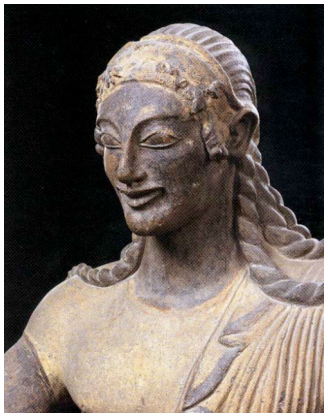
Creation of the New Industry-Standard Space Test for GNSS Constellations



Presented by S. Dell'Agnello for the International ETRUSCO Team

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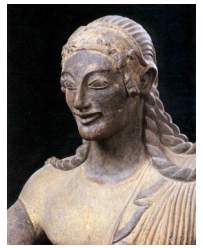
[7] *University of Bologna, Bologna, Italy*

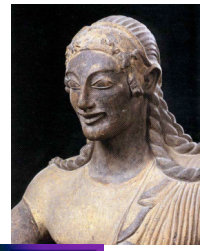
ILRS Workshop on "SLR Tracking of GNSS Constellations", Metsovo, Greece, Sepetember 14-19, 2009

Outline

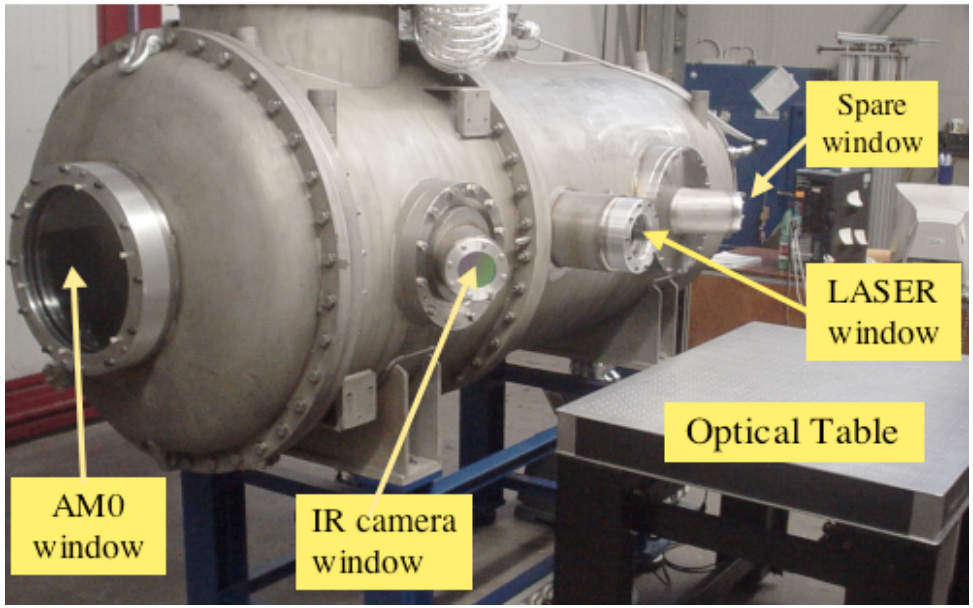


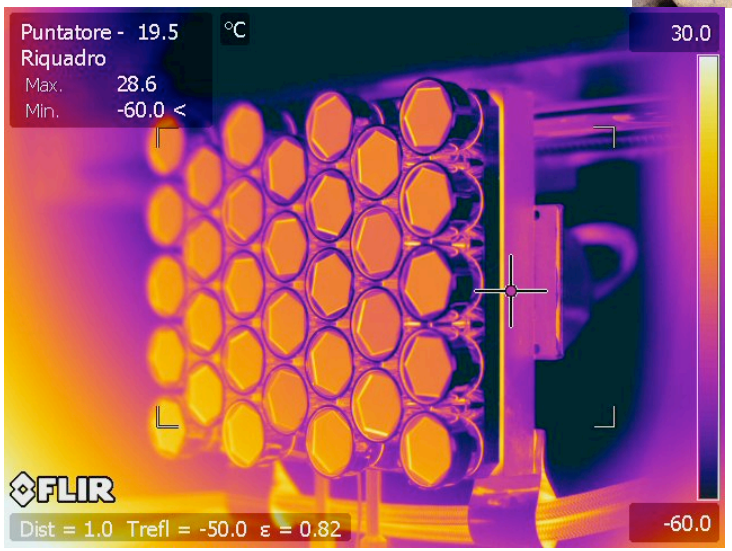
- Completion of new industry standard, the “SCF-Test”
  - **Space characterization of laser retro-reflector arrays (LRA) in representative space conditions**
    - INFN experiment, ETRUSCO
    - Developed with GPS/Glonass/Giove CCRs and with Apollo/LAGEOS CCRs
- **Industrial issues for LRAs of new GNSS Constellations**
- ASI approved evolution of INFN program into, an industry-class 30-month project, ETRUSCO-2 (**ET-2**)
- Conclusions and reference paper

SCF-Test of 3rd GPS flight LRA from U of Maryland

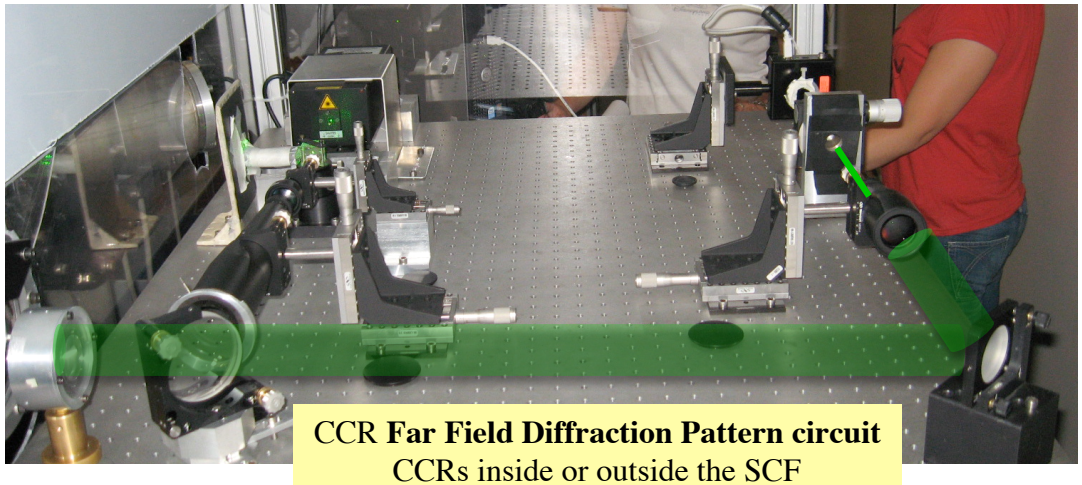


SLR/LLR Characterization Facility (SCF)

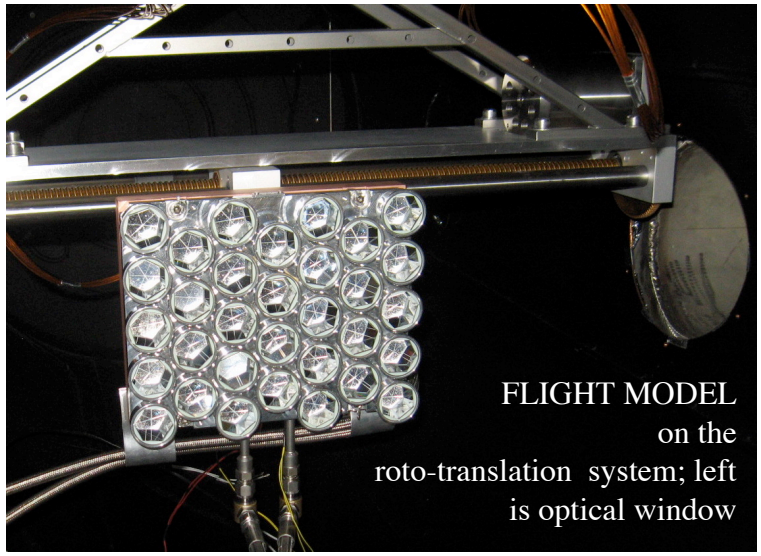




λ=532 nm

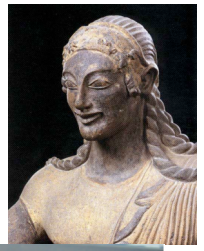


CCR **Far Field Diffraction Pattern circuit**
CCRs inside or outside the SCF



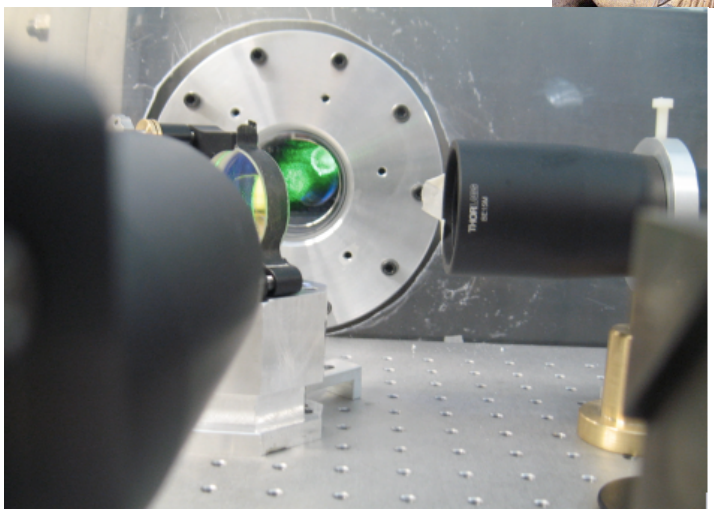
FLIGHT MODEL
on the
roto-translation system; left
is optical window

The SCF-Test

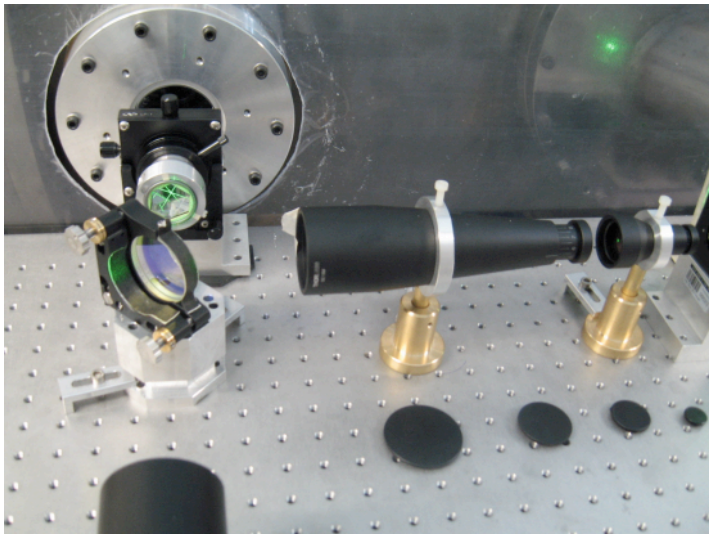


- Test conditions
  - Dark/cold/vacuum, Solar/IR Simulators
  - Non-invasive IR and contact **thermometry**
  - Optical Far Field Diffraction Pattern (**FFDP**)
  - Default configuration: Sun on (90°) --> Sun off
    - Anything else TBA on LRA-by-LRA basis
- Inputs from LRA supplier
  - IR emissivity & Solar absorptivity of LRA materials
  - LRA operating temperature range
- Deliverables
  - $T_{SURFACE}$ and thermal relaxation time of CCR and metal (plastic if possible)
  - **FFDP in SCF**
  - **FFDP in air, as pre-acceptance test**
  - **Thermal and optical model of**
    - SCF data; ORBIT data TBA
- Approved by ASI. In use for LLR
- **Proposed for**
  - GNSS and in particular for GALILEO
  - ESA's European Space Technology Master Plan

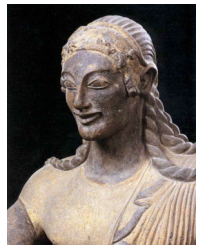
Glonass CCR inside SCF



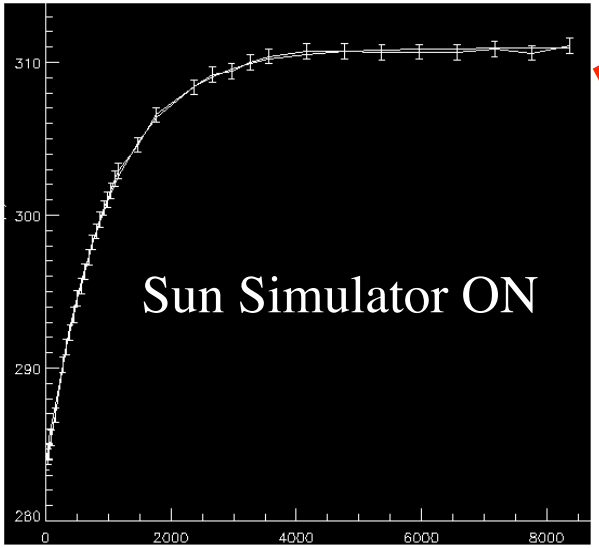
Glonass CCR outside SCF

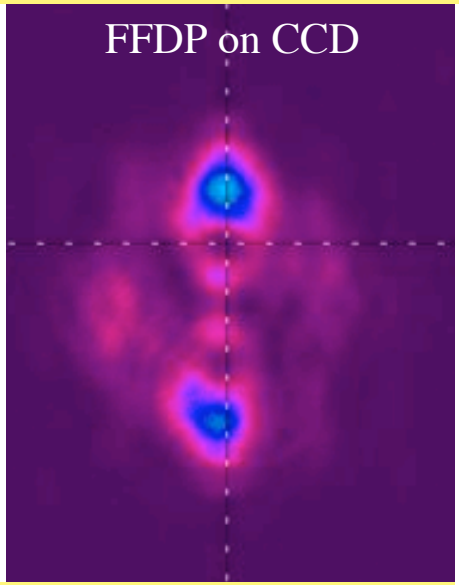


SCF-Test of GPS/Glonass/Giove CCR type

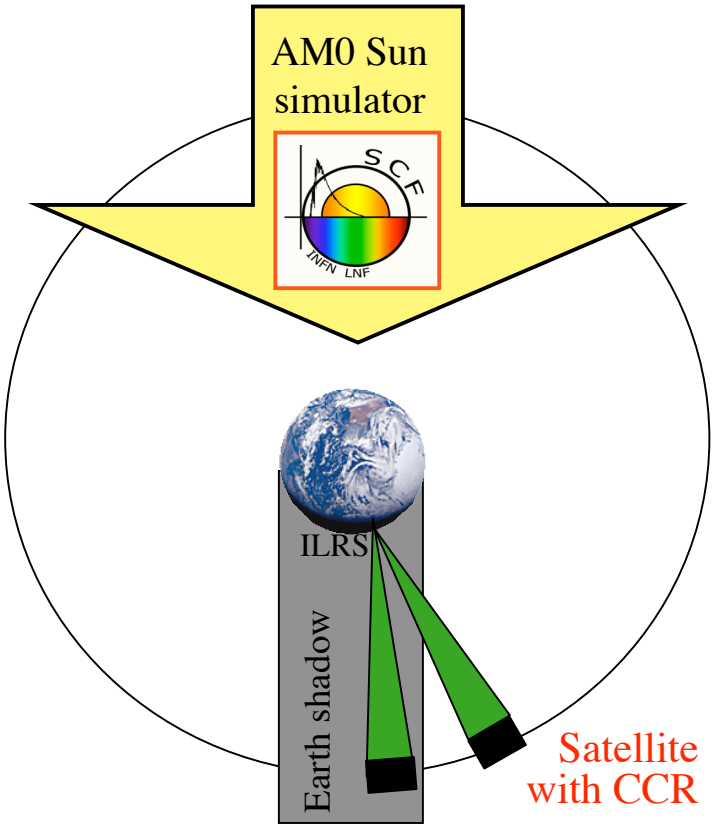


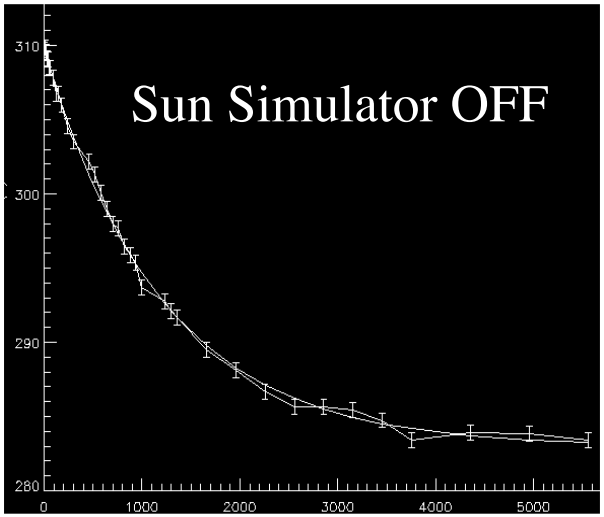
Laser return peaks reduced by factor 2, their distance increased to 2 Km



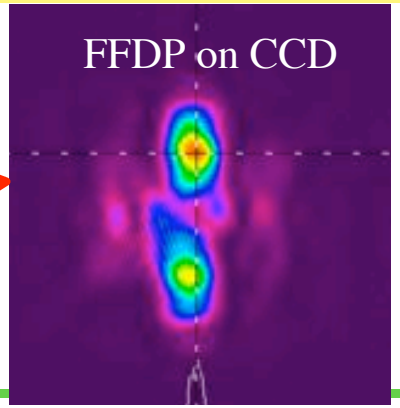


Factor ~7 reduction of FFDP



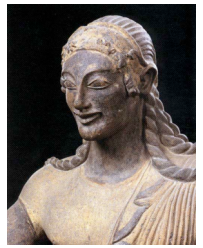


Laser peaks increase AND get back to nominal velocity aberrated distance = 1 Km



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

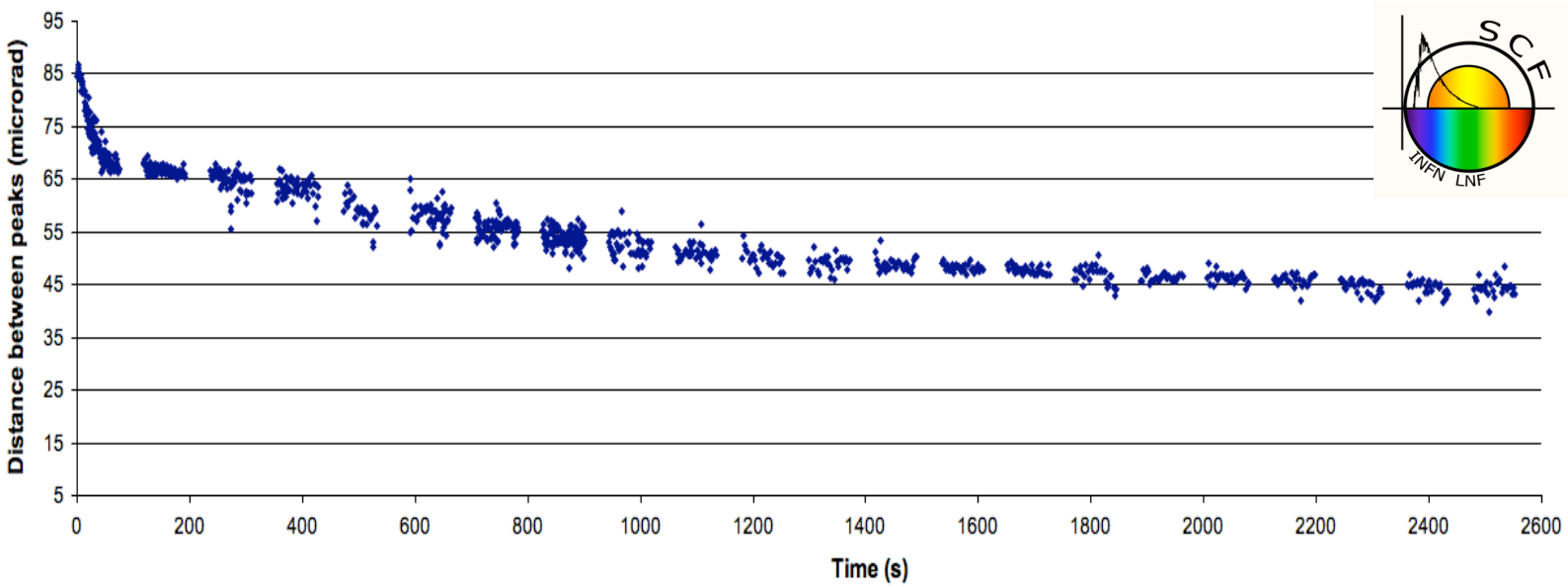
Glonass 2008 SCF-Test



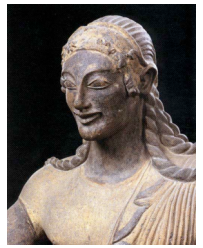
The Sun induces thermal gradients in the CCR which make FFDP peaks move away from the correct velocity aberration

Two time constants

- quick conductive cooldown (CCR back Al-coating …)
- slow radiative cooldown (non-insulating CCR mounting)



Glonass 2008 SCF-Test



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

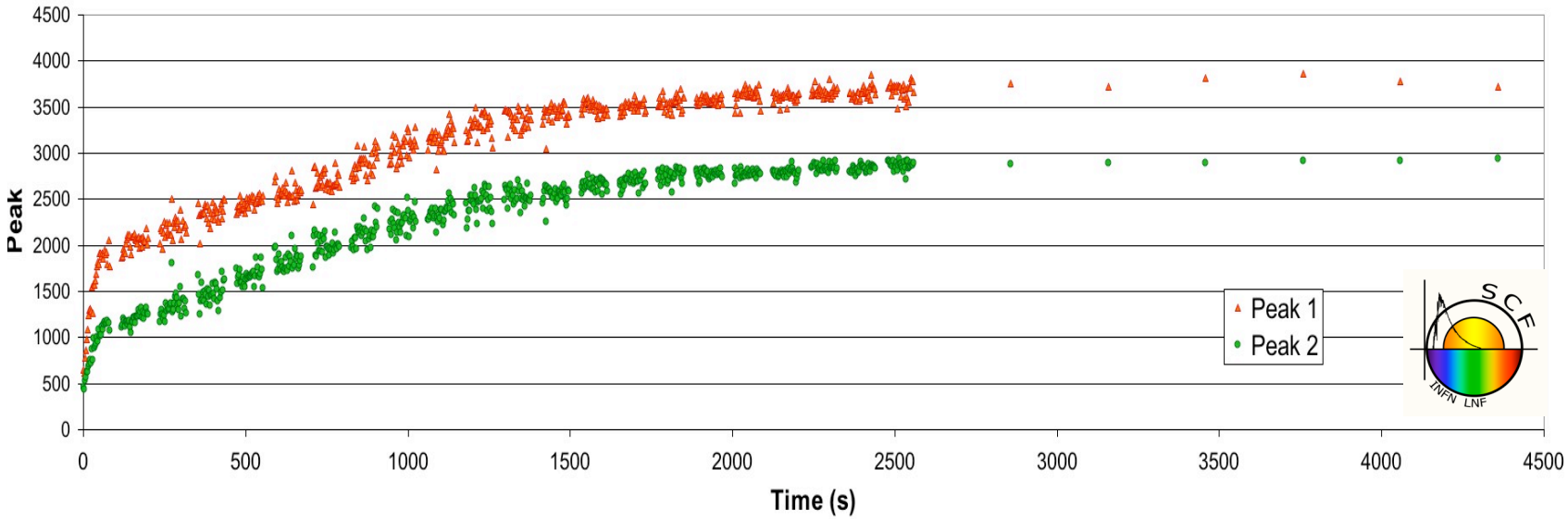
~3 hours of Sun illumination, then Sun=off and FFDP measurement

FFDP peak intensity restored at the correct velocity aberration after a significant time (~2500 sec), with the two different time constants.

