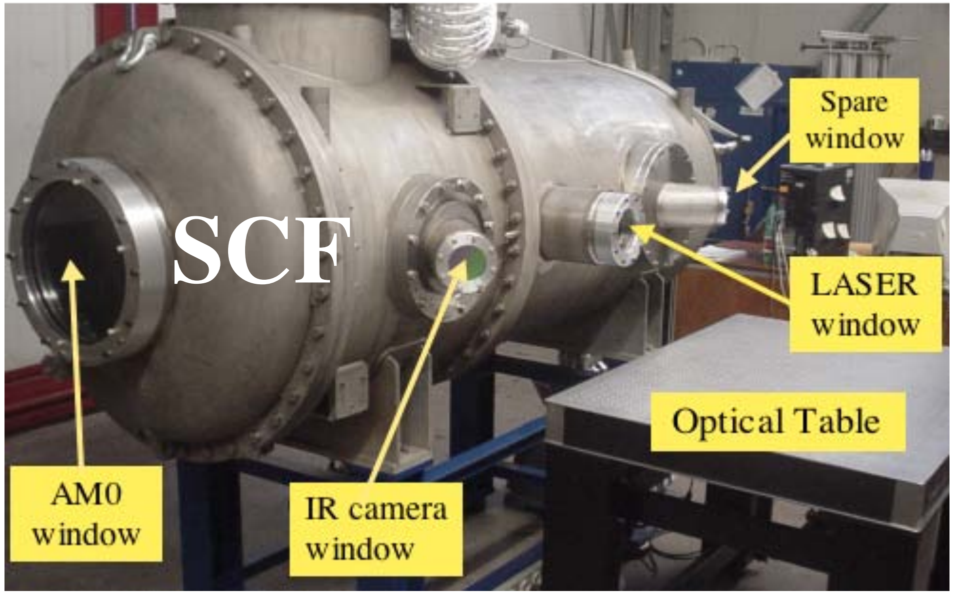
A Lunar Laser Ranging Retroreflector Array for Next Lunar Surface Missions

SCF:

Satellite/lunar laser ranging (SLR/LLR) Characterization Facility



Presented by S. Dell'Agnello

Italian National Institute for Nuclear Physics, Laboratori Nazionali di Frascati (INFN-LNF),

Via Enrico Fermi 40, Frascati (Rome), 00044, Italy

Landing Site Selection for LUNA-GLOB mission, International Workshop #2

Moscow, Institute for Space Research (IKI), May 31 – June 2, 2011

The INFN-LNF SCF Team

S. Dell'Agnello, G. Delle Monache, D. Currie[1], R. Vittori[2], S. Berardi, G. Bianco[3], A. Boni, C. Cantone, M. Garattini, N. Intaglietta, C. Lops, M. Martini, M. Maiello, G. Patrizi, M. Tibuzzi, C. Graziosi

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[1]*University of Maryland at College Park, MD, USA and NLSI,*

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Outline

- Satellite/Lunar Laser Ranging
- LLR science
  - Test of General Relativity and spacetime torsion
- LLR for next lunar surface missions
- SCF: Retroreflector Characterization Facility
  - SCF-Test results
- International Lunar Network recommendations
- Conclusions and proposal of collaboration

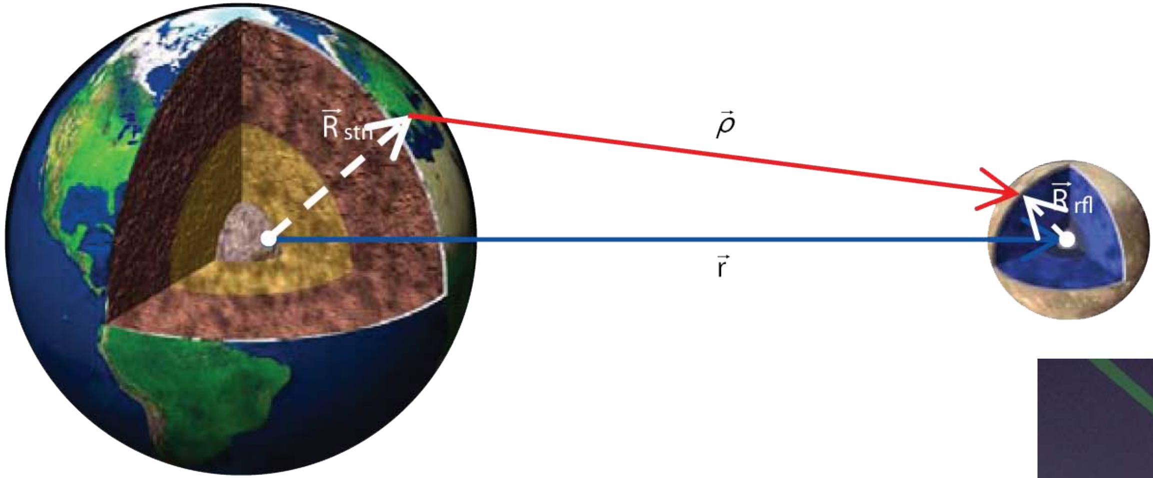
(Plus reference and spare material)

Satellite/Lunar Laser Ranging (SLR/LRR)

Unambiguous Time of Flight (distance) measurement with laser pulses < 500ps

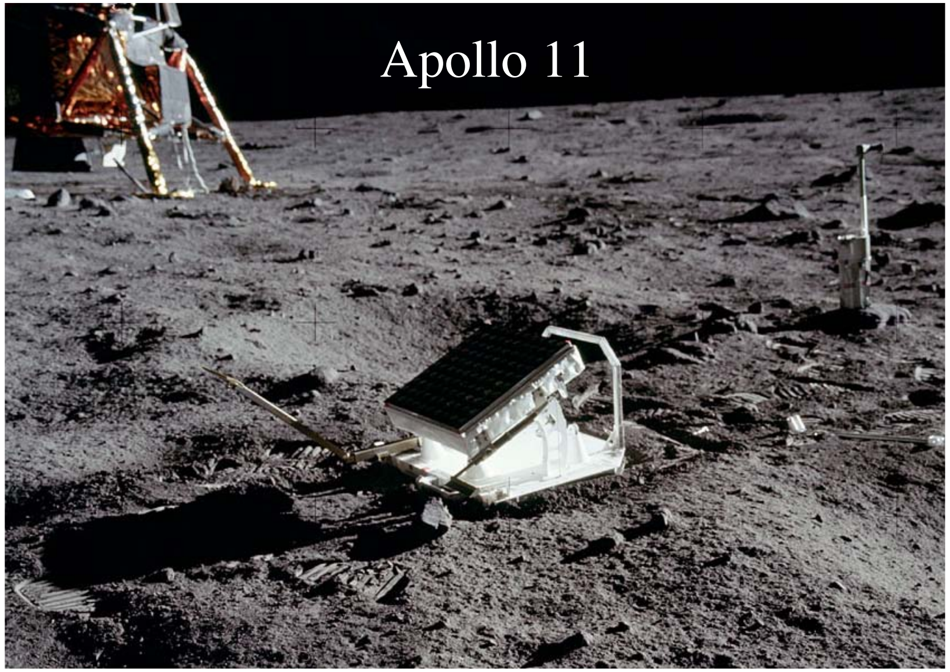
SLR: started in 1964, 1st demo on Beacon satellite (from GSFC)

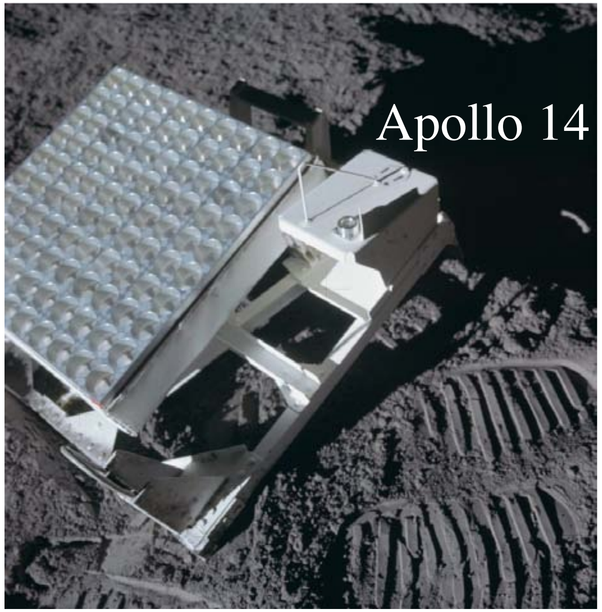
LLR: started in 1969, Apollo (UMD, PI) and Luna missions

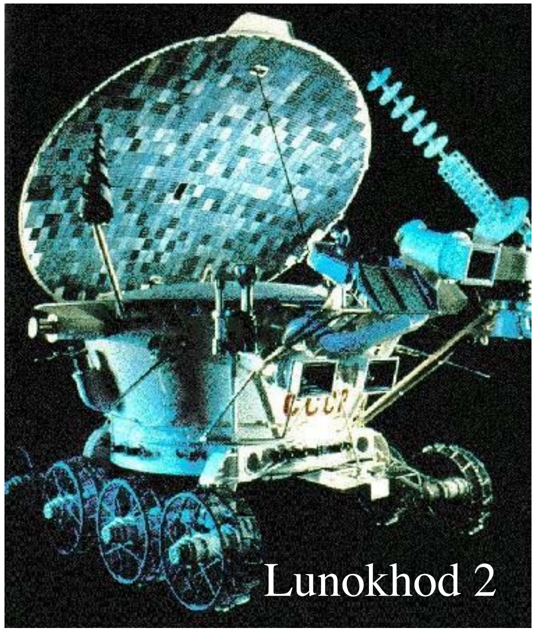


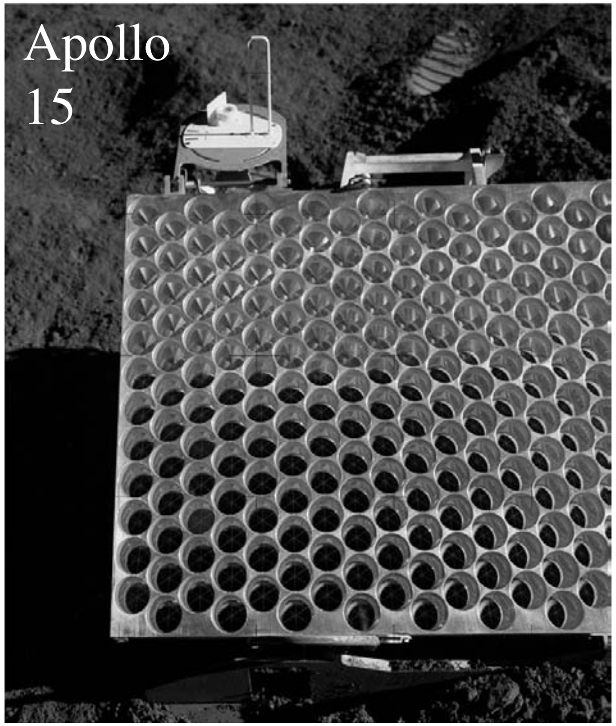
- **Precise** positioning (normal points at mm level, orbits at cm level)
- **Absolute** accuracy (used to define Earth center of mass, geocenter, and scale of length)
- **Passive**, maintenance-free Laser Retroreflector Array, **LRA**

