The INFN-LNF
Satellite/lunar laser ranging Characterization Facility (SCF):
results on (LAGEOS and) GNSS


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Outline

• Space characterization of laser retro-reflector arrays in space with the SCF
  – The issues, the Facility, the Test

• LAGEOS testing (will skip today due to lack of time)
  – LNF 3x3 prototype; the “sector” prototype; collaboration with GSFC and ILRS; preliminary thermal/orbital/spin model tuned to SCF measurements

• The ETRUSCO INFN experiment on GNSS
  – SCF-Test of the “GPS3” flight model and Glonass-type prototype
CCRs in space: critical thermal & optical issues

- **Velocity aberration.** Relative station-satellite velocity requires expensive non-zero dihedral angle offsets with 0.5 arcsec accuracy to widen laser return (FFDP) to ground by angle $\theta$

  \[
  \theta \sim 2 \frac{v}{c} \cos \phi \sim 25 \mu \text{rad} \\
  \text{(~ 500 m on the ground)}
  \]

  Achievable with dihedral angle offsets $\sim 2''-3''$

  \[
  \text{Nominal distance between FFDP peaks is} \\
  2 \times \theta = 50 \mu \text{rad} \Rightarrow 1 \text{Km}
  \]

- **Thermal perturbations:** temp. gradients across CCR can degrade laser performance
  - A CCR could work at STP, BUT not in space for thermal reasons

- **Design** CCR array to control thermal and optical properties

- **SCF-Test:** characterize performance at the INFN-LNF dedicated facility

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GPS/GLONASS velocity aberration is

$$\theta \sim 2 \frac{v}{c} \cos \phi \sim 25 \mu \text{rad}$$

($\sim 500 \text{ m on the ground}$)

Achievable with dihedral angle offsets $\sim 2''-3''$

Example of Retro-reflector in space (CCR)
SCF-Test of LAGEOS “sector” proto from NASA-GSFC

Thermal and optical test of laser retro-reflector array in space conditions
New space test: the “SCF-Test”

- **Space conditions**
  - Dark/cold/vacuum, Solar/IR Simulators
  - IR thermometry, laser measurements

- **Measurement of**
  - IR emissivity & Solar absorptivity of CCR and metal
  - $T_{\text{SURFACE}}$ of CCR and metal
  - Thermal relaxation time of CCR ($\tau_{\text{CCR}}$), plastic, metal
  - $T$ difference of outer face and inner tip of CCR
  - CCR Far field diffraction patterns (FFDP) in SCF
    - Developing CCR interferogram
    - CCR FFDP at STP

- **Thermal and optical model of** SCF data, SPACE data

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**Glonass CCR “in space”, inside SCF**

**Glonass CCR at STP, outside SCF**

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Figure 3. LAGEOS CCR assembly

Side channels to measure CCR $T$ with IR camera
Calculations of CCR thermal relaxation time vary by ~300%.

*Our measurement, which was never done before:*

\[ \sigma(\tau_{CCR}) \sim 10\% \]
around T~300K

**SW suite:**
Thermal Desktop by C&R-Tech.

SCF work led by Giovanni Delle Monache

**PRELIMINARY**

Temperature vs time of CCR and mounting rings (see photo)

Sun Simulator = ON

Sun Simulator = OFF

Temperature [K] (300 K range)

Time [s]
Comparison of thermal thrusts vs time (one orbit) between:

- LageOS Spin Axis Model (LOSSAM): some input data were not measured
- LNF model: based on orbital/thermal FEM model tuned to SCF measurements

Two completely different models agree qualitatively; ours is wholly based on the SCF

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ETRUSCO, a multidisciplinary INFN experiment on GNSS

GALILEO will be a “Unified” constellation: standard MW antennas AND laser retro-reflectors on all 30 satellites

GPS-2 has CCRs on two satellites

Collaboration with Ital. Air Force, UMD, MLRO, ILRS, GSFC

D.G. Currie of UMD, one of the inventors of Lunar Laser Ranging, with the 3rd (and last existing) GPS CCR array loaned to LNF, the “GPS3”
GNSS Retro-reflector Arrays (GRA) on GIOVE-A/B

CCRs like those on Glonass and GPS

MW antennas
and one GRA

Benefits of laser ranging wrt standard microwave tracking

- Absolute positioning wrt Geocenter
- Factor ~10 better positioning
- Long term stability & geodetic memory

GNSS: Global Navigation Satellite System
Glonass prototypes FFDPs @STP ($\lambda=532$ nm)

Optical modeling software: CodeV, by ORA

Optical circuit for CCR
Far Field Diffraction Pattern test at LNF

MEASURED PATTERN

SIMULATED PATTERN

MEASURED

SIMULATED
Note: positioning system is so big because meant for larger arrays.
SCF-Test of Glonass Al-coated CCR prototype

Hot, non-isothermal CCR under the Sun=ON 3 hrs
Laser signal reduced significantly AND it goes to the wrong place (distance increases to 2 Km)!

Significant **loss and spread** out of laser signal

Sun=OFF: colder, more isothermal CCR.
Laser peaks increase AND get back to correct place, ie, nominal distance = 1Km

$\lambda=532 \text{ nm}$
Glonass SCF-Test

Sun Simulator ON

Sun Simulator OFF

$T_{\text{OUTER CCR FACE}}(K) \text{ vs } t \text{ (sec)}$

Laser return peaks reduced by factor 2, their distance increased to 2 Km

Laser peaks increase AND get back to nominal velocity aberrated distance = 1 Km

Note: sun at 90°, ie, this is a “worst case”

AM0 Solar simulator

FFDP on CCD

FFDP on CCD

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Next: from 90°, “worst case” to “orbit-like” case

NEXT SCF-Tests

Will rotate slowly the CCR in a ~3-hour, quarter-orbit SCF-Test. Plus ~2 hour shadow.
Thermal effects make FFDP peaks move away from the ‘angular location’ where the stations are located.

More than one time constant. Candidates:
- CCR back Al-coating
- non-insulating CCR mounting

We will try to disentangle the two effects.

Note: the vertical scale is mis-calibrated by 50/85. The corrected asymptotic distance is ~50 μrad.)
Reduction of intensity of laser return

SUN=ON at $t<0$, SUN=OFF for $t>0$

2.5 hours of Sun illumination, then Sun=off and FFDP measurement

This effect has been measured for the very 1st time.

It may help understand the performance of Glonass/GPS CCRs in orbit

CCR non-isothermal: strong reduction of laser signal

CCR more isothermal: laser signal restored

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Image of graph showing peak height (CCD counts) vs time (sec)
GRA flight model for the GPS-2 (the “GPS3”)

3rd made for GPS-2
Property of Univ. of Maryland, loaned to INFN for space characterization @SCF

19 x 24 cm²
1.3 Kg, 32 CCRs

D.G. Currie of UMD, one of the inventors of Lunar Laser Ranging
SCF-Test of GPS-2 flight model from Univ. of Maryland

Thermal and laser tests never performed before in space conditions

λ = 532 nm

FLIGHT MODEL on the roto-translation system; left is optical window
GPS-2 SCF-Test: FFDP spoiled by Sun thermal perturbation

Explanation of problematic performance? To be avoided for GALILEO

“Hot” FFDP @ t = 0 sec

“Cold” FFDP @ t = 3000 sec

FFDP height (CCD counts) vs time (s) after exposure to Sun

Strong reduction of signal

FFDP peak-to-peak distance (µrad) vs time (s) after exposure to Sun

Correct peak-to-peak distance

Laser return goes to the wrong place
Thermal effects: CCR coating, mounting; the “hollows”

The Glonass/GPS CCR mounting scheme

Bare Glonass/GPS CCR, held by KEL-F spacers

Be or Al hollow CCR
Proposed by GSFC

The uncoated LAGEOS CCR with its “pristine” mounting scheme
FFDP test of the GPS3 in air (STP), $\lambda=632$ nm
GPS3 FFDPs in air (just 6 out of 32), $\lambda=632$ nm

…. and 26 more. Next time that D. Currie will be at LNF will do $\lambda=532$ nm
Conclusions

• At INFN-LNF we developed a dedicated facility to characterize the detailed optical performance and thermal properties of laser retro-reflector arrays in space, the “SCF-Test”

• With the ETRUSCO experiment we:
  – SCF-Tested a few CCR of the GPS-2 flight model and Glonass-type CCR prototype
  – We tested the full GPS-2 flight model in air (STP)
  – Will SCF-Test an innovative hollow retro-reflectors for GPS-3 loaned to LNF by NASA-GSFC

• SCF-Test: effective new tool for the GNSS and for our beloved GALILEO. But also for Space Geodesy and for experimental tests of Gravitation in the Solar System