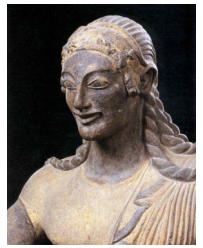
Effect measured for the 1st time in the lab

CCR non-isothermal: strong reduction of FFDP peak intensity

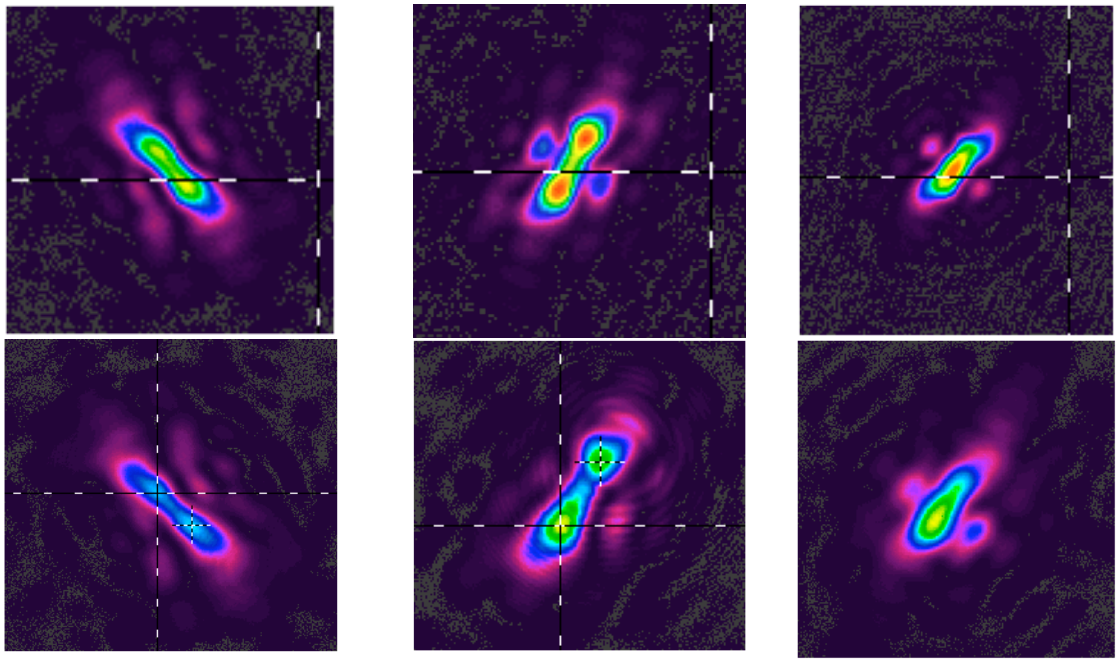
CCR more isothermal: Peak intensity restored



Optical cross section of 3rd GPS flight LRA in air



Top three FFDPs @ 633 nm

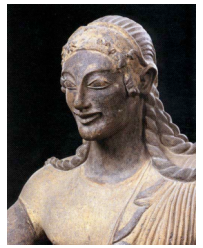


~19 x 24 cm^2

1.3 Kg, 32 CCRs

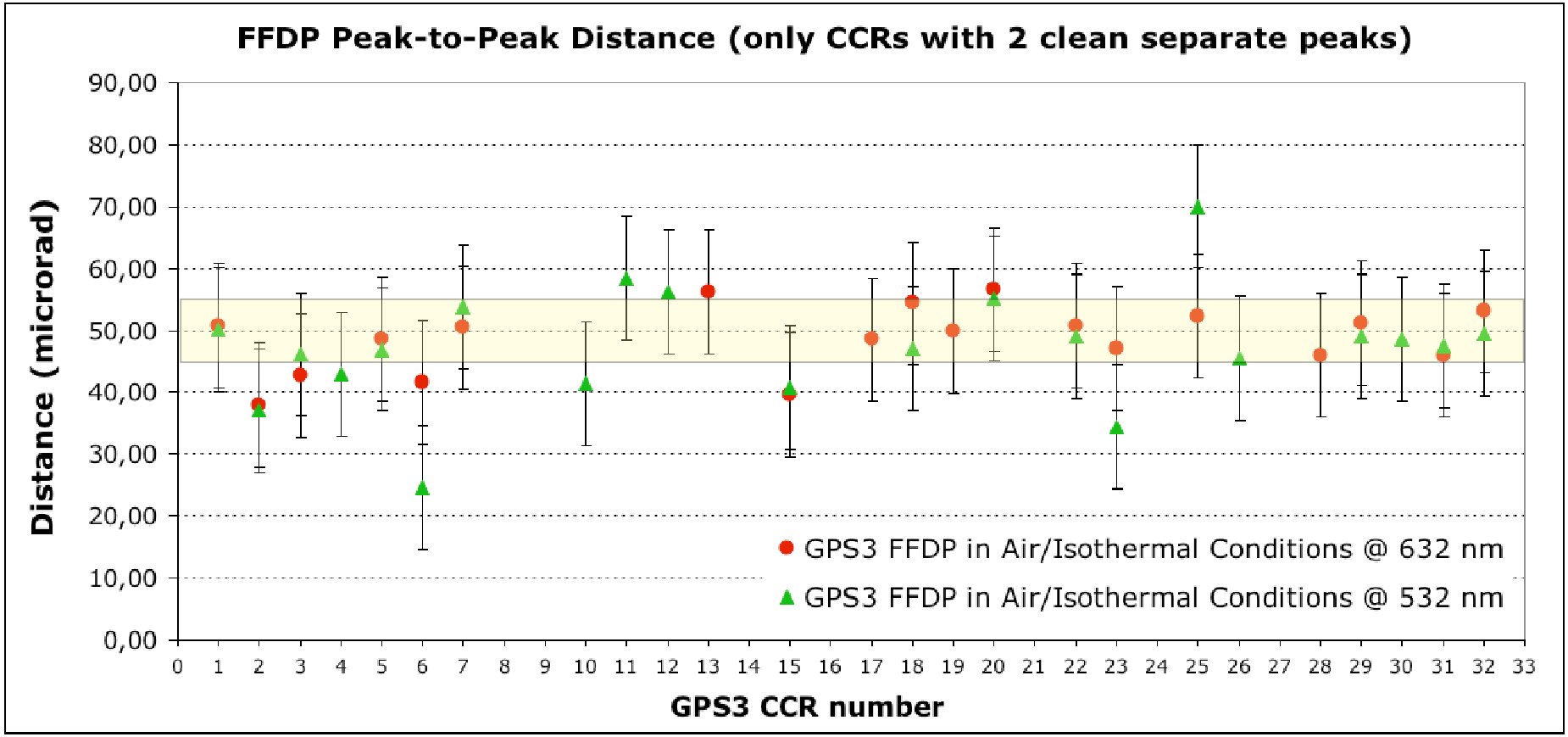
Bottom three FFDPs @ 532 nm

GPS FFDP test in air

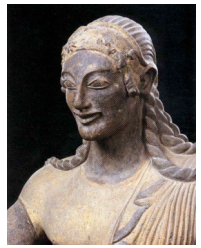


Absolute μrad units, both at 532 nm and 633 nm

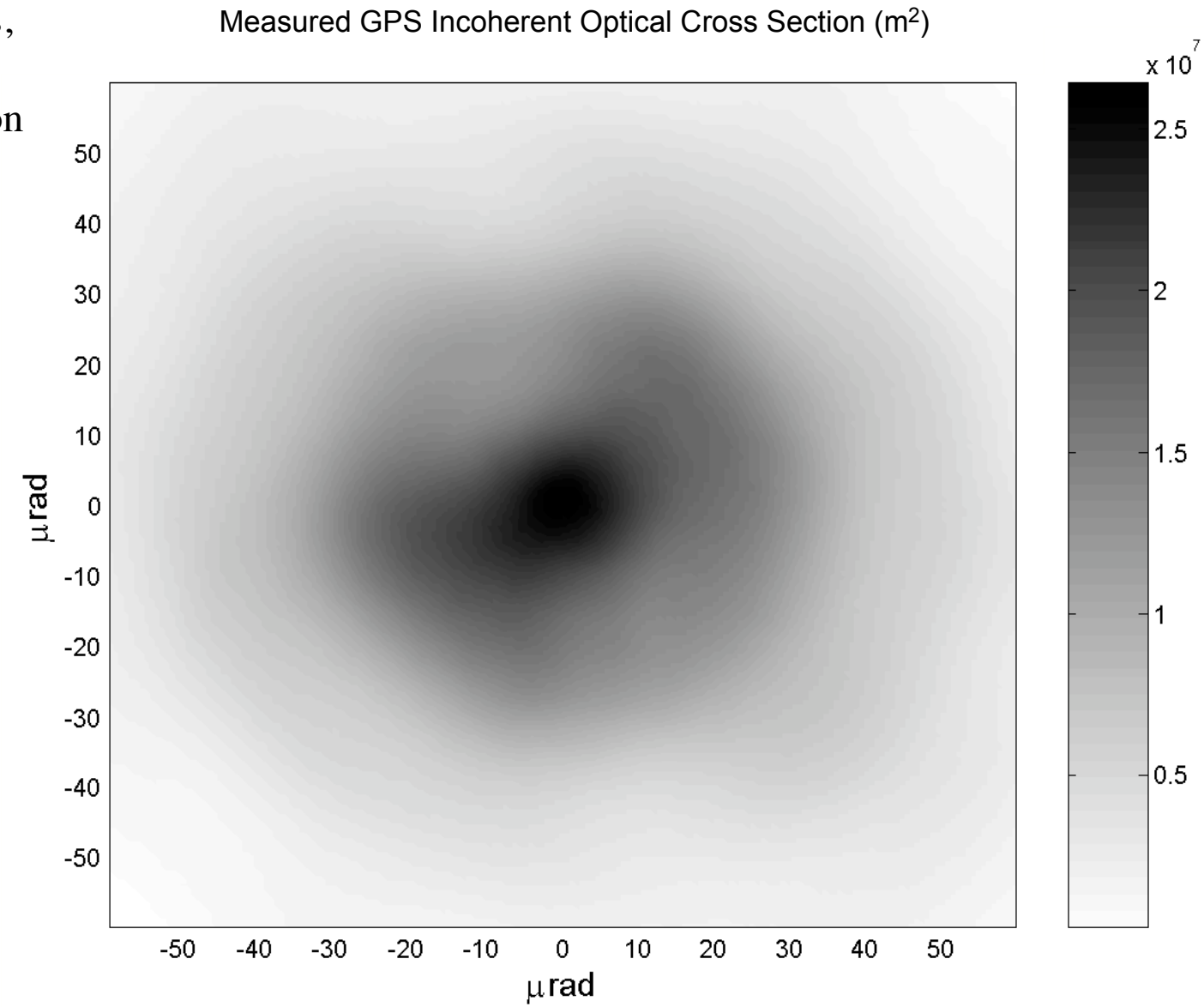
Yellow band: velocity aberration/FFDP based optical specs



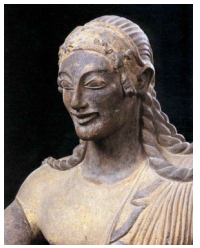
GPS measured optical cross section in air at λ=532 nm



CCR FFDPs, Airy Peak normalization

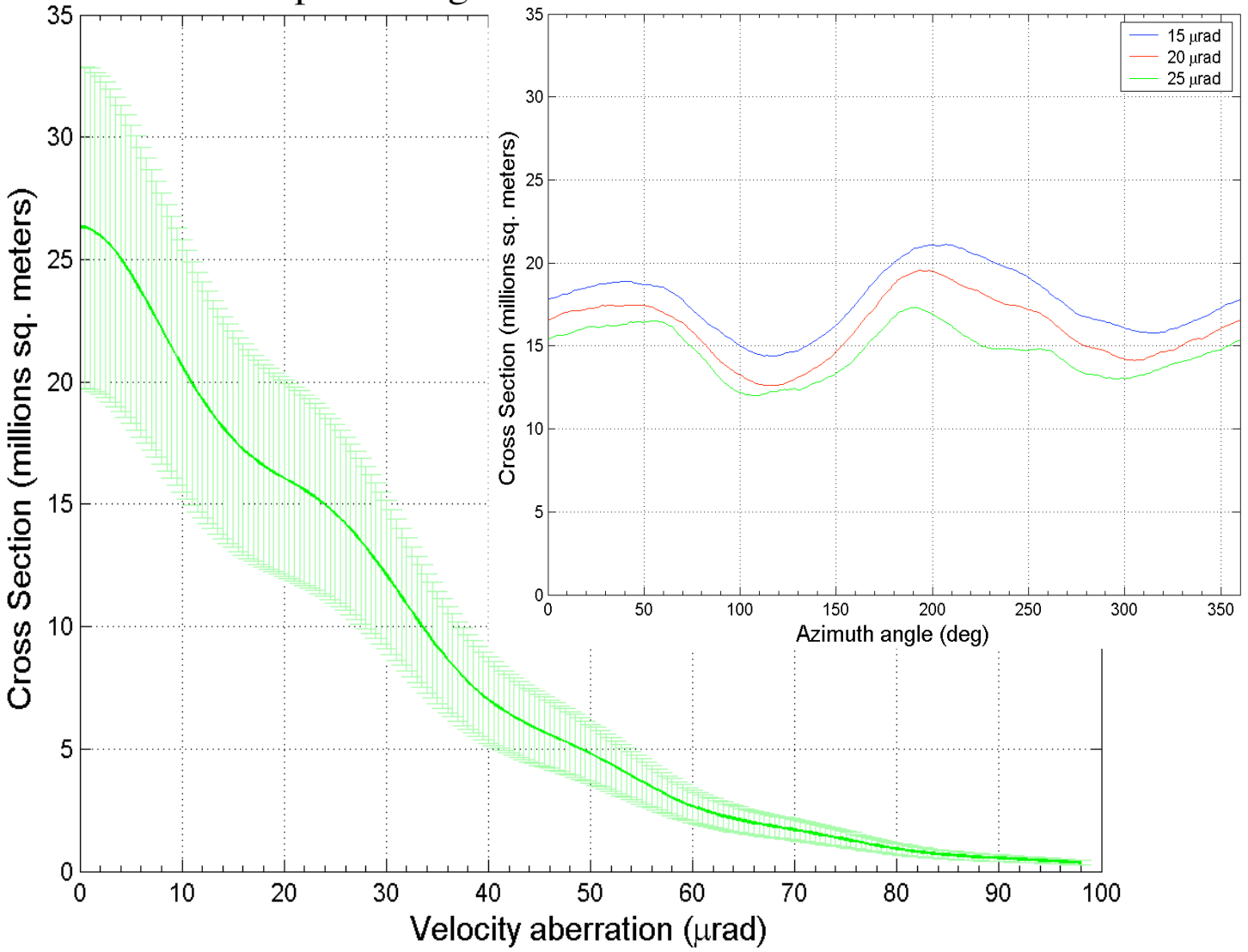


GPS measured optical cross section in air at λ=532 nm

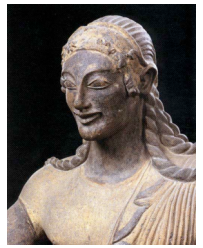


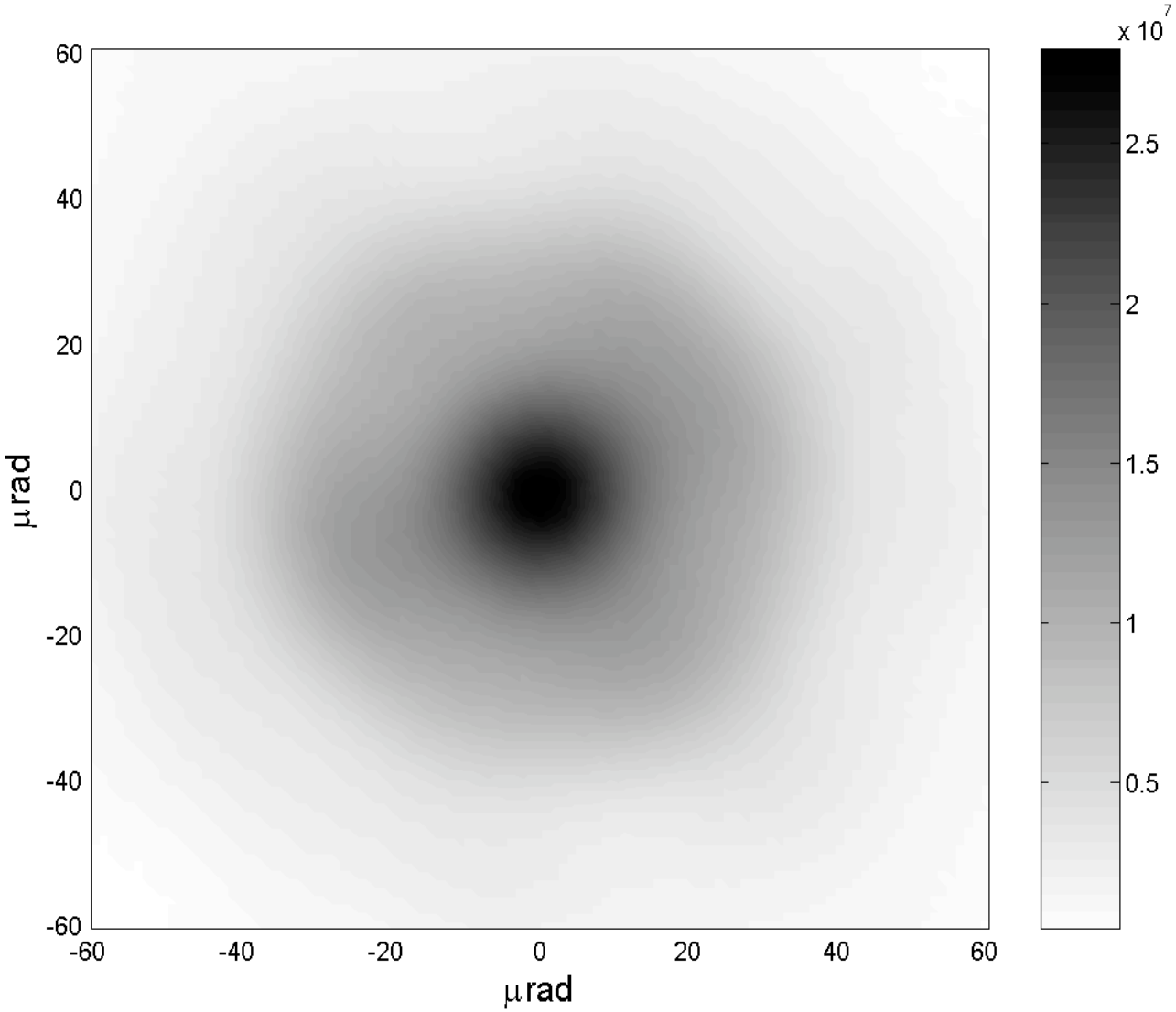
Compare with ILRS requirement of **100 million m² at 20-25 μrad**

SCF-Test shows that in space can get x7 further reduction of this in-air cross section

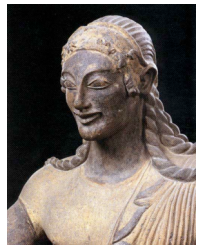


GPS measured optical cross section in air at λ=632 nm

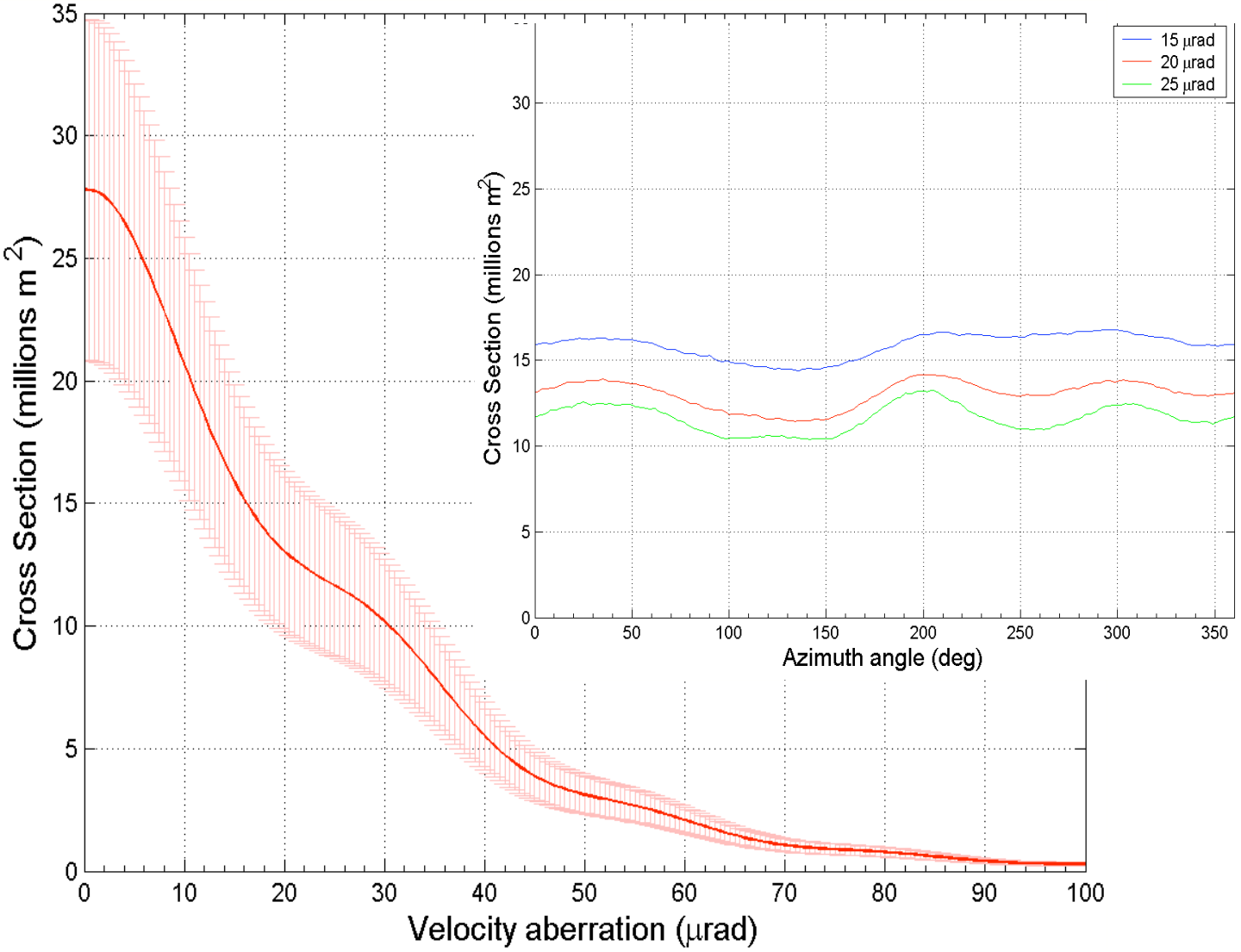




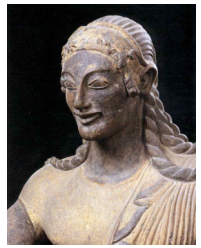
GPS measured optical cross section in air at λ=632 nm



Compare with ILRS requirement of **100 million m² at 20-25 μrad**

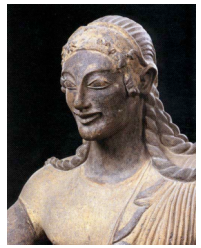


LRAs for next GNSS constellations



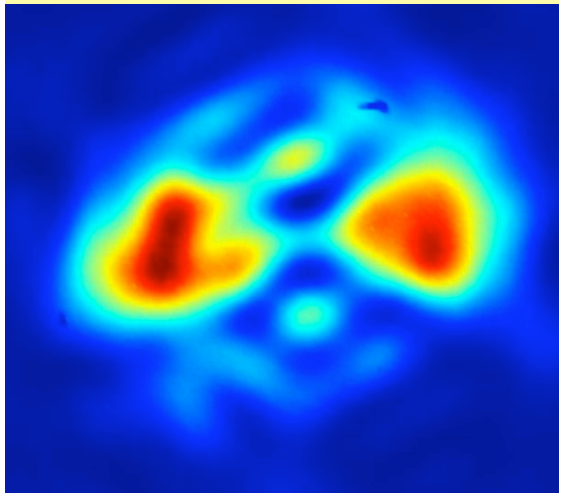
- **Critical industrial issues**
  - ILRS standard optical cross section
    - Requirement: 100×10^6 m^2 @GPS altitude (200×10^6 m^2 for GALILEO)
  - The **daylight ranging** challenge
    - Ultimate goal
  - From coated (Gps, Glonass, Giove) to uncoated CCRs
    - Back to the Apollo design
  - CCR optical specs: from **FFDP** to **dihedral angle offsets (DAOs)**
    - GNSS FFDP specs can be obtained with DAO = 0" to 3" !!
      - **Very difficult** to make an optical model
      - **Even more difficult** to make a thermal and optical model
    - GNSS DAO specs: central value with ±0.5" manufacturing tolerance, are more 'industry-grade' specs, suffer much less the above limitations
  - **FFDP test in air** is a pre-acceptance test
    - If passed you can pay the CCRs
  - **SCF-Test**: FFDP in realistic space conditions of LRA (CCRs+plastic+metal)

LAGEOS: uncoated, DAO specs = 1.25” ± 0.5”

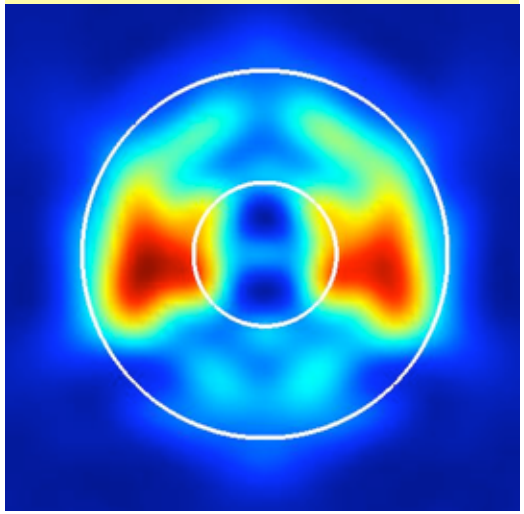


- **Performed FFDP test in air as ‘industrial pre-acceptance test’** of the 37 CCRs of Goddard’s LAGEOS sector (in absolute μrad and Airy Peak units)
- **Specific polarization configuration,** which produces two lobes of FFDP energy: horizontal polarization, 1 CCR edge vertical

MEASURED FFDP

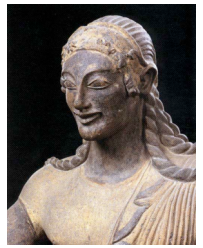


SIMULATED FFDP

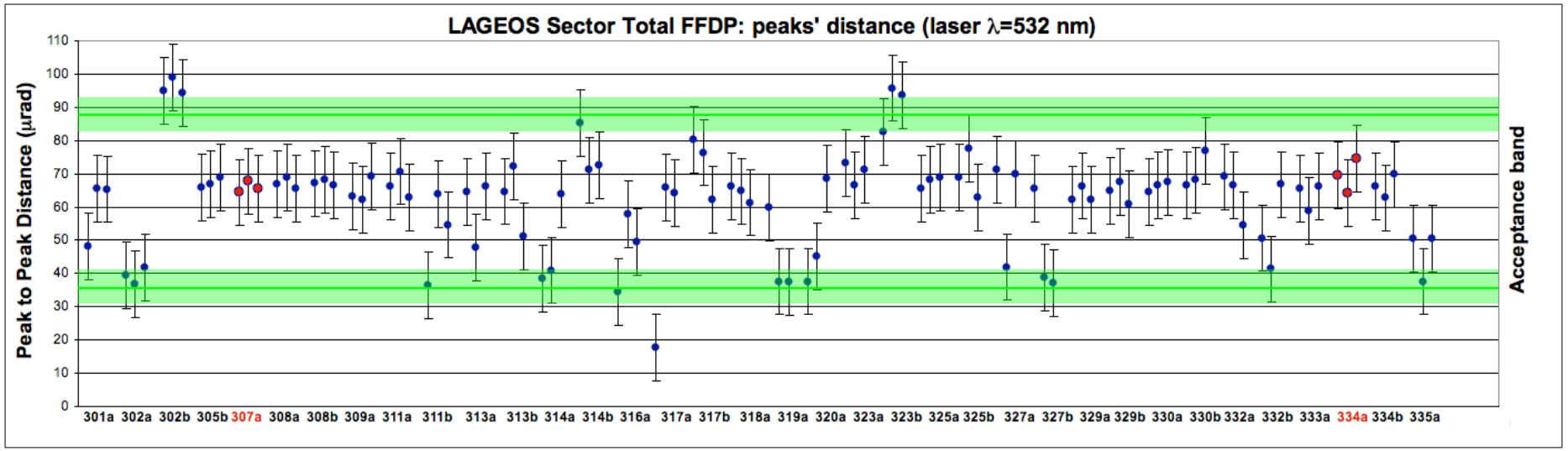


Circles show FFDP region corresponding to DAO specs

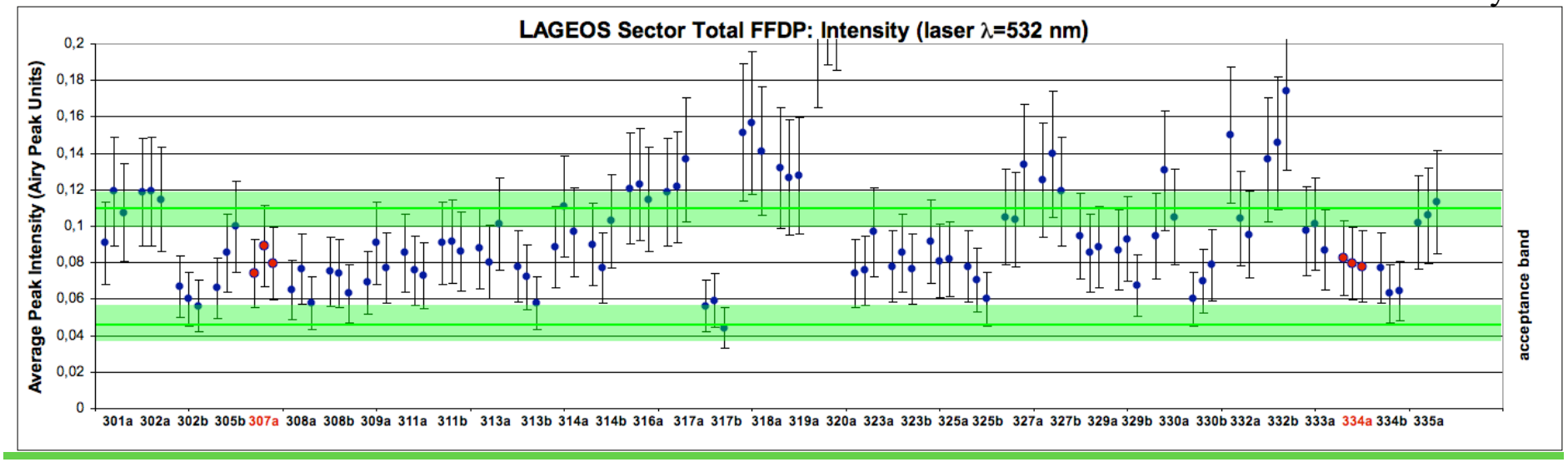
LAGEOS "Sector" FFDP test in air at λ=532 nm



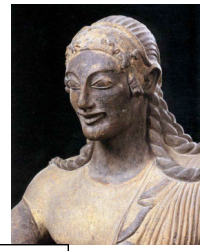
Horizontal polarization, 1 edge vertical, 1 point/edge, 3 pts/CCR



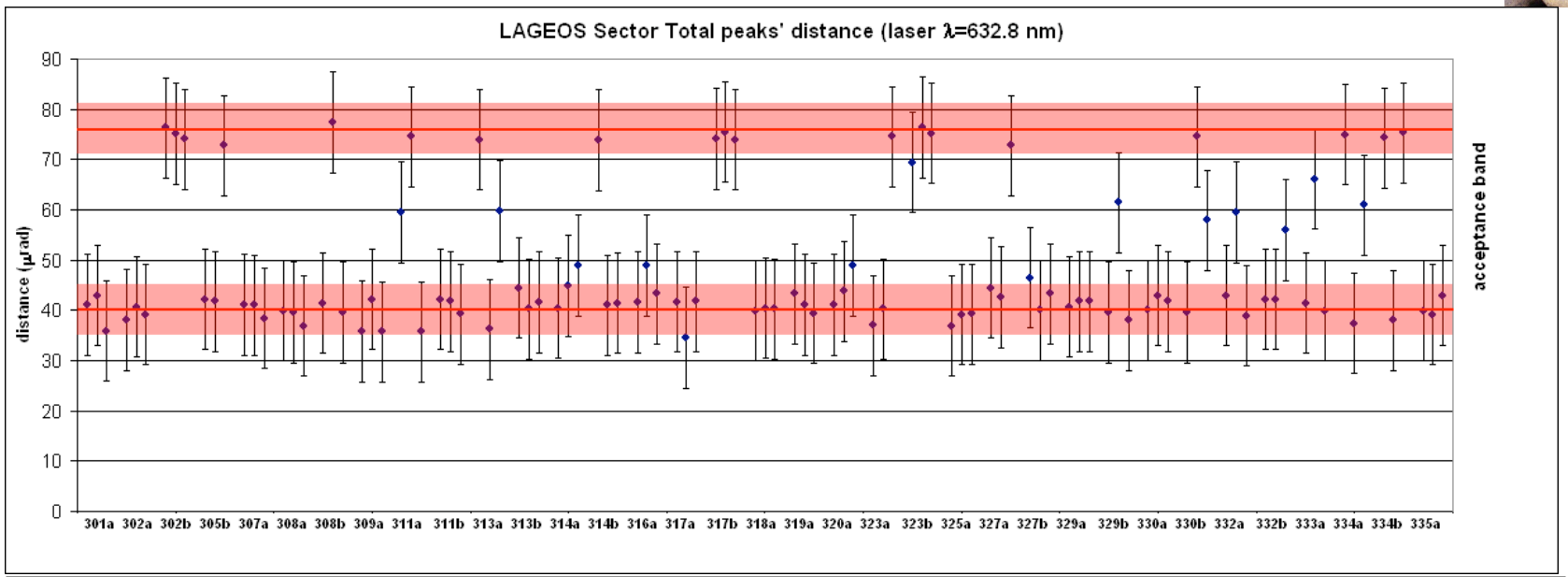
Preliminary

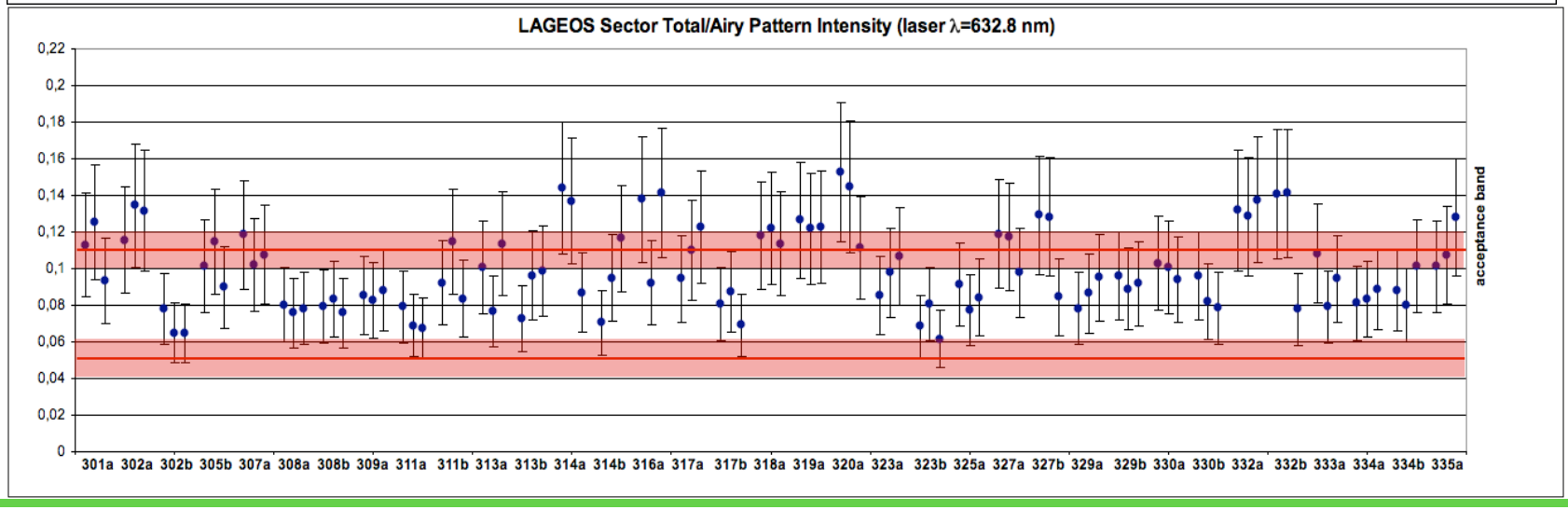


LAGEOS "Sector" FFDP test in air at λ=632 nm



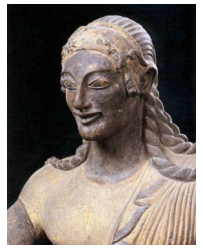
Horizontal polarization, 1 edge vertical, 1 point/edge, 3 pts/CCR



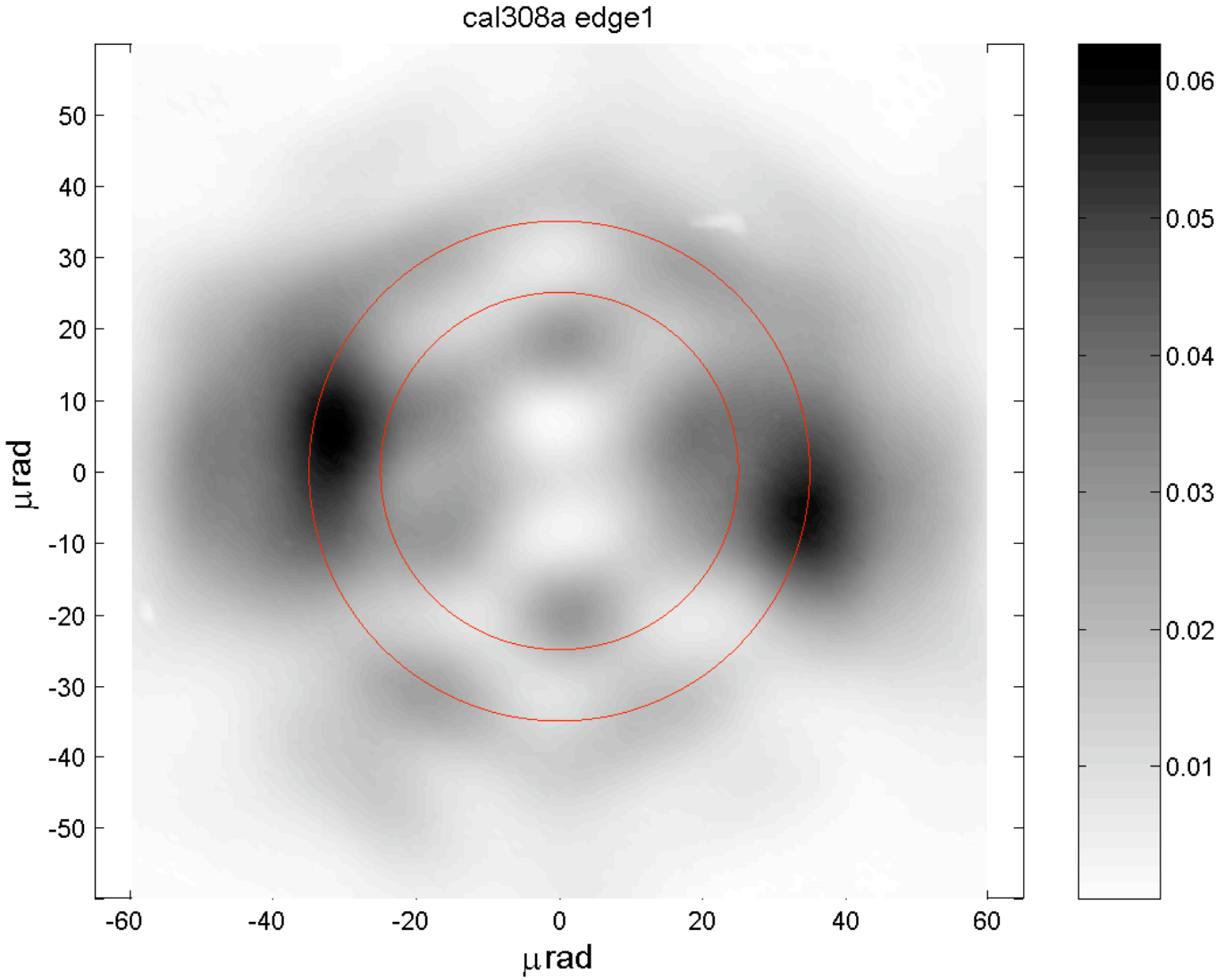


Preliminary

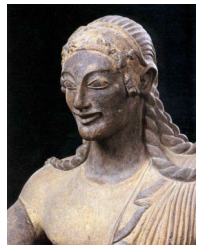
Full measured FFDPs info (not just the “peaks”)



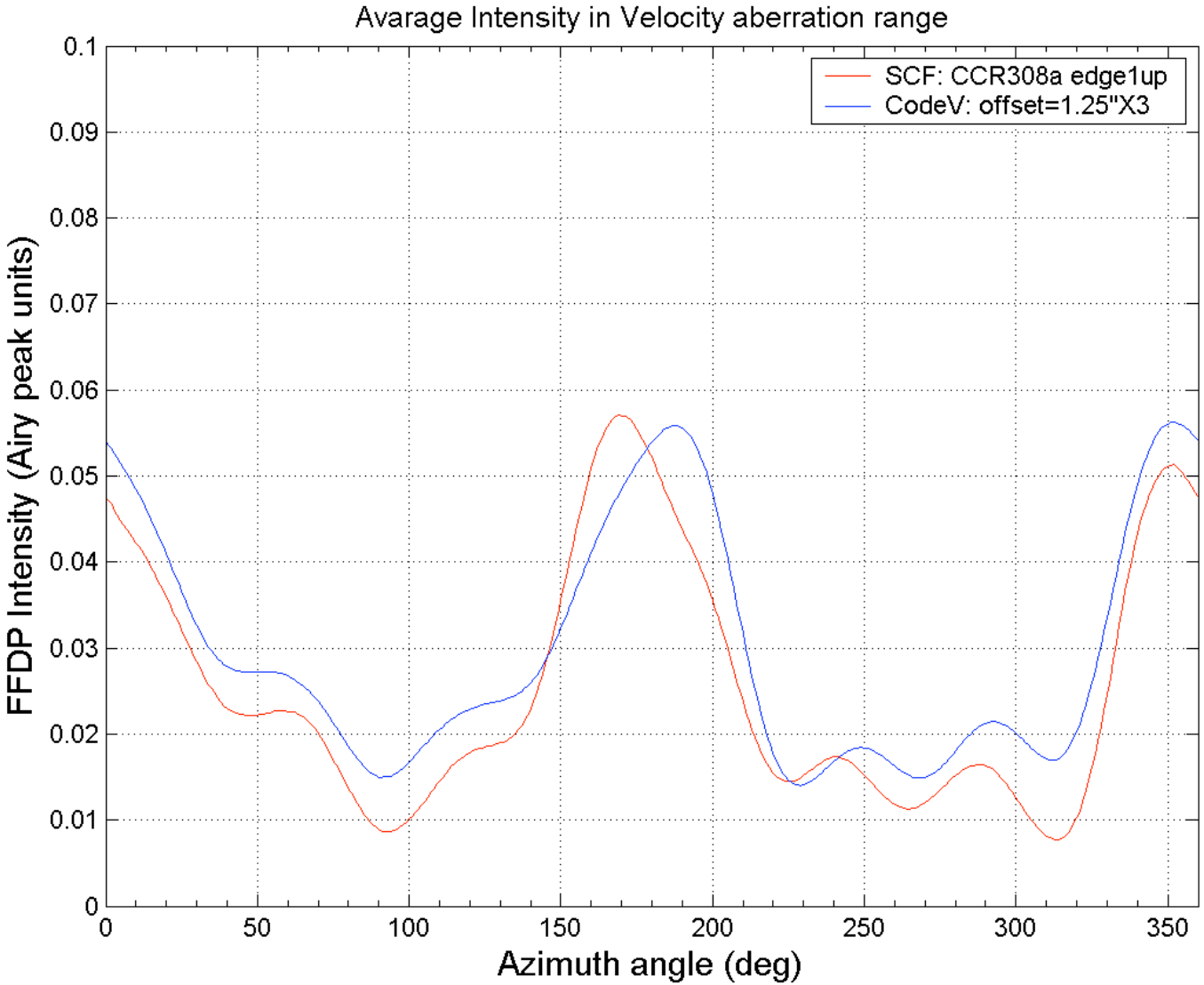
One CCR of the LAGEOS sector out of 37; 532 nm



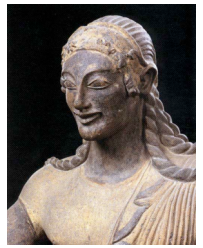
Full FFDPs info (not just the “peaks”)



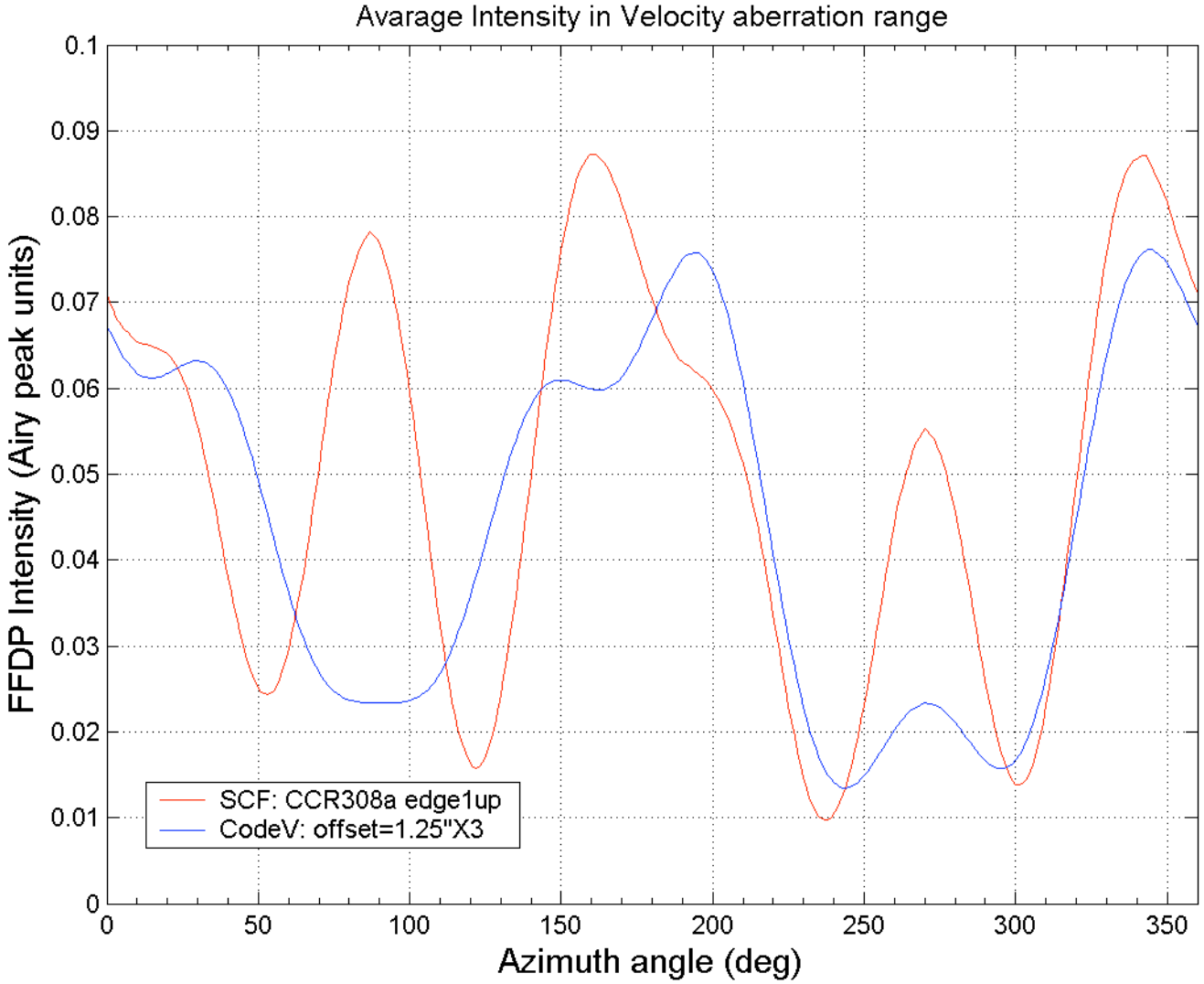
532 nm



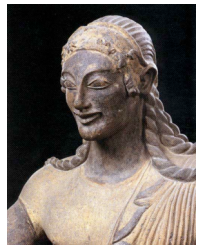
Full FFDPs info (not just the “peaks”)



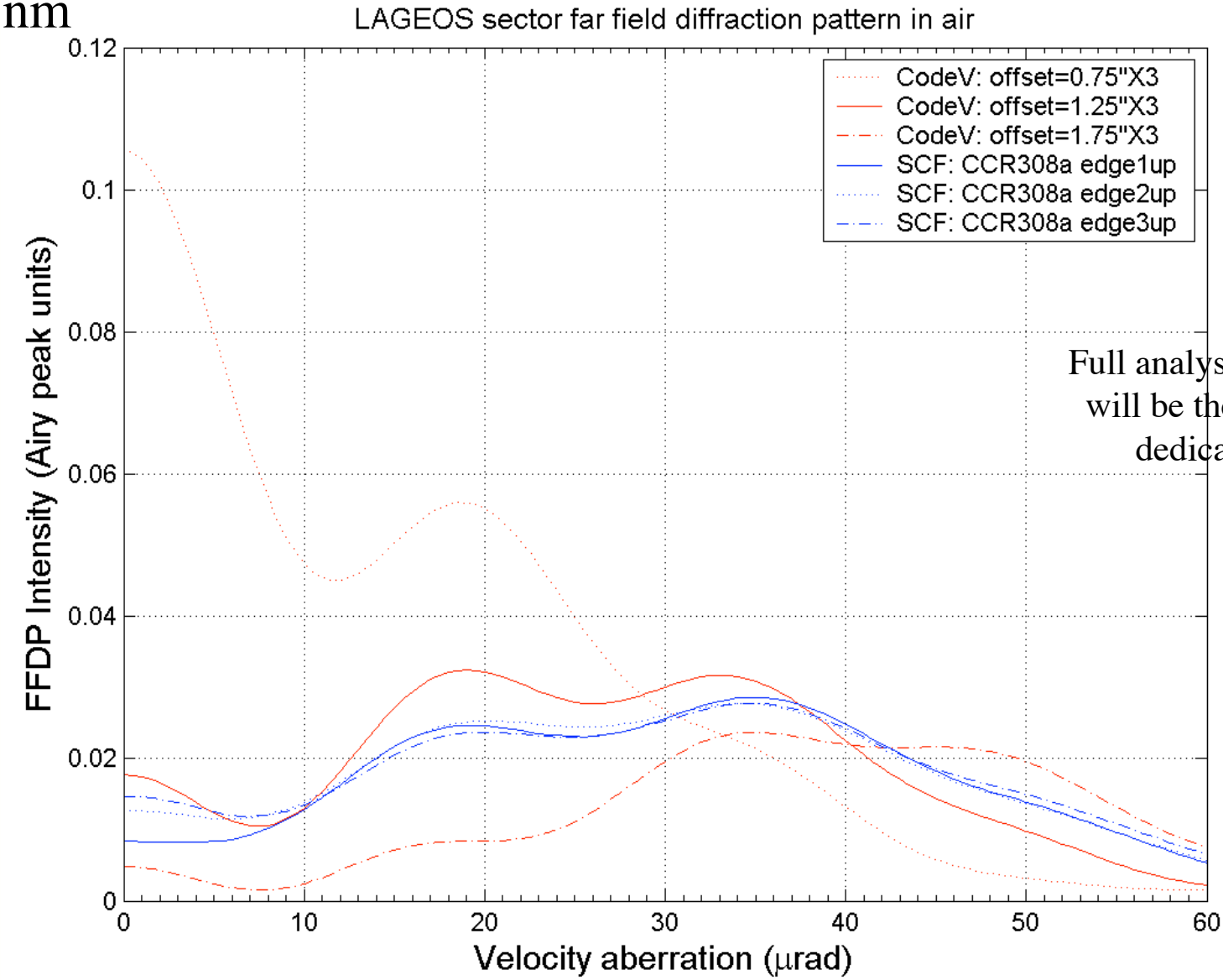
633 nm



FFDPs contain more info than just the “peaks”

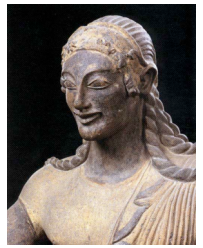


532 nm



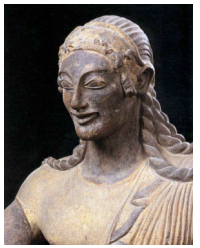
Full analysis of all CCRs will be the subject of a dedicated paper

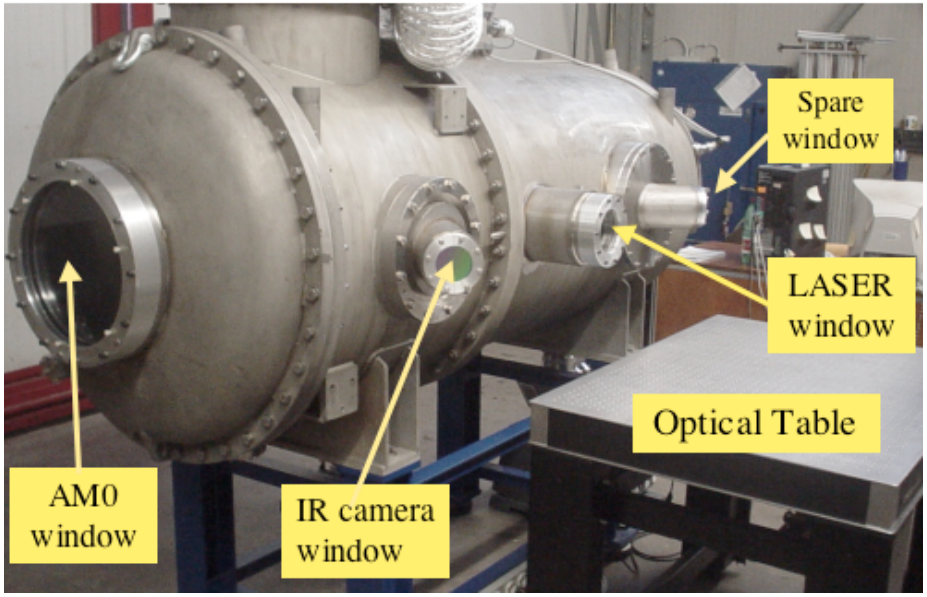
CCRs that we FFDP-tested

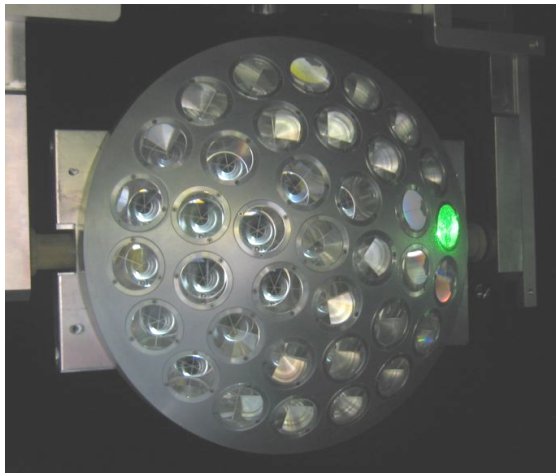


- 37 LAGEOS Sector CCR (GSFC)
  - Uncoated, 1.5 inch, DAO specs = (1.25 ± 0.5) arcsec
- 110 flight CCRs and 5 proto CCRs to be deployed on the first flight of ESA's new launcher, VEGA
  - Uncoated, 1.5 inch, DAO = (1.50 ± 0.5) arcsec
- 32 GPS flight CCRs (Maryland), 3 Glonass proto CCRs (IPIE)
  - Coated, 1.06 inch, FFDP specs = 20 μrad - 25 μrad
- 2nd generation lunar CCR, in progress
  - Uncoated, 4 inch, DAO specs = 0.00" ± 0.20"
    - largest AND most accurate ever
- Others …

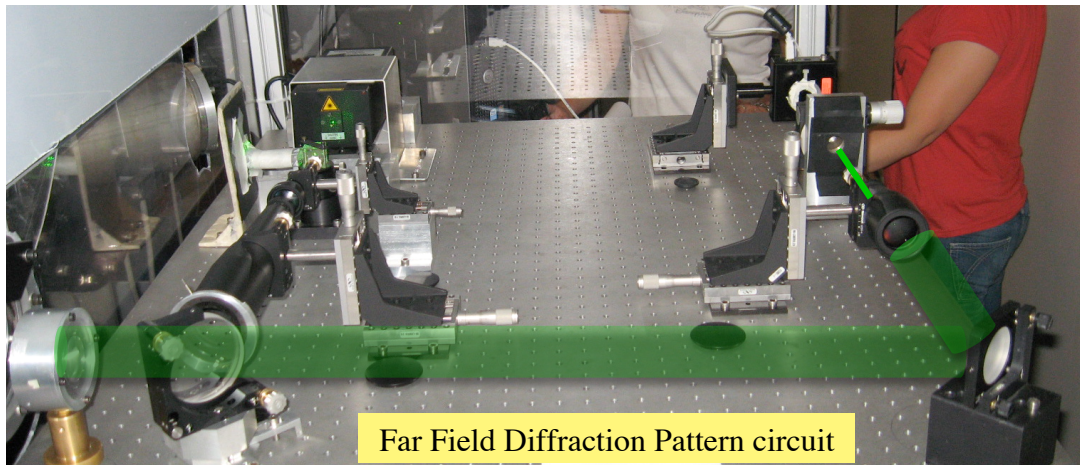
SCF-Test of 1 CCR of LAGEOS **"sector"** proto from GSFC

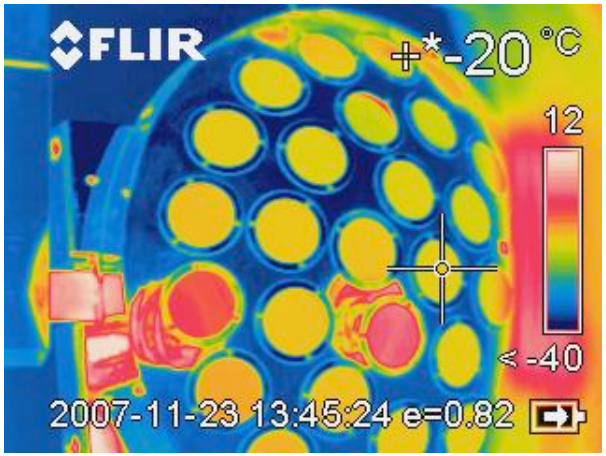




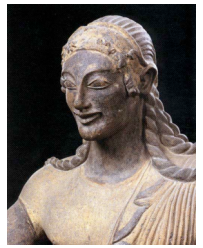


Sector in the SCF. Cu plate attached to the back of the Sector for its thermal control





ETRUSCO-2

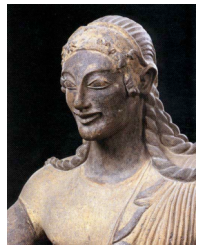


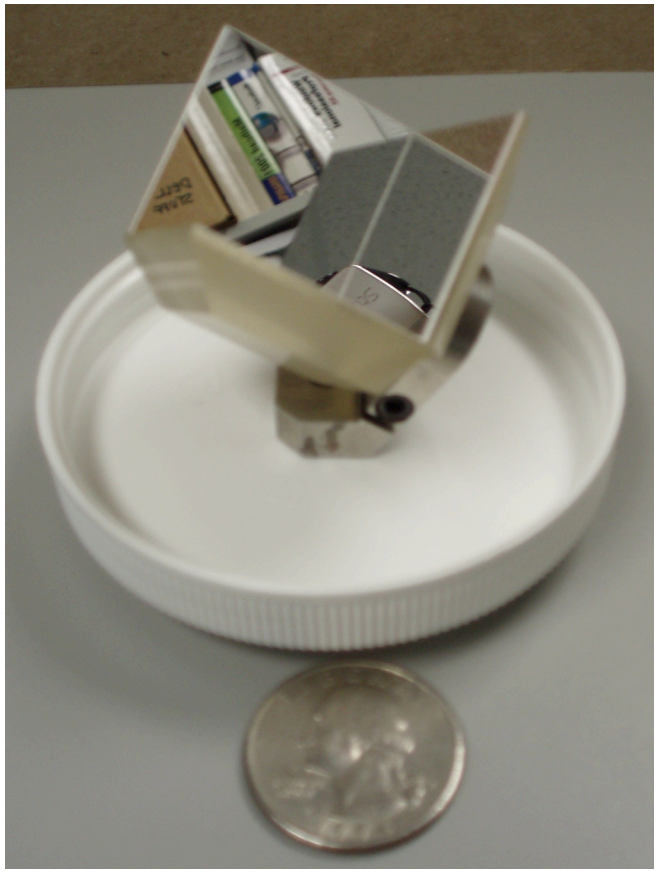
- ASI endorsed evolution of INFN program into an industry-class, 30-month project, ETRUSCO-2 (**ET-2**)
  - Nation-wide call for "Space projects of Technological Development'
    - 163 proposals, ET-2 ranked 4th out of 163, 11 (co-)funded
  - INFN is Prime Contractor; participation of ASI-CGS (G. Bianco et al)
  - Subcontractors: U. of Bologna (Susanna Zerbini), Italian SMEs
- ET-2 targeted to GNSS Constellations and especially to GALILEO
- Other areas of work
  - Hollow retroreflectors; will build and SCF-Test proto
    - array or single large CCR (proposed by GSFC for LLR and by others for GALILEO)
  - ASI-CGS and U. of Bologna will work on the geodesy benefits of SLR tracking of GNSS constellations

ET-2 Poster.

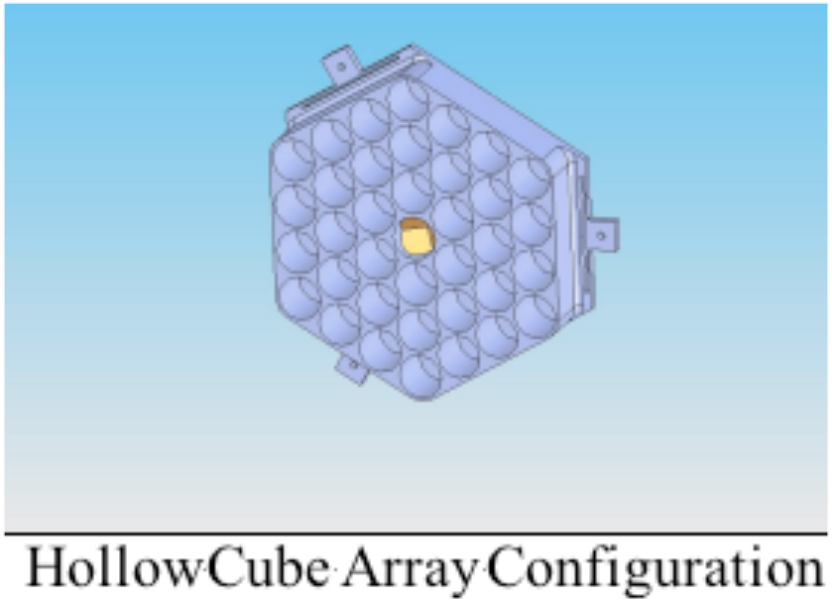
ET-2 Intl. team: **Italian sub contractors, ILRS, Intl. Partners**

Hollow retroreflectors



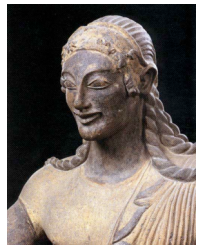


Pyrex hollow cube now at LNF
To be SCF-Test by end of year



Hollow LRA, one option proposed for GPS-III by GSFC

Conclusions



- SCF-Test: new space test for the GNSS, Space Geodesy and for experimental tests of Gravitaty in the Solar System

- With the ETRUSCO and ETRUSCO-2 we want to use the SCF-Test as an industrial tool for the SLR and LLR missions
  - And especially for GALILEO

Comprehensive, reference paper on SCF-Test & results

LABORATORI NAZIONALI DI FRASCATI
SIS – Pubblicazioni

LNF–09/02 (P)
February 24, 2009

CREATION OF THE NEW INDUSTRY-STANDARD SPACE TEST OF LASER RETROREFLECTORS FOR THE GNSS, FUNDAMENTAL PHYSICS AND SPACE GEODESY: THE SCF-TEST

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[5] *Harvard-Smithsonian Center for Astrophysics (CfA), Cambridge, MA, USA*
[6] *ASI, Centro di Geodesia Spaziale "G. Colombo" (ASI-CGS), Matera, Italy*
[7] *University of Bologna, Bologna, Italy*

Abstract

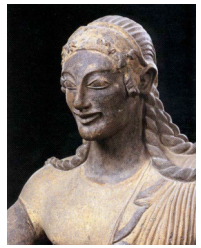
We created a new experimental apparatus (the SCF) and a new test procedure (the SCF-Test) to characterize and model the detailed thermal behavior and the optical performance of laser retroreflectors in space for industrial and scientific applications. The primary goal of these innovative tools is to provide critical diagnostic capabilities and industrial services for the advent of the European GNSS (Global Navigation Satellite System), GALILEO: (i) optimization of the design of GNSS laser retroreflector payloads to maximize the efficiency of satellite laser ranging (SLR) observations by the International Laser Ranging Service (ILRS), with particular regard to the feasibility of daylight SLR, which now is not operational; (ii) pre-launch validation of the 'as-built' functionality of laser retroreflector payloads in representative space conditions. All this will allow for a one-order of magnitude improvement of the positioning of GNSS satellites, especially in terms of long-term stability and absolute accuracy with respect to the International Terrestrial Reference Frame (ITRF). In addition, thanks to its superior H-maser clocks and SCF-Tested retroreflectors GALILEO can provide a large improvement in the measurement of its gravitational redshift with respect to H-masers at some of ILRS stations. A comprehensive and non-invasive space characterization like the SCF-Test has never before been performed. We applied it to current GNSS retroreflectors: a recent GLONASS prototype, nominally identical to those deployed on the GIOVE-A/B satellites, and an older GPS *flight* array, nominally identical to those deployed on the GPS-35 and GPS-36 satellites. From these measurements we showed that the optical cross section of the GPS flight model at 532 nm in some space configurations is lower than the standard value required by ILRS by a factor 35 to 63 (evaluated in the range of velocity aberration of ILRS stations from 20 to 25 μrad). Our measurements were complemented by optical, thermal and orbital modeling, validated with Apollo/LAGEOS reflectors.

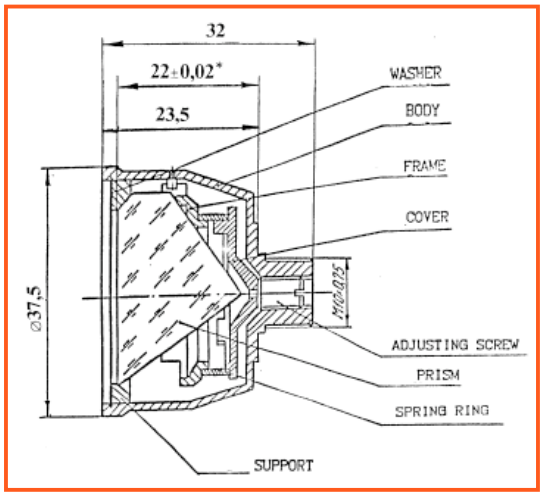
The SCF-Test was developed in the context of the ETRUSCO INFN experiment at INFN-LNF, Frascati (Italy), a large-scale infrastructure of the European Research Framework Programme (FP). This research has been funded by INFN and carried out at two dedicated LNF facilities, in collaboration with Italian and US partners. Our results are relevant to maximize the SLR performance of GALILEO and the fundamental physics reach of 2nd generation lunar laser ranging (LLR) in view of the new wave of lunar exploration. We identified the SCF-Test as a missing industry standard for space applications and as a necessary service/functionality for GALILEO. The SCF-Test is background intellectual property of INFN, which we propose as a tool for the simulation and testing of GALILEO SLR, 2nd generation LLR for the robotically deployed International Lunar Network (ILN) and for NASA's manned lunar landings. We also propose the adoption of the SCF-Test by ESA's European Space Technology Master Plan.

ETRUSCO is now evolving into an industry-class project, ETRUSCO-2, recently approved by the Italian Space Agency. INFN is the Prime Contractor of ETRUSCO-2, whose main goals are the preparation for the SCF-Test of GALILEO (possibly other GNSS constellations) and for fundamental physics and space geodesy measurements.

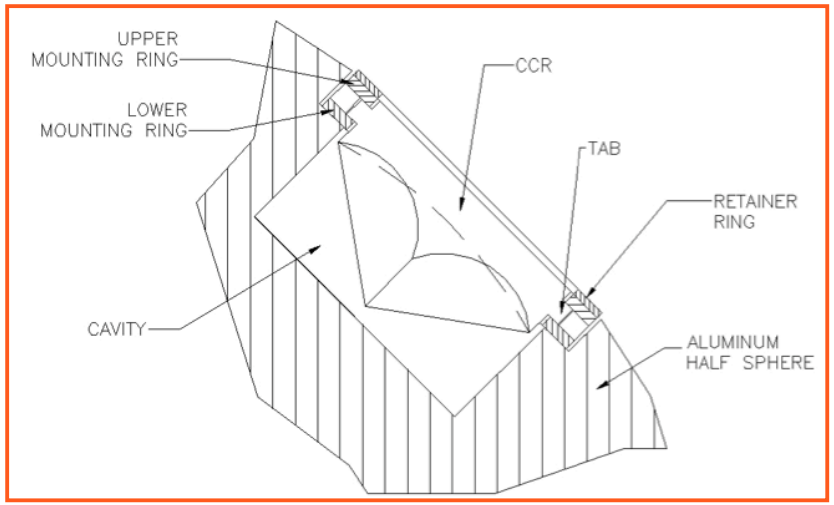
INFN intellectual property developed @LNF with ETRUSCO

Thermal effects: CCR coating, mounting scheme



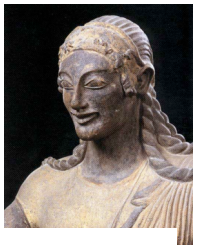


The coated Glonass/GPS/Giove CCR mounting scheme



The uncoated Apollo/LAGEOS CCR with its pristine mounting scheme

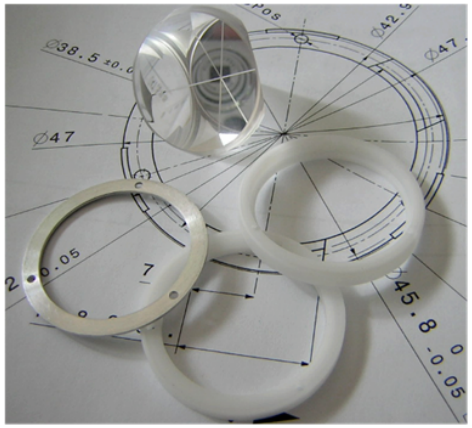
LAGEOS: thermal SCF-Test and simulation



Calculations of CCR thermal relaxation time vary by ~300%

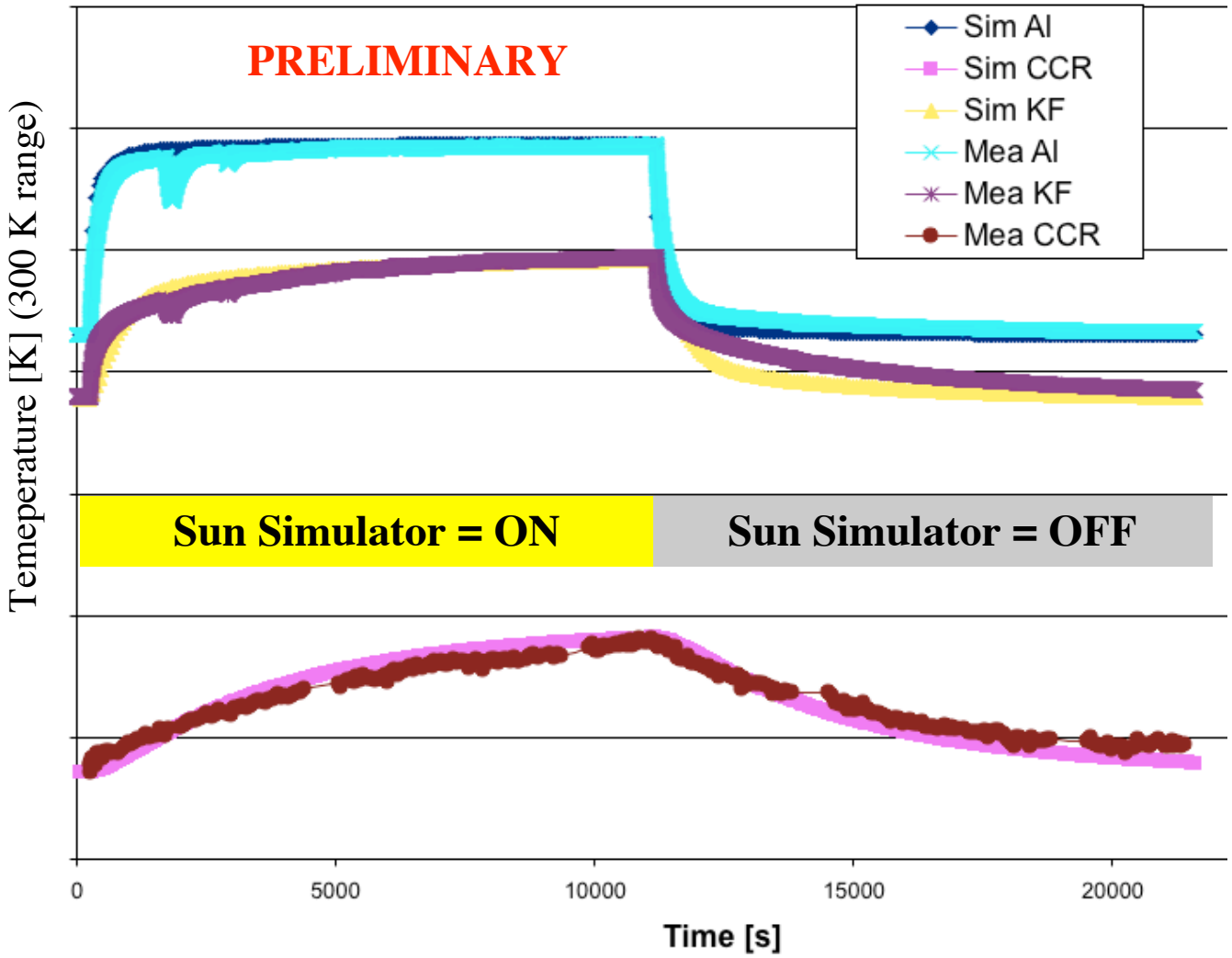
Can measure
$\sigma(\tau_{CCR}) \sim 10\%$
around T~300K

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

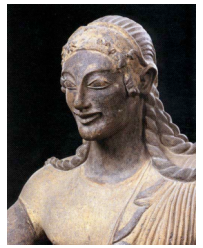


SCF work led by Giovanni Delle Monache

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



Thermal NGPs on LAGEOS: orbit, spin, Earth shadow



Comparison of thermal thrusts vs time (for one orbit) between:

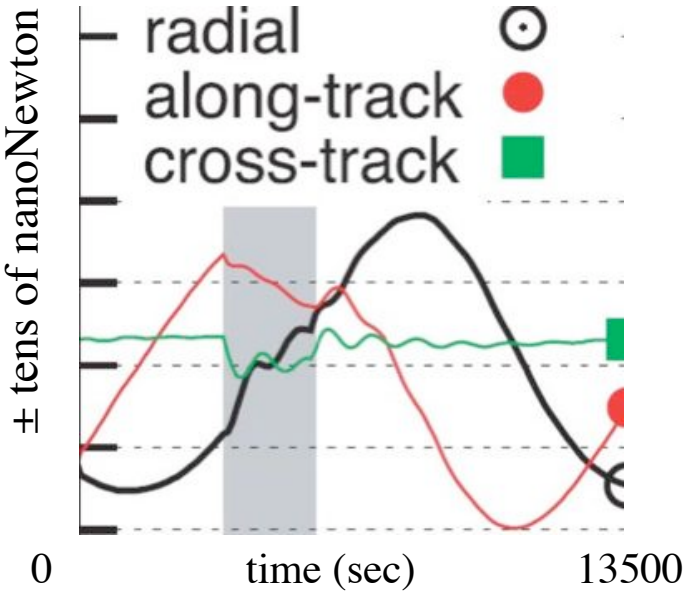
- LageOS Spin Axis Model (LOSSAM): some input data were not measured
- LNF model: based on orbital/thermal FEM model tuned to SCF measurements

Two completely different models agree **qualitatively**

Spin and Orbit of **1/1/2000**
(with longest Earth shadow)

PRELIMINARY

LOSSAM (Nacho Andres *et al*)
Earth shadow = grey area



LNF model tuned to SCF data
Earth shadow = grey area