LRAs on the Moon

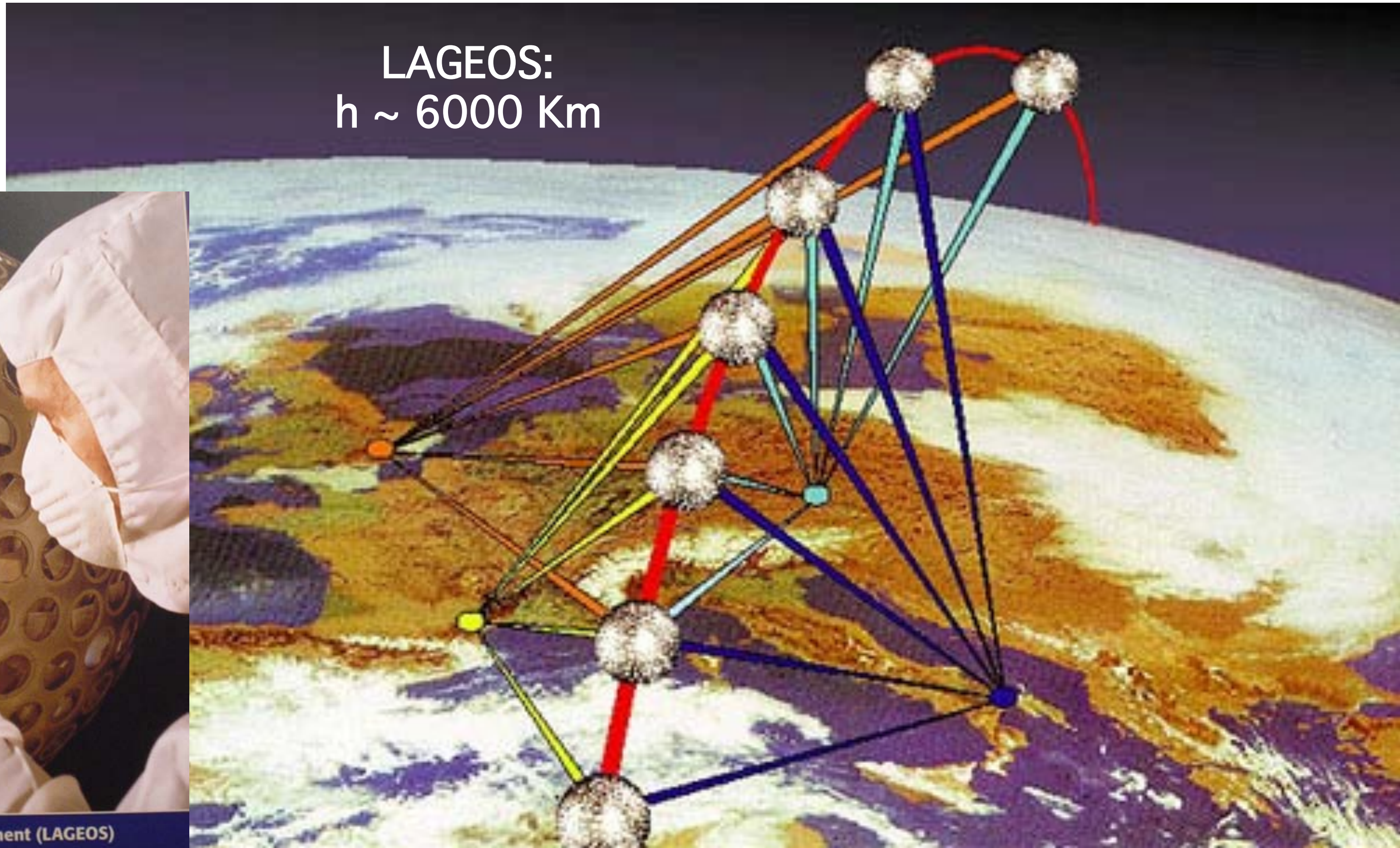


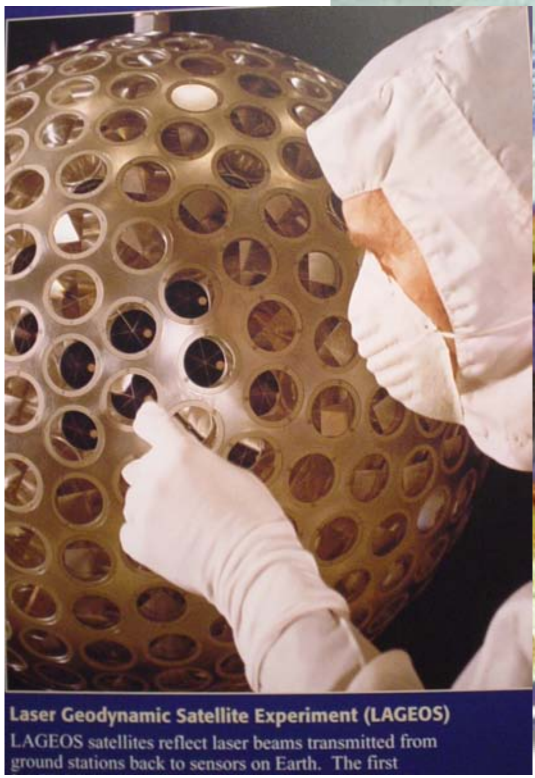






LAGEOS (LAser GEOdynamics Satellites) SLR-tracked by ILRS stations in Matera (IT), Herstmonceux (UK), Graz (AT), OCR (FR)





Space geodesy, GNSS, fundamental physics

LEO, GNSS, GEO, Moon

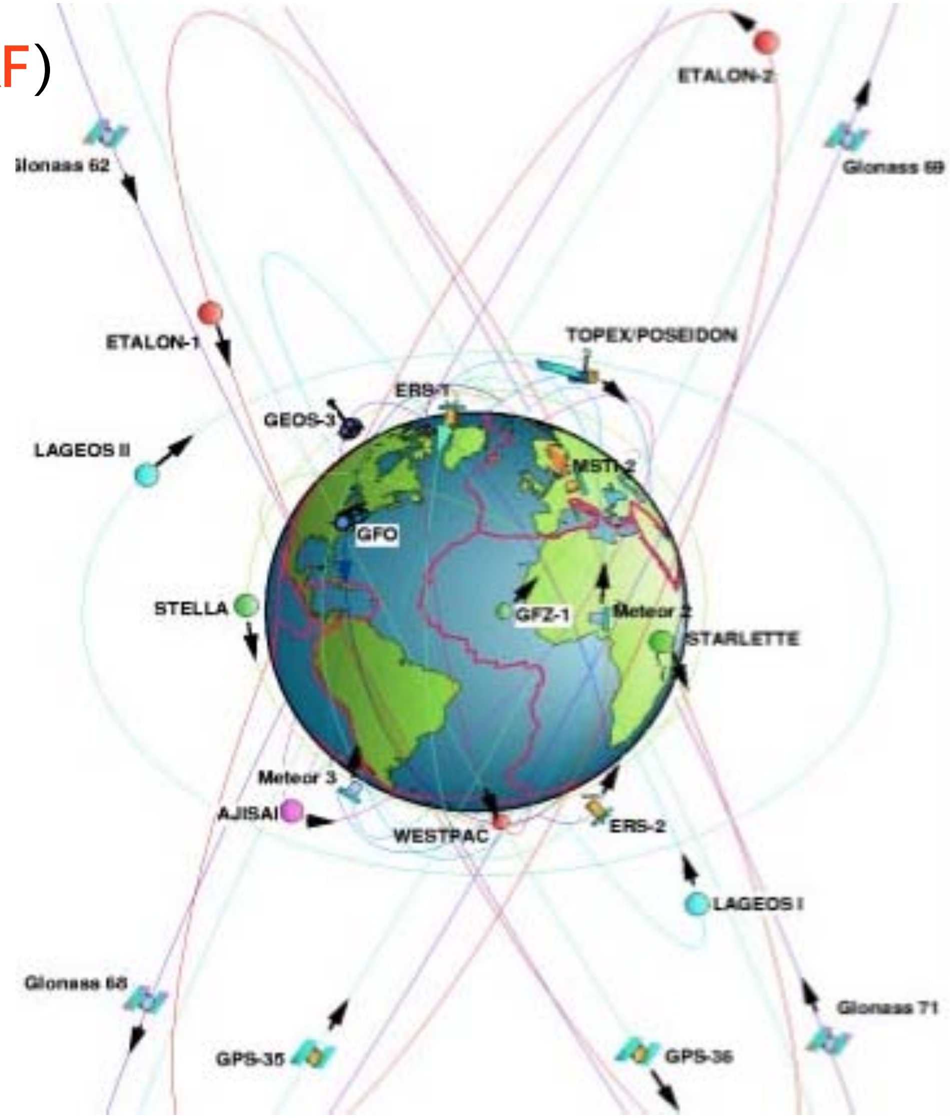
Int. Terrestrial Reference Frame (ITRF)

- Geocenter from SLR (LAGEOS)
- Scale from VLBI and SLR (LAGEOS)
- Orientation (wrt ICFR) from VLBI
- TRF distribution w/GNSS
- DORIS, ...

LAGEOS

International Laser Ranging Service

SLR constellation



Science with SLR

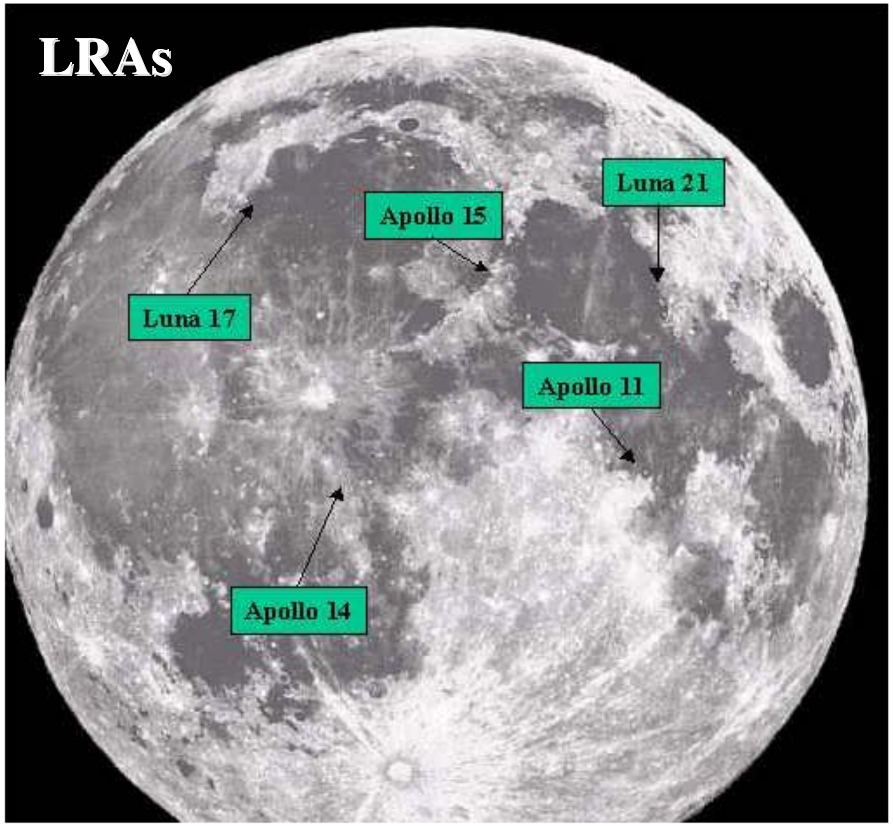
Benefits of LRAs on GNSS

- Only independent validation/calibration of GNSS orbits, with 2-4x better precision
- Absolute positioning, ie, wrt ITRF
- Long term stability & geodetic memory
- Therefore: **combining SLR+GNSS data will improve orbit reconstruction**

- **Global Navigation Satellite System** (see [RD-1], [RD-2])
  - GLONASS: metal-coated CCRs, deployed also to GPS-35/-36 and GIOVE-A/-B
  - Uncoated CCRs from GLONASS-115
  - 4 Galileo IOVs (In-Orbit Validation): uncoated CCRs
  - COMPASS-M1/-G1: uncoated CCRs
  - ETS-8, QZS1: uncoated CCRs
  - IRNSS: will have CCRs
  - GPS-III: growing interest to have CCRs

LLR accuracy (best orbit residuals, by JPL): ~few cm

This is ~ 5×10^{-11} Earth-Moon distance (384000 km)

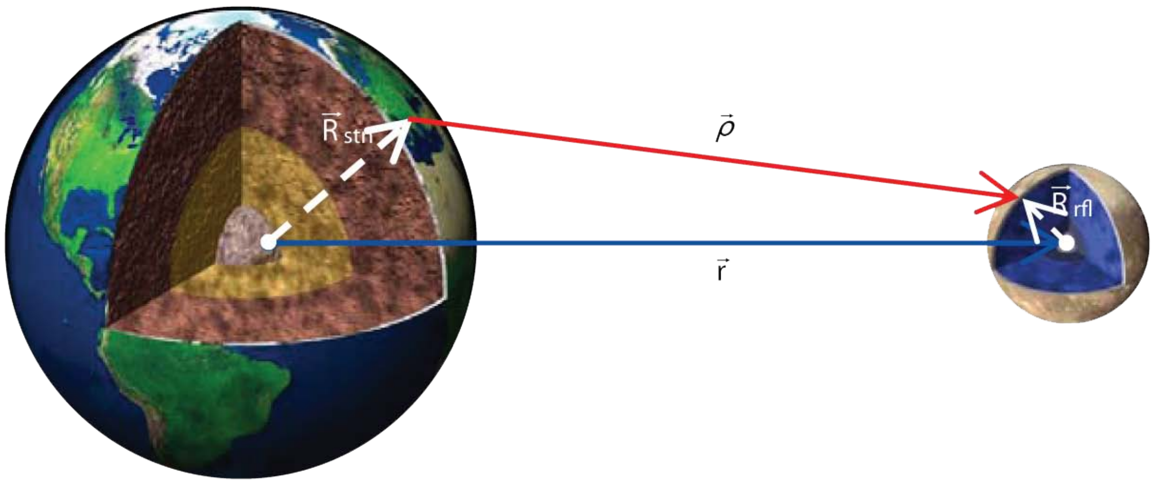


Science with LLR

- Lunar geophysics
  - Librations, Interior parameters (Love numbers …)
    - Love number until now by LLR, then by GRAIL (k_2)

- IMRF (International Moon Reference Frame) referenced to ITRF with laser and/or radio. Realized by network of geodetic points
  - Apollo/Lunokhod + ANY lander, or rover, with radio-beacon and/or laser retroreflector
  - For lunar surface exploration and colonization

ITRF



IMRF, proposed by SDA in RD-4, RD-8

Science with LLR

- Precision test of General Relativity
  - GR verified by many solar system experiment
  - But not the final theory, because it has unexplained singularities and cannot be unified with Quantum mechanics

- Dark matter, dark energy, new particle physics is needed for consistency of modern physics

- Looking for new physics everywhere, included space

Best test with a single experiment

- Measurement of relativistic geodetic precession of lunar orbit, a true three-body effect (3m ± 1.9 cm)/orbit (0.64% error)
- Violation of: Weak (composition dependent) and, through the Nordtvedt effect, Strong Equivalence Principle (related to gravitational self-energy)
- Parametrized Post-Newtonian (PPN) parameter β, measures the non-linearity of gravity. In RG $\beta=1$
- Time variation of universal gravitational constant G
- Tests of inverse square law ($1/r^2$)

J. G. Williams, S. G. Turyshev, and D. H. Boggs, PRL 93, 261101 (2004)

Constraining spacetime torsion with the Moon and Mercury

Theoretical predictions and experimental limits on new gravitational physics

Most general mathematical connection in Riemann-Cartan spacetime has BOTH curvature and torsion. Therefore it is interesting to search for torsion with space experiments

Spacetime torsion described at order higher than MTGC, by three dimensionless torsion parameters, $\mathbf{t_1}$, $\mathbf{t_2}$, $\mathbf{t_3}$ (we added t_3 compared to MTGC). General approach, no specific model assumed

These 3 parameters (and the other, frame draging parameters, described in the next slides) combine with the PPN to determine the gravitational physics of several types of solar system natural bodies and artificial satellites.

Therefore, we used data from past and present space missions to test (to limit, to constraint) the torsion parameters. We also showed how future mission will improve this search

Value of t_1 fixed by imposing validity of newtonian limit of the theory

We demonstrated that Mercury's perihelion precession depends on torsion, unlike in the MTGC paper

Constraining spacetime torsion with the Moon and Mercury

Theoretical predictions and experimental limits on new gravitational physics

Extension of work by *Y. Mao, M. Tegmark, A. H. Guth and S. Cabi*, PRD 76, 1550 (2007) [indicated ad **MTGC**]

PHYSICAL REVIEW D **83,** 104008 (2011)

Constraining spacetime torsion with the Moon and Mercury

We report a search for new gravitational physics phenomena based on Riemann-Cartan theory of general relativity including spacetime torsion. Starting from the parametrized torsion framework of Mao, Tegmark, Guth, and Cabi, we analyze the motion of test bodies in the presence of torsion, and, in particular, we compute the corrections to the perihelion advance and to the orbital geodetic precession of a satellite. We consider the motion of a test body in a spherically symmetric field, and the motion of a satellite in the gravitational field of the Sun and the Earth. We describe the torsion field by means of three parameters, and we make use of the autoparallel trajectories, which in general differ from geodesics when torsion is present. We derive the specific approximate expression of the corresponding system of ordinary differential equations, which are then solved with methods of celestial mechanics. We calculate the secular variations of the longitudes of the node and of the pericenter of the satellite. The computed secular variations show how the corrections to the perihelion advance and to the orbital de Sitter effect depend on the torsion parameters. All computations are performed under the assumptions of weak field and slow motion. To test our predictions, we use the measurements of the Moon's geodetic precession from lunar laser ranging data, and the measurements of Mercury's perihelion advance from planetary radar ranging data. These measurements are then used to constrain suitable linear combinations of the torsion parameters.

Constraining spacetime torsion with the Moon and Mercury

Theoretical predictions and experimental limits on new gravitational physics

Extension of work by *Y. Mao, M. Tegmark, A. H. Guth and S. Cabi*, PRD 76, 1550 (2007) [indicated ad **MTGC**] and correction of their error on Mercury's perihelion advance

LLR measurement of the lunar geodetic precession (deviation from general relativity):

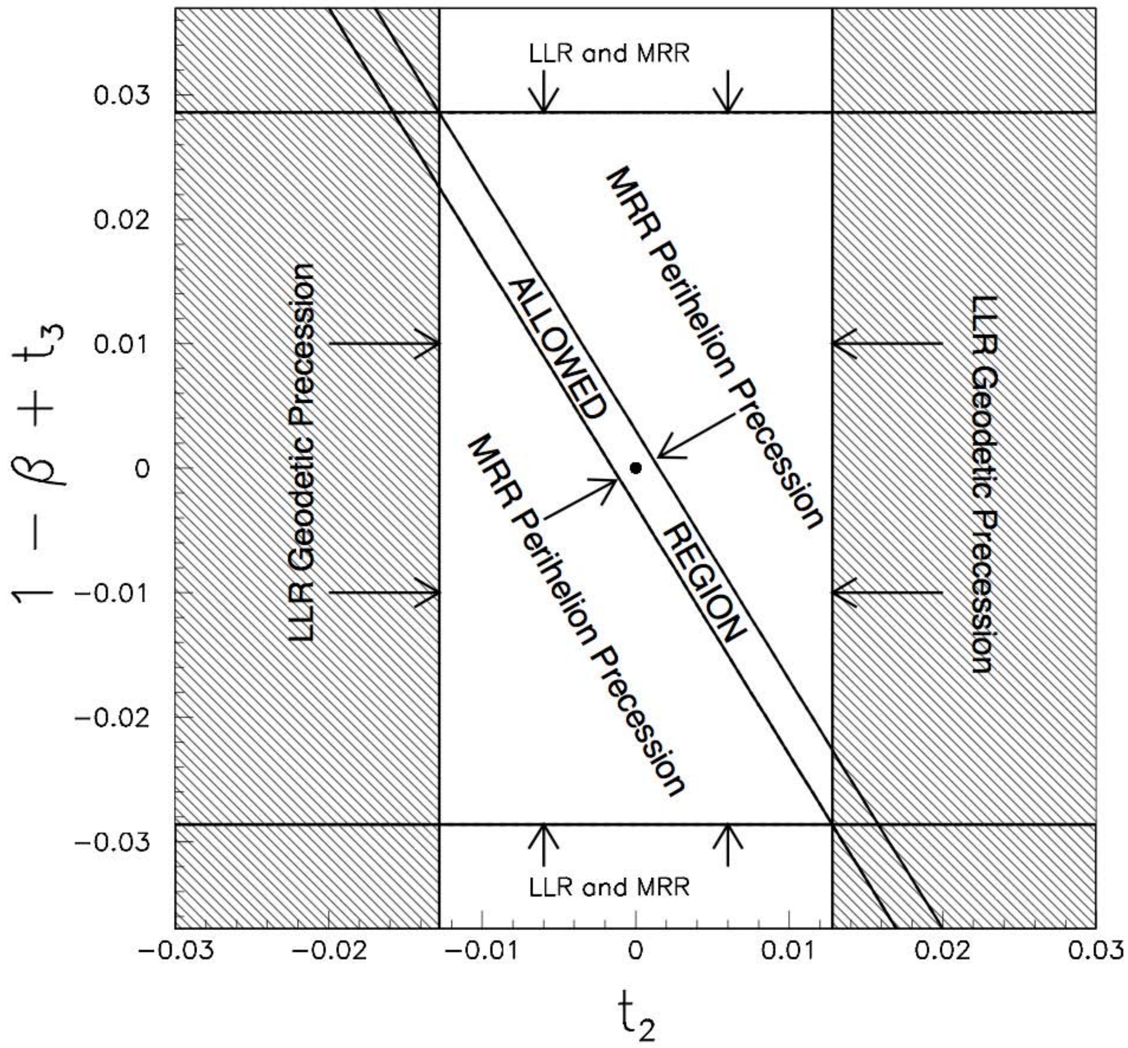
K_{gp} = -0.0019+/- 0.0064

J. G. Williams, S. G. Turyshev, and D. H. Boggs, PRL 93, 261101 (2004)

MRR measurement of Mercury perihelion precession (deviation from general relativity):

0.1% accuracy on (β-1)

I. I. Shapiro, Gravitation and Relativity 1989, edited by N. Ashby, D. F. Bartlett, and W. Wyss (Cambridge University Press, Cambridge, England, 1990), p. 313.



Improving test of spacetime torsion
(an example of search for new gravitational physics)

Geodetic precession (GP) plays special role, because measured with very different techniques:

- Continuing LLR of Apollo/Lunokhod and by high accuracy APOLLO

- Next lunar surface missions

- New, better LLR payloads

- Gravity Probe B

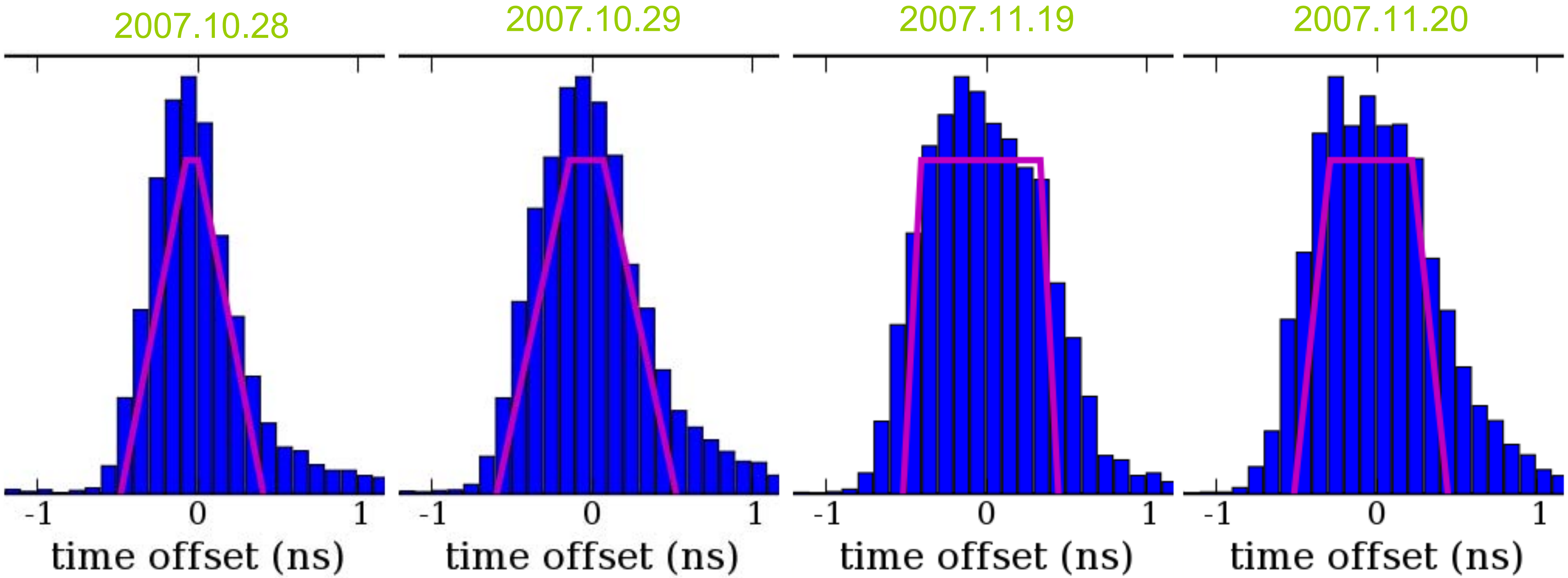
- BepiColombo (ESA, JAXA …)

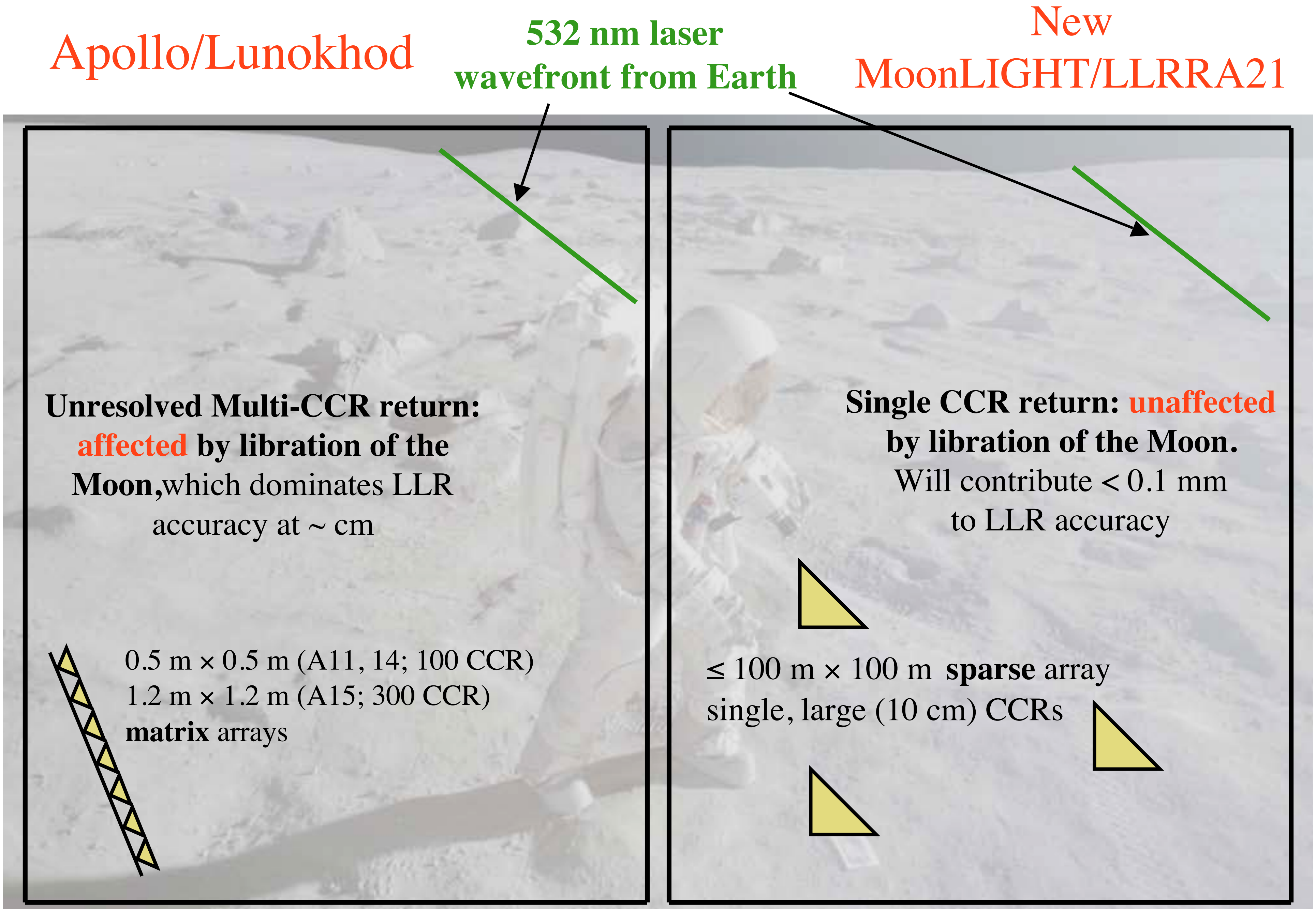
<u>Further improvements</u>:

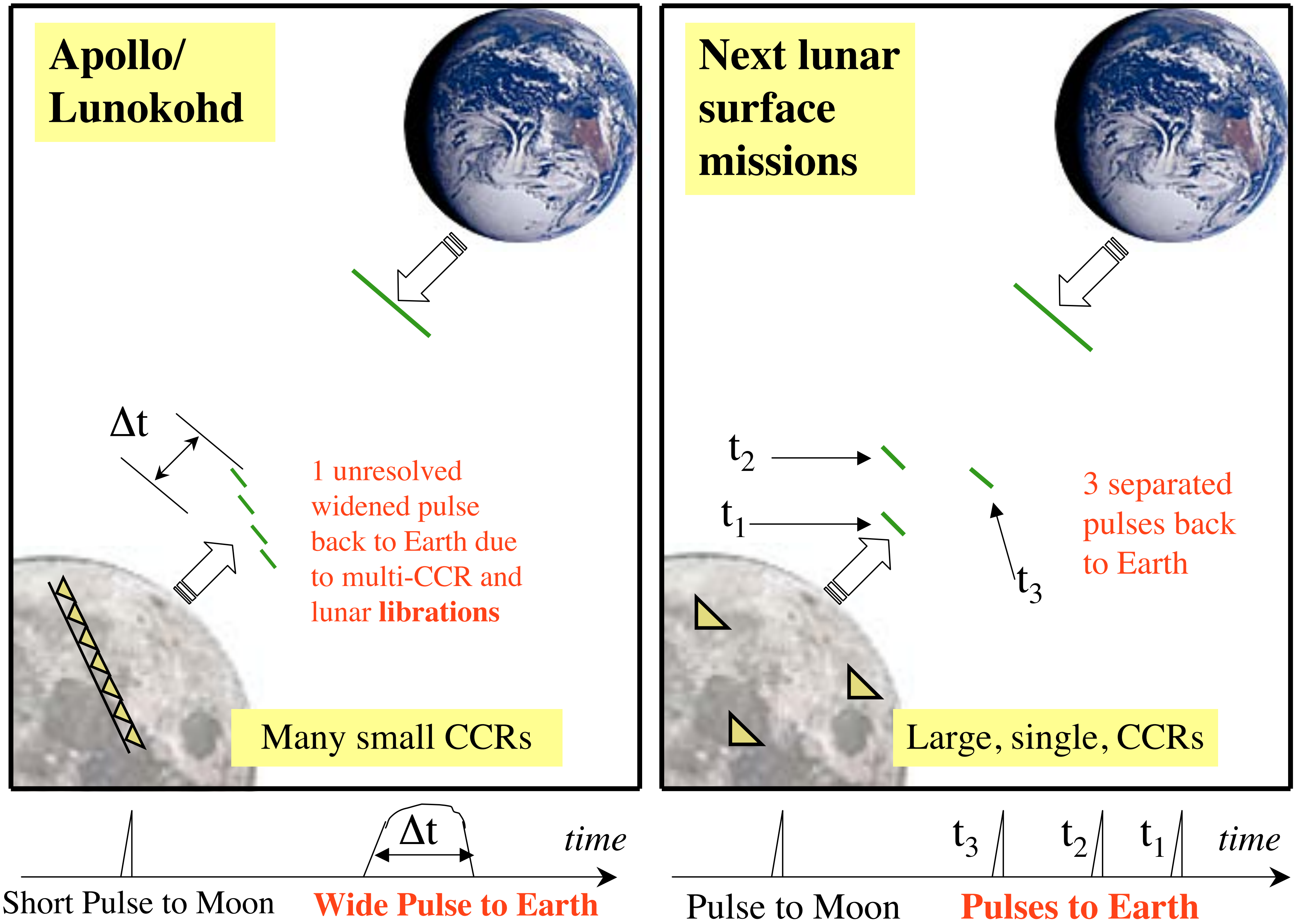
- 10 years of MRR data taken after 1990 and so far not analyzed

Librations: the main limitation of Apollo/Lunokhod

Effect of mluti-CCR array orientation due to lunar librations

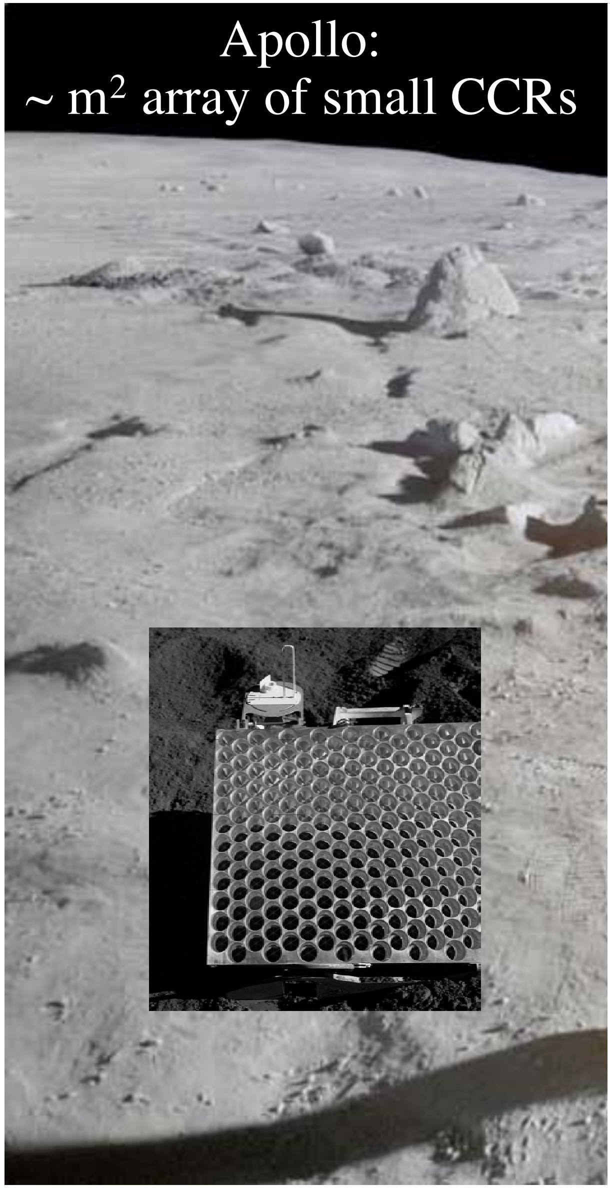


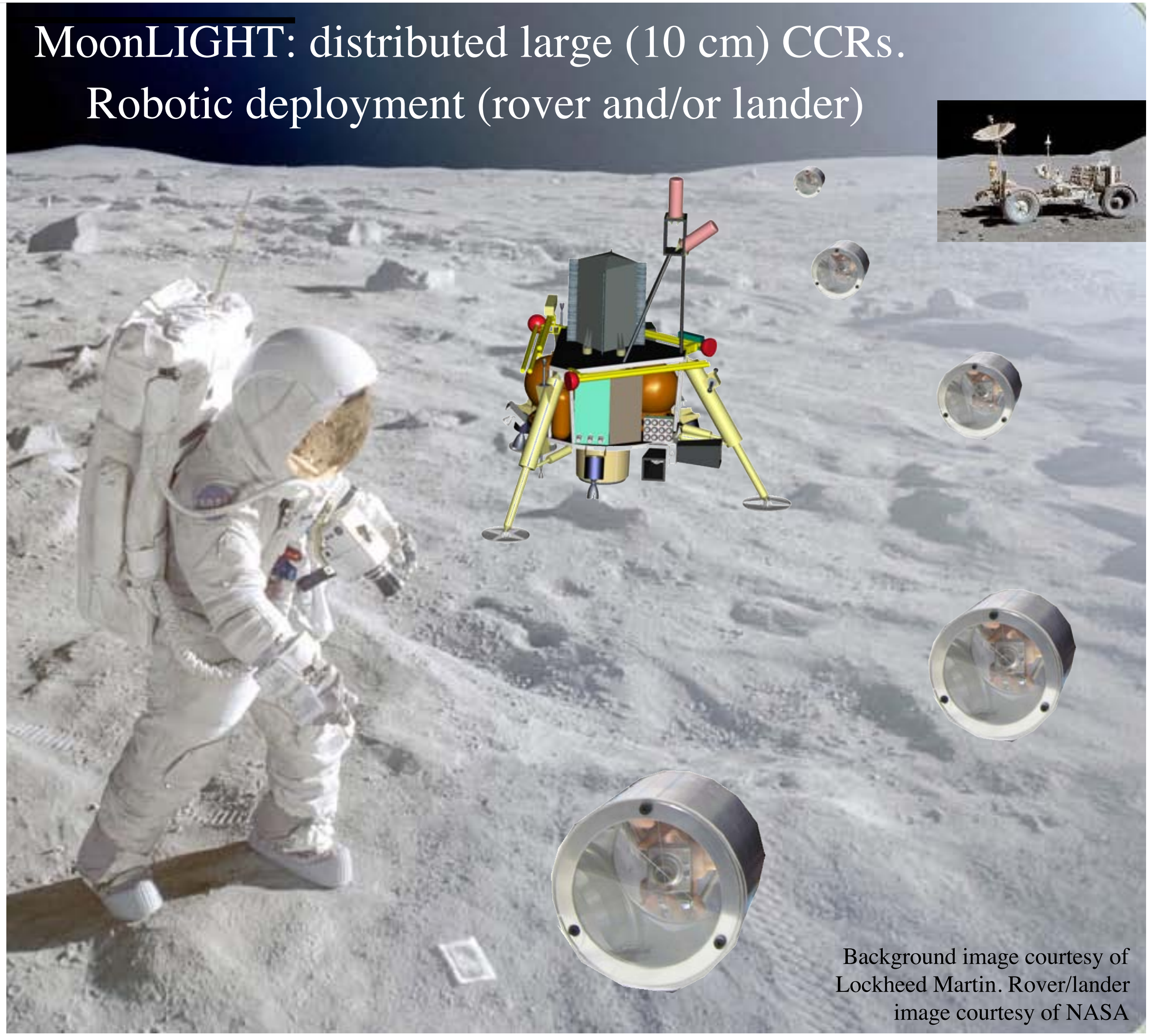

Apollo/Lunokhod
532 nm laser
wavefront from Earth
New
MoonLIGHT/LLRRA21
Unresolved Multi-CCR return: affected by libration of the Moon, which dominates LLR accuracy at ~ cm
0.5 m × 0.5 m (A11, 14; 100 CCR)
1.2 m × 1.2 m (A15; 300 CCR)
matrix arrays
Single CCR return: unaffected by libration of the Moon.
Will contribute < 0.1 mm to LLR accuracy
≤ 100 m × 100 m sparse array
single, large (10 cm) CCRs



Apollo/
Lunokohd
Δt
1 unresolved
widened pulse
back to Earth due
to multi-CCR and
lunar **librations**
Many small CCRs
Δt
time
Short Pulse to Moon
Wide Pulse to Earth
Next lunar
surface
missions
t_2
t_1
t_3
3 separated
pulses back
to Earth
Large, single, CCRs
t_3
t_2
t_1
time
Pulse to Moon
Pulses to Earth

MoonLIGHT: large distributed reflectors





LLR: Precision Tests of General Relativity

Improvement in LLR efficiency and precision can only come from single large retroreflectors.
Efficiency (n. returns to make a normal point) of single/large reflector vs. Apollo/Lunokhod array is larger by factor of a few thousands

Science measurement	Time scale	Apollo/Lunokhod few cm accuracy	Single Reflectors 1 mm	0.1 mm
Parameterized Post-Newtonian (PPN) β	Few years	$\lvert\beta-1\rvert<1.1\times10^{-4}$	10^{-5}	10^{-6}
Weak Equivalence Principle (WEP)	Few years	$\lvert\Delta a/a\rvert<1.4\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	Few years	$\lvert\eta\rvert<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of the Gravitational Constant	~5 years	$\lvert\dot{G}/G\rvert<9\times10^{-13}yr^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	~10 years	$\lvert\alpha\rvert<3\times10^{-11}$	10^{-12}	10^{-13}

LLRRA21/MoonLIGHT Team

Lunar Laser Ranging Retroreflector Array for the 21st century (US) /
Moon Laser Instrumentation for General relativity High-accuracy Tests (It)

D. G. Currie (US PI) — ***University of Maryland at College Park, MD, USA***

S. Dell'Agnello (It. PI), G. O. Delle Monache C. Cantone, M. Garattini, A. Boni, M. Martini, N. Intaglietta, C. Lops, M. March, R. Tauraso, G. Bellettini, M. Maiello, S. Berardi, L. Porcelli, G. Patrizi, C. Graziosi — ***INFN-LNF, Frascati (Rome), Italy***

T. Murphy — ***University of California at San Diego (UCSD), CA, USA***

G. Bianco — ***ASI - CGS "G. Colombo", Matera, Italy***

J. Battat — ***MIT, USA***

J. Chandler — ***CfA, USA***

R. Vittori — ***ESA-EAC and Aeronautica Militare Italiana, Rome, Italy***

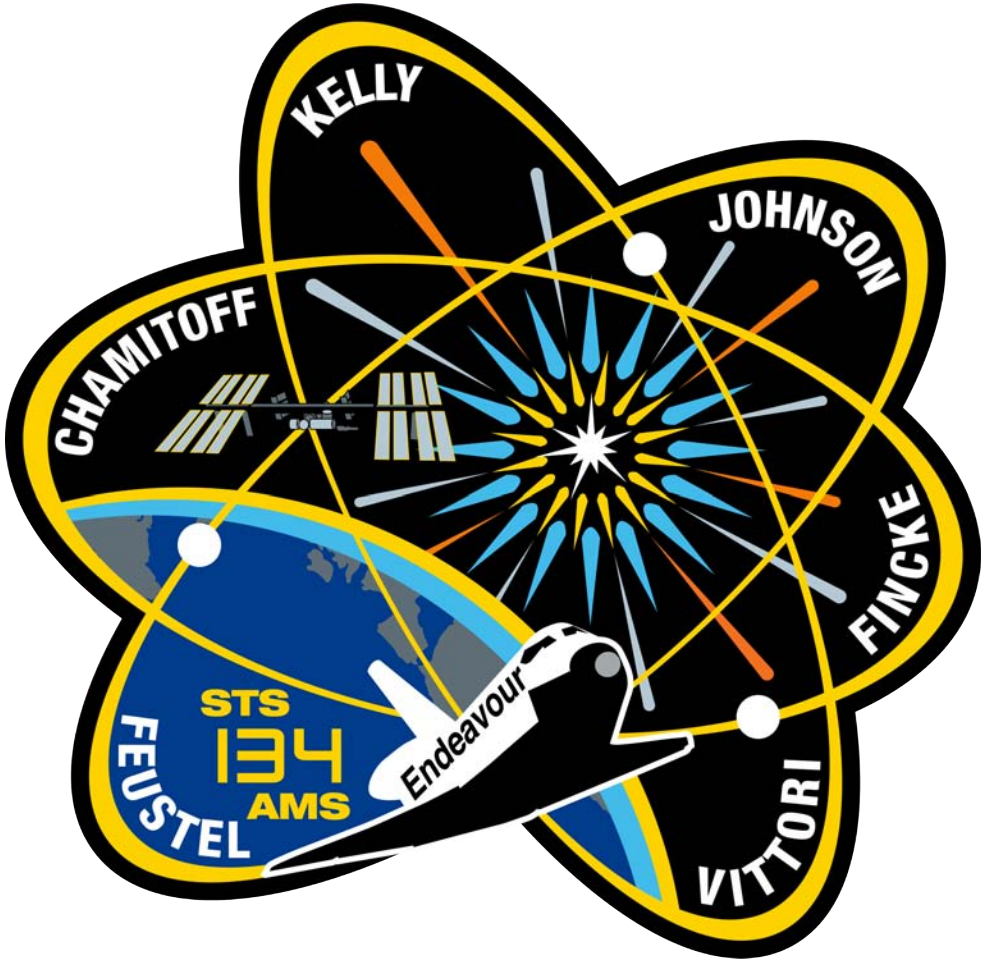
R&D supported by INFN and by NASA contracts (both at critical levels).
Only in mininal part by ASI, with MAGIA orbiter Phase A study

Some people of the MoonLIGHT/LLRRA21 team

March 25, 2010, during 24x7 shifts for the SCF-Test of MoonLIGHT/LLRRA21

Kosmonaut Roberto Vittori, who flew on ISS with Soyuz in 2002 and 2005, and with STS-134 Endeavor last flight, launched on May 16, 2011 and landed TODAY!

STS-134, with Kosmonaut Roberto Vittori, landed successfully today



R. Vittori and G. Bianco (ASI-CGS) are my Co-PI of ETRUSCO-2

ETRUSCO-2: ASI-INFN project, 2010-2013

(Simone Dell'Agnello, PI)

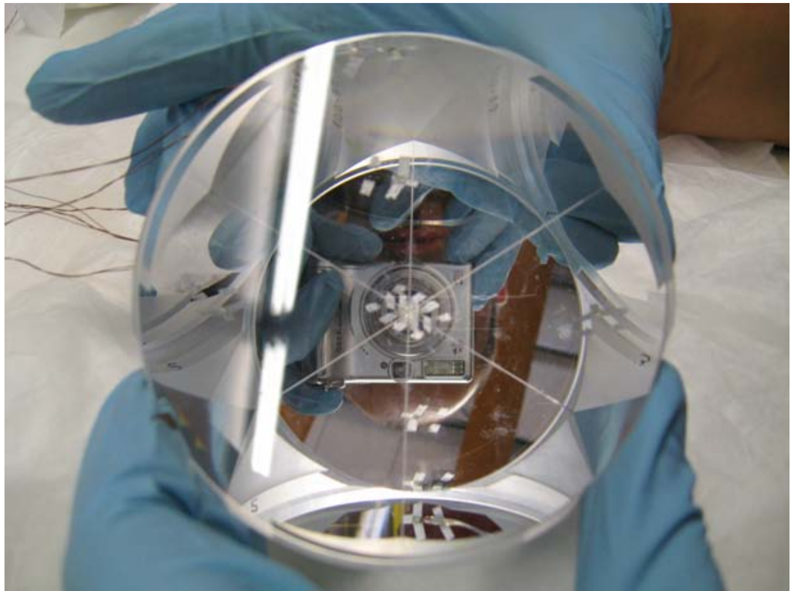
Will double our metrology capabilities with new, 2nd SCF-G, optimized for GNSS

MoonLIGHT/LLRA21 LASER RETURN: OK!

- On-axis LLR laser return scales as diameter[4]

- MoonLIGHT <u>uncoated</u> 100 mm CCR optical cross section:
  - ~ 50 APOLLO <u>uncoated</u> CCRs, ~½ of APOLLO 11, 14 array (100 CCRs)
  - ~ 50 GLONASS <u>coated</u> CCRs
  - ~ 150 GLONASS <u>uncoated</u> CCRs

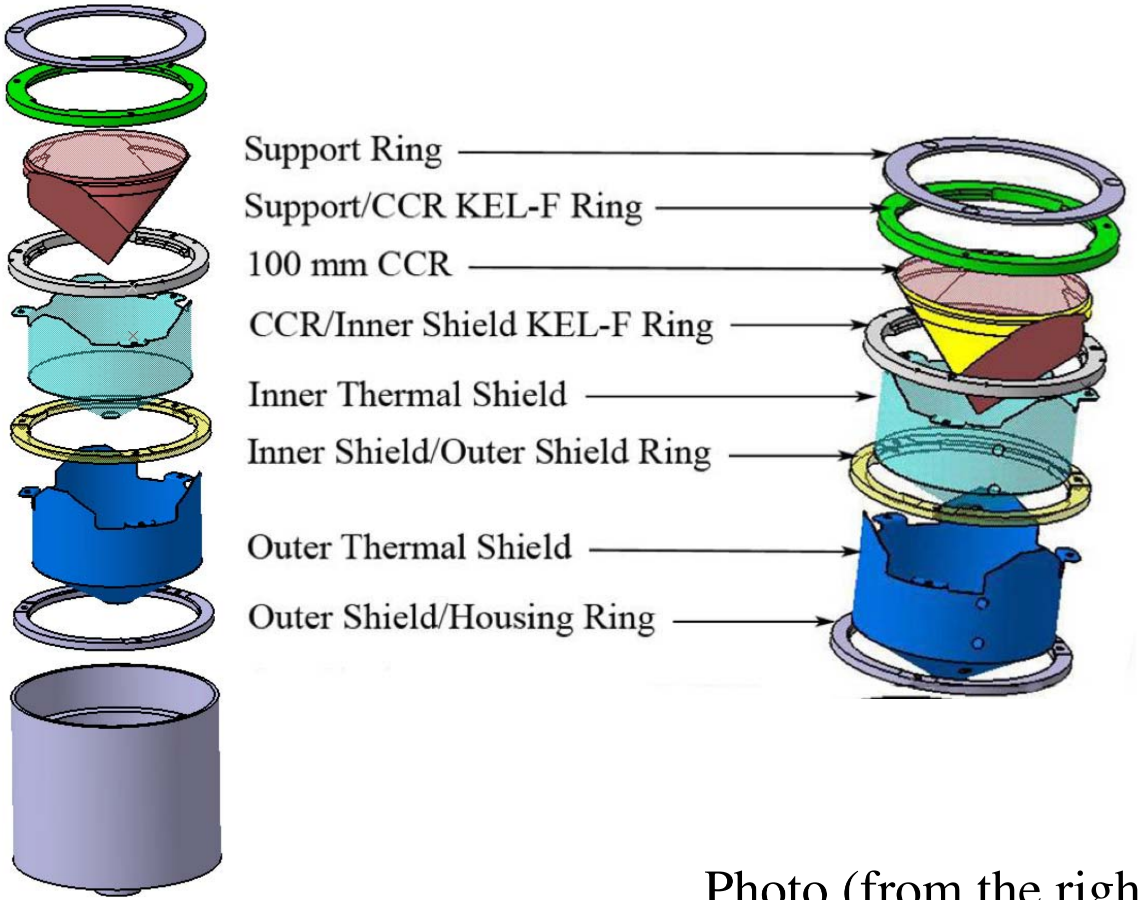
- Thermal degradations of laser return
  - Measured and under control for uncoated MoonLIGHT
  - Measured (at 300 K) and very critical for GLONASS design



Retroreflector for the Moon

- Multi-CCR array is inefficient: APOLLO station experience shows that several thousands of laser returns are needed to be equivalent to a single return from a single large retroreflector
- This is critical especially for the pole sites, where Earth visibiltiy near horizon can significantly reduce the number of laser returns to Earth
- JPL, JAXA, ASI, International Lunar Network …. are considering only a single, large retroreflector

MoonLIGHT/LLRRA21 reflector CCR



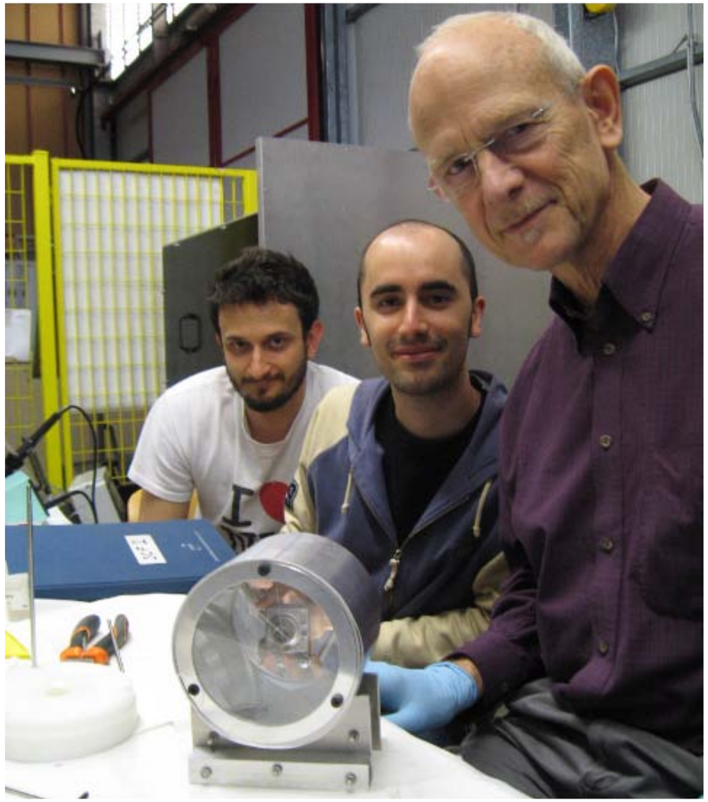
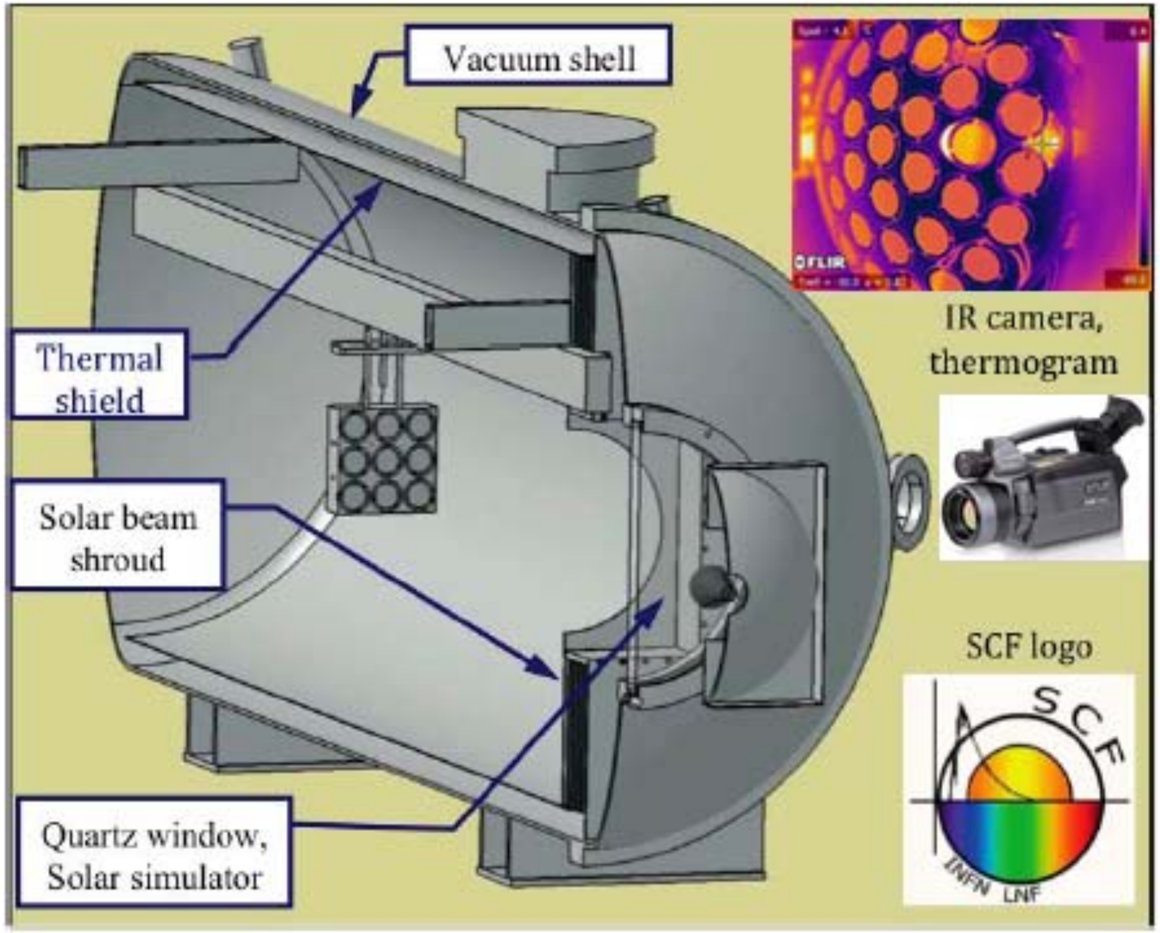
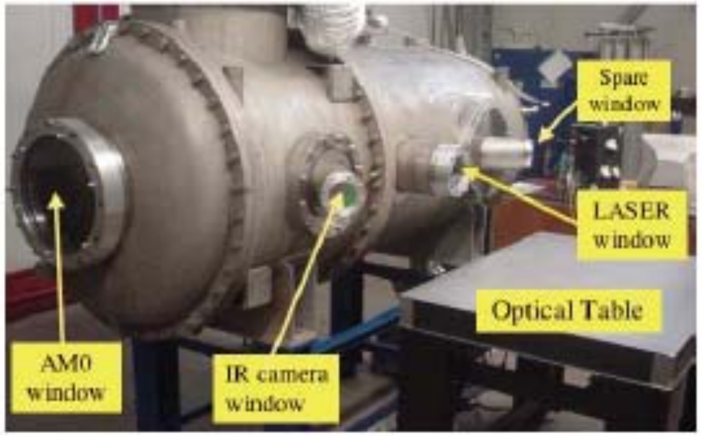


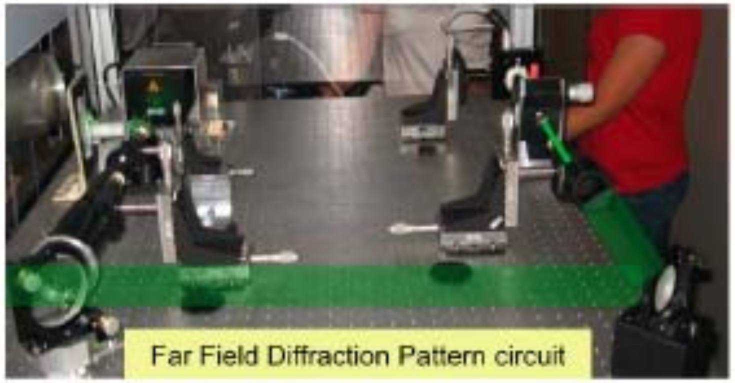
Photo (from the right):
Doug Currie (Univ. of Maryland at College Park), co-designed and tested Apollo retroreflectors; A. Boni, PhD student @Univ. Roma 2;
M. Garattini, PhD student @Univ. Roma 2.
(myself retroreflected upside-down on the CCR …)

SLR/LLR Characterization Facility (SCF)





Optical circuit



Integrated and concurrent thermal and optical measurements in laboratory-simulated space environment

The SCF-Test (background IP of INFN)

- Laboratory-simulated space conditions. Concurrent/integrated:
  - Dark/cold/vacuum
  - Sun (AM0) and Earth IR **simulators**
  - Non-invasive IR and contact **thermometry**
  - Payload **roto-translations**
  - **Laser interrogation and sun perturbation at varying angles**
  - Payload **thermal control**
- Deliverables / Retroreflector Key Performance Indicators (KPIs)
  - **Thermal behavior**
    - τ_{CCR}, thermal relaxation time
  - **Optical response**
    - Orthogonal polarizations (for uncoated reflectors)

- Note: reduced, partial, incomplete tests (compared to the full space environment) can be misleading (either optimistic or pessimistic)

The SCF-Test (Intellectual Property of INFN)

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Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 47 (2011) 822–842

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS

S. Dell'Agnello [a,*], G.O. Delle Monache [a], D.G. Currie [b], R. Vittori [c,d], C. Cantone [a], M. Garattini [a], A. Boni [a], M. Martini [a], C. Lops [a], N. Intaglietta [a], R. Tauraso [e,a], D.A. Arnold [f], M.R. Pearlman [f], G. Bianco [g], S. Zerbini [h], M. Maiello [a], S. Berardi [a], L. Porcelli [a], C.O. Alley [b], J.F. McGarry [i], C. Sciarretta [g], V. Luceri [g], T.W. Zagwodzki [i]

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[b] *University of Maryland (UMD), Department of Physics, John S. Toll Building, Regents Drive, College Park, MD 20742-4111, USA*
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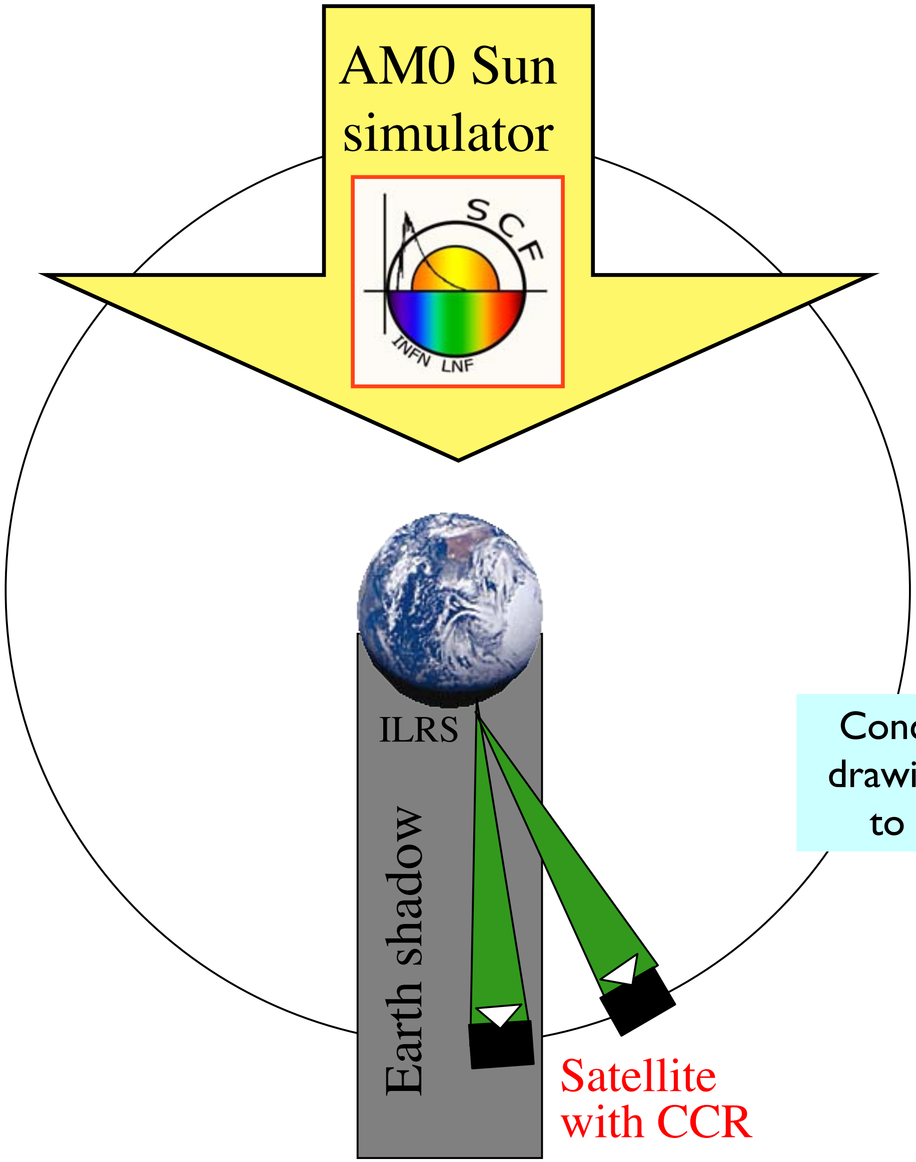
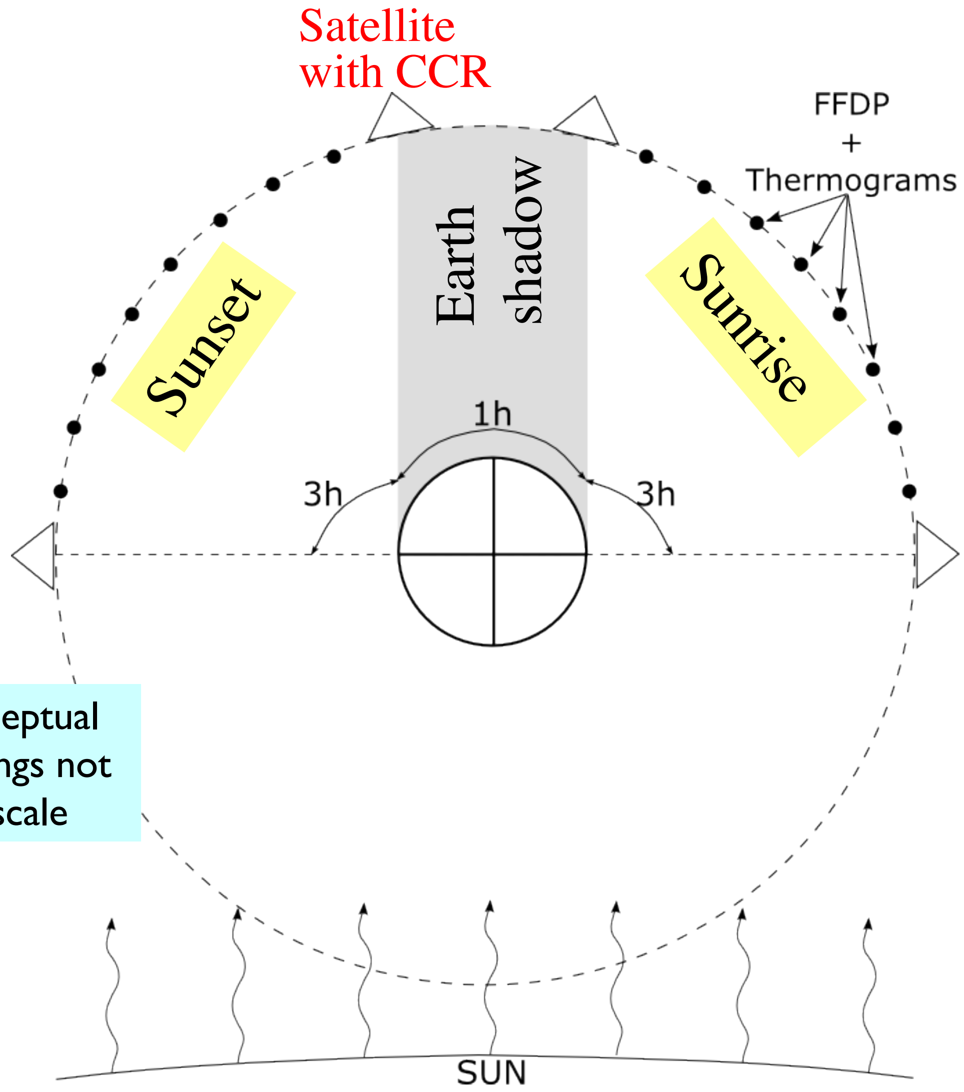
[f] *Harvard-Smithsonian Center for Astrophysics (CfA), 60 Garden Street, Cambridge, MA 02138, USA*
[g] *ASI, Centro di Geodesia Spaziale "G. Colombo" (ASI-CGS), Località Terlecchia, P.O. Box ADP, 75100 Matera, Italy*
[h] *University of Bologna, Department of Physics Sector of Geophysics, Viale Berti Pichat 8, 40127 Bologna, Italy*
[i] *NASA, Goddard Space Flight Center (GSCF), code 694, Greenbelt, MD 20771, USA*

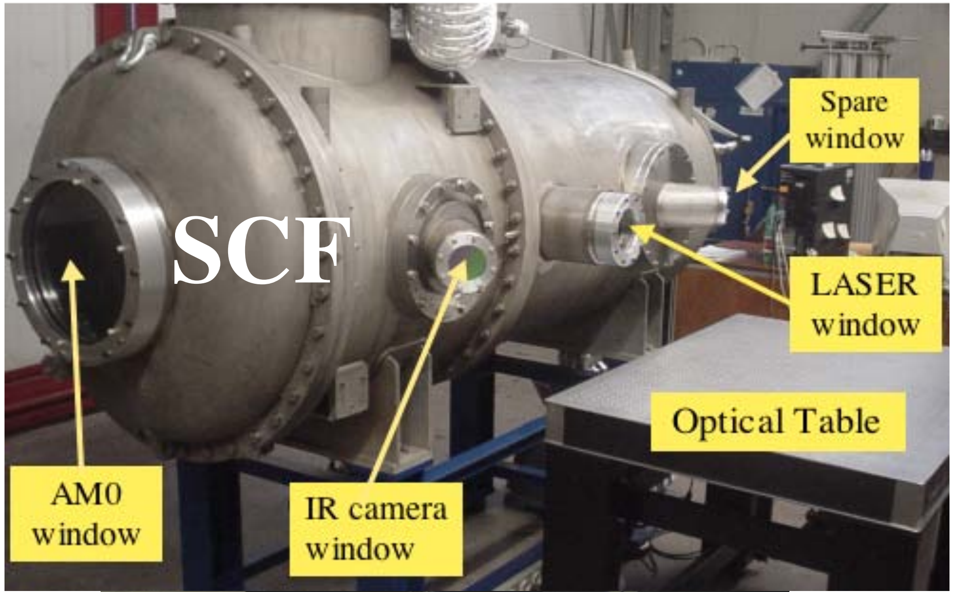
SCF-Test: Sun-ON/OFF or orbit-like movement

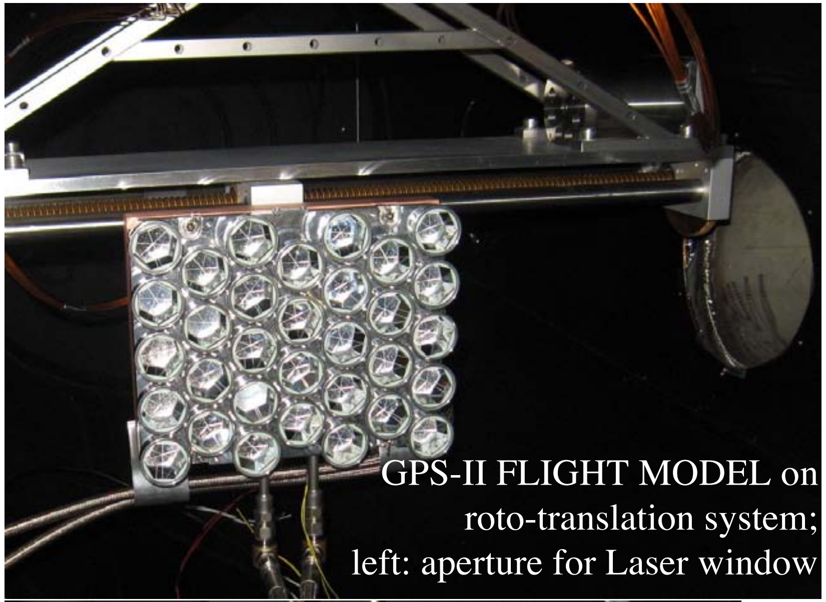


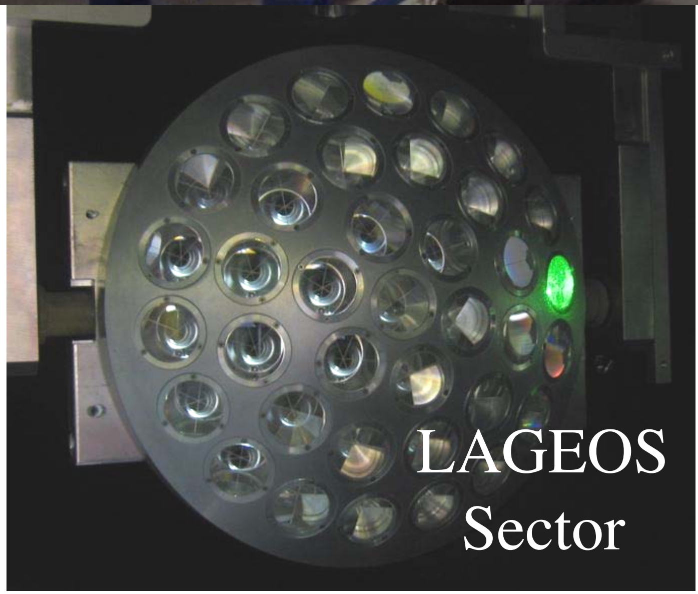
Conceptual drawings not to scale

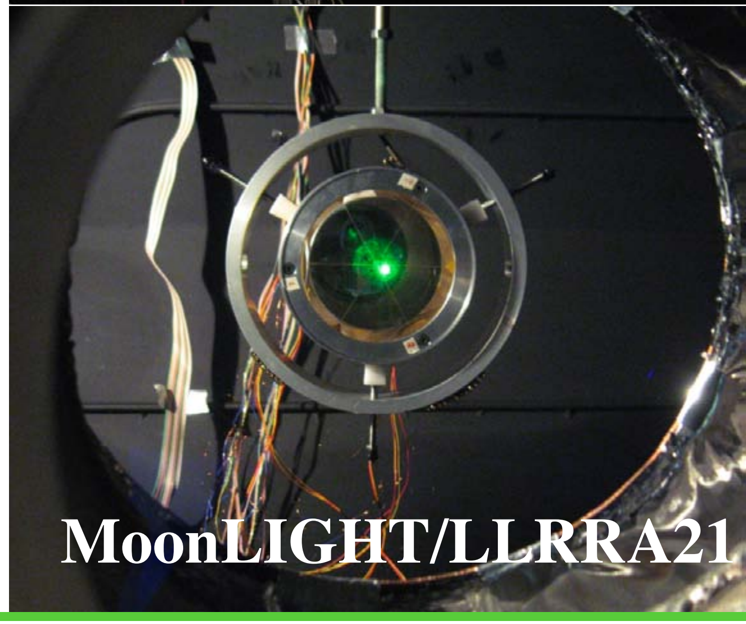


SCF-Tested payloads







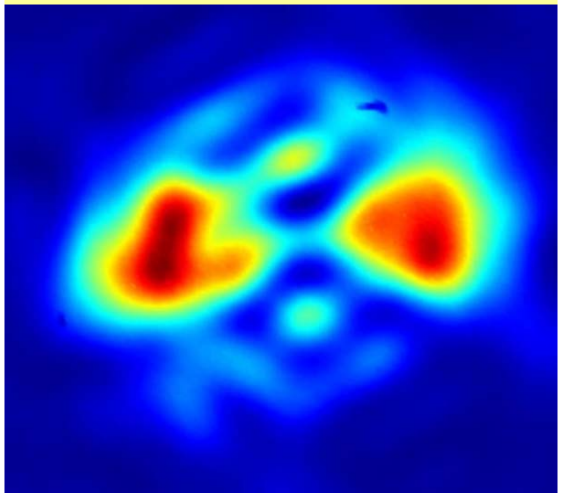


LAGEOS: uncoated, DAO specs = 1.25” ± 0.5”

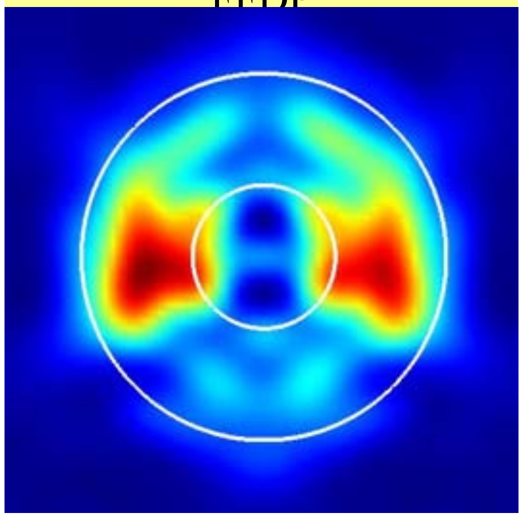
- **Performed FFDP test in air as demo, reference ‘industrial pre-acceptance test’** of the 37 CCRs of Goddard’s LAGEOS sector (in absolute μrad and Airy Peak units)
  - Polarization configuration which produces two lobes of energy in the FFDP

- Then did the industrial pre-acceptance test for real, for LARES (uncoated DAO = 1.5” ± 0.5”), a geodesy satellite of ASI to be launched with ESA’s new Vega rocket

LAGEOS MEASURED FFDP



LAGEOS SIMULATED FFDP



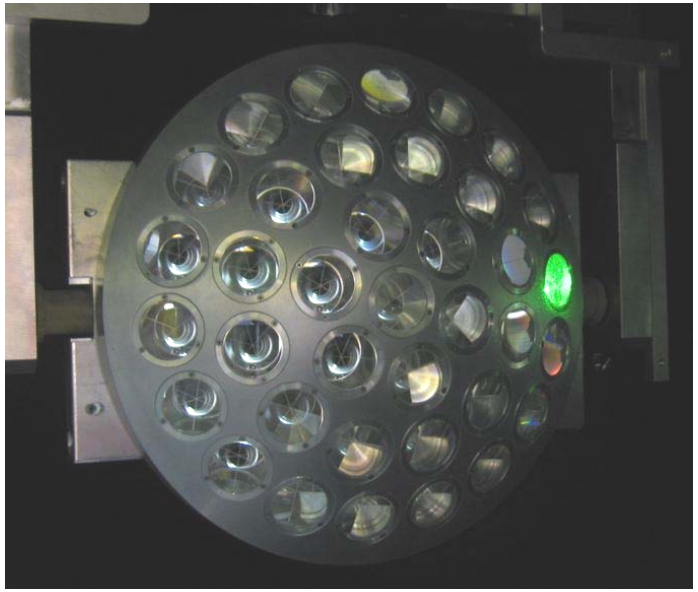
Circles show FFDP region corresponding to DAO specs

LAGEOS: ILRS reference payload standard

LAGEOS inherits from Apollo.

