specific retro-reflectors 10 K€
- Optics consumables 5 K€
- Mechanics consumables 5 K€

Missioni interne ed estere



- Missioni estere
  - Meeting e misure per il GNSS coi collaboratori ILRS, NASA-GSFC, UMCP (tutti vicino a Washington DC) 5 K€
  - Training sull'analisi dati del Pioneer presso gli esperti del JPL di Pasadena (una volta sola) 5 K€
- Missioni interne
  - Meeting con colleghi teorici di INFN-Firenze e del Dip. di Fisica del Politecnico di Torino sull'impatto del GNSS sulla Relativita' Generale 2 K€
  - Misure ottiche e test di laser ranging sui prototipi dei LNF col laser impulsato di potenza del Centro di Geodesia Spaziale di Matera dell'ASI (MLRO). Trasporto prototipi e strumenti 3 K€
    - MLRO e' una delle migliori stazioni di laser ranging del mondo

Total financial requests



- Inventariabile (retros/test mass protos) 25 K€
- Costruzione apparati (SCF upgrade) 25 K€
- Consumi (software, mechanics, optics) 25 K€
- Missioni interne (ASI-Matera, teorici) 5 K€
- Missioni estere (NASA-GSFC, NASA-JPL) 10 K€

Totale 90 K€