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

G. O. Delle Monache (INFN-LNF) for the LARES and ETRUSCO Collaborations

ILRS 2006 Conference
Canberra, Australia, 28-30, Oct. 2006
Prototypes built at LNF

LAGEOS (LARES)

Screw (AA)
Retainer ring (AA)
Upper mounting ring (KEL-F)
Lower mounting ring (KEL-F)
AA Base (T6 6061)
LAGEOS assembly
CCR
"Shell over the core"
Proposal for TT limitation under study

LARES (1:2)
Simulation of $\tau_{\text{CCR}}$ (thermal relaxation time)

NEVER measured. Computations vary by 300%.
Goal for LARES and LAGEOS: measure $\tau_{\text{CCR}}$ at $\leq 10\%$ accuracy. This will make the error on Lense-Thirring of LARES due to thermal perturbations negligible (permil level)

$\tau_{\text{CCR}} = 2400 \pm 40$ sec (2% error)
$\sigma(T) = 0.5$ K
Steady state $t=0$ sec
SUN=ON
SUN=OFF for 4500 s
then SUN=ON.
IR always ON

Thermal Thrusts on LAGEOS
CCR solar absorptivity = 1.5 %
Inside the SCF

- Side tunnel for IR camera
- Service turret
- Support for GNSS array...
- Support for Earth IR disk simulator
- ... or proto

ILRS 2006 Conference Canberra, Australia, 16-20, Oct. 2006
G. Delle Monache, INFN-LNF
SCF commissioning complete

\[ T_{\text{shield}} = 80 \text{ K}, \quad P = 2 \times 10^{-6} \text{ mbar} \]

Sun simulator tested in August, Earth IR simulator tested in Sep.
The Sun Simulator

- **Beam Splitter**
- **Radiation Loss > 10%**
- **10-12 kW Quartz Halogen Lamp**
- **Filter**
- **6 kW Metal Halide Lamp**
- **Solar Beam**
  1. AM0 Spectrum
  2. 1366.1 W/m²
- Acceptance test at TS-Space (UK) in June
- Delivered to LNF on July 12
- Final calibration at LNF end of July
• “AM0” standard spectrum (400-3000 nm)
• Absolute calibration @1% w/Solarimeter
• HV adjusted for lamp ageing w/Photo diode
Earth IR simulator

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

- T_{AL\ base} = 290 - 310 K
- T_{Earth\ SYM} = 254 K

- Assembly screw to be changed with the original ones (from NASA GSFC) to get nominal torque on the assembly
Preliminary: tune simulation to the data

Sw model to be tune to experimental data:

- Accurate optical properties measurement on the prototypes
- Refining the values of the interfaces thermal resistance in the model

**SIMULATED**

$T = 263 \text{ K}$

**MEASURED**

$T = 261 \text{ K}$
Preliminary: CCR cool-down after SSSS

Preliminary in Air test, @ 75% of the NEO solar constant. Cool-down curve from SS turned off

\[ \tau_{CCR} \sim 3400 \text{ sec} \]
\[ \Delta T \sim 9 \text{ K} \]
(exp. fit to data)

\[ T (\degree C) \text{ vs } t (\text{sec}) \]
Indoor, in-air measurement at room temperature

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

$\varepsilon_{\text{IR}}(\text{CCR}) \approx 0.82$
$\varepsilon_{\text{IR}}(\text{Al}) \approx 0.15$
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: 6.1 mW
Pol. 2
Faraday Rotator
Pol. 1
Laser

Object. 1
Lens 1
Flat Mirror or CCR

Mirror 1

405 µW
400 µW

45°
45°
0°

450 µW
500 µW
6.9 mW

Beam Splitter

52 µW
48 µW

360 µW

75 µW

Lens 2
Object. 2
Filter

0.125 nW

CCD camera readout via FireWire by PC
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 proto from 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!
Measurements of spin direction and rate initiated at UMCP (SW1)

- Later: LOSSAM (LAgeOS Spin Axis Model), based on past measurements predicts future direction and rate (DELFT+UMCP)
- SW1 revived and now run at LNF, especially in view of LARES
The SCF was funded with a small contribution of the INFN Astroparticle Committee and by the LNF Director. We used heavily existing LNF resources.

The Director asked to use it for LARES and to find other projects of space physics and technology to maximize the output.

ETRUSCO, described in the following, has been approved by INFN from now until Dec 31, 2008!!
“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

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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
GNSS Unified Constellation

- **MW Ranging**: standard measurement of (space-)time coordinates of the “GPS” satellite with microwaves. \( s \sim 10-20 \text{ cm} \). No long term memory (periodic clock re-synchronization), but great for real-time navigation.

- **LASER Ranging**: \( s \sim \text{few mm} \) (w/complete climatic-optical characterization), absolute position wrt ITRF, long term stability (tens of yrs).

Prototype of the 30 GALILEO satellites (≥ 2008)

- Standard MW emitters
- 100 Retro reflectors

MW RANGING
LASER RANGING
Current GNSS solid retroreflector arrays

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

GPS-35  Orbit: $h = 20200$ km, $i = 54^\circ$
GPS-36  Number of CCR’s: 32

GALILEO TEST satellites

Orbit: $h = 23200$ km, $i = 56^\circ$

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
- Solar thermo-optical parameters with solar simulator in the SCF/room-T

OPTICAL measurements
- FFDP
- Range correction
Preliminary test of UMCP GPS array at LNF

Preliminary in air test, in Air @ 75% of the NEO solar constant.
“GPS3” cool-down constant

Preliminary in air test, in Air @ 75% of the NEO solar constant.

\[ T_{CCR} \quad (^\circ C) \]

\[ t \quad (hr:min:sec) \]

\begin{align*}
12:00:00 & \quad 12:28:48 & \quad 12:57:36 & \quad 13:26:24 & \quad 13:55:12 & \quad 14:24:00 & \quad 14:52:48 & \quad 15:21:36
\end{align*}
GALILEO (≥ 2008) and GPS-3 (≥ 2011)

• GALILEO
  - “Unified”: 100 CCRs on each satellite
  - Use of quartz solid CCRs improves performance for space geodesy and for commercial services of enormous €-value

• ILRS-GSFC proposal 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

Simulated spacecraft

3 Be planes

Stycast bonding (10W/K)

Post

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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.
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 mystery of Pioneer deceleration

- \( a_{PIO} = (8.74 \pm 1.33) \times 10^{-10} \text{ m/s}^2 \)
  \(~ 10 \times \text{maximum LAGEOS thermal accelerations that we are studying with great care}\)

- Effect of asymmetric thermal forces?
  - forward-backward asymmetry in thermo-optical parameters

Radioisotope Thermoelectric Generators (RTGs)
A MISSION TO EXPLORE THE PIONEER ANOMALY

Measurement Concept: Formation-flying

A CONSTELLATION OF SLR TEST MASSES IN DEEP SPACE

- 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 controlled location.

Courtesy of
S. Turyshhev (JPL)
Thermal model to be tuned to SCF data

Different suprasil (CCR) thermo-optical properties
\( (\alpha = \text{absorptivity}, \varepsilon = \text{emissivity}) \)

\[ \alpha_{\text{SOLAR}} = 0.15, \quad \varepsilon_{\text{IR}} = 0.81 \]

\[ \alpha_{\text{SOLAR}} = 0.015, \quad \varepsilon_{\text{IR}} = 0.20 \]

\[ \alpha_{\text{SOLAR}} = 0.015, \quad \varepsilon_{\text{IR}} = 0.81 \]
LAGEOS model of thermal thrusts for $\alpha_{\text{SUN}} = 15\%$

Thermal Thrusts on LAGEOS
CCR solar absorptivity = 15 %

Steady state: $t=0$ sec
SUN=ON
SUN=OFF for 4500 s
then SUN=ON.
IR always ON
Simulation results on $\tau_{CCR}$ vs Temperature

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

- $T_{Al}=300$ K, Sun ON, IR OFF
- $T_{Al}=300$ K, Sun OFF, IR ON
- $T_{Al}=300$ K, Sun ON, IR OFF
- $T_{Al}=300$ K, Sun OFF, IR ON
- $T_{Al}=280$ K, Sun ON, IR OFF
- $T_{Al}=280$ K, Sun ON, IR ON

$\tau_{CCR}$ (sec) retroreflectors

$LAGEOS$ matrix

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

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FE model and thermal simulation of LARES

- New shell-over-the-core design
- Model with 15000 nodes. Being optimized
- Steady steady with LARES in front of a solar lamp

**CCRs, front view**

**Core, side view**

Temperature [K], Time = 0 sec

287 K

263 K

295.6 K

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

Temperature shifts, but shape stays about the same: 
\( \tau_{CCR} \) insensitive, at \(<10\%\), to this large variation of 
\( \varepsilon(Al) \)
Simulation result on “ageing” of Al (Sun absorptivity)

CCR temperatures with matrix temperature fixed at 303.022 K that would be its asymptotic temperature in the case of IR emissivity of 0.2 and solar absorptivity of 0.5

CCR temperatures with matrix temperature fixed at 309.663 K that would be its asymptotic temperature in the case of IR emissivity of 0.2 and solar absorptivity of 0.35
**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 velocità angolare (tesi di Ph.D. di Petras Avizonis, Relatore Douglas Currie, University of Maryland at College Park - UMCP).

**Problemi:** le posizioni 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 azimut e altezza del satellite nel cielo della stazione e degli istanti degli eventuali impulsi riflessi.
Extended AM0 spectrum (400 - 3000 nm)
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.

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 $\Delta t = (t_{\text{arrival}} - t_{\text{start}})$ after retro-reflection from satellite. Satellite distance = $\Delta t \times c$. 

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

Peter O. Minnett and Thomas W. Zegwodzki
Goddard Space Flight Center
Greenbelt, Maryland

Thomas Vergheze and Michael Seldon
Alliant Signal Aerospace Company
Suitland, Maryland
LAGEOS I prototype sent by NASA-GSFC to LNF

LAGEOS I sand-blasted
Al: $\epsilon(\text{IR}) = 20\%$

LAGEOS II, instead, had
$\epsilon(\text{IR}) = 5\%$

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

Simulations at Galileo altitude for Effective Cross Section of 100 million sq. meters.

<table>
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<tr>
<th>Design</th>
<th># of cubes</th>
<th>Diam. (inch)</th>
<th>Approx. Area of the cornercubes (sq cm)</th>
<th>Approx Mass of the cornercubes (gm)</th>
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<tr>
<td>uncoated</td>
<td>50</td>
<td>1.3</td>
<td>428</td>
<td>1000</td>
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<tr>
<td>coated</td>
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<td>0.5</td>
<td>508</td>
<td>460</td>
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<tr>
<td>hollow</td>
<td>400</td>
<td>0.5</td>
<td>508</td>
<td>201</td>
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<tr>
<td>hollow</td>
<td>36</td>
<td>1.4</td>
<td>356</td>
<td>400</td>
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<td>Present GPS cubes</td>
<td>160</td>
<td>1.06</td>
<td>1008</td>
<td>1760</td>
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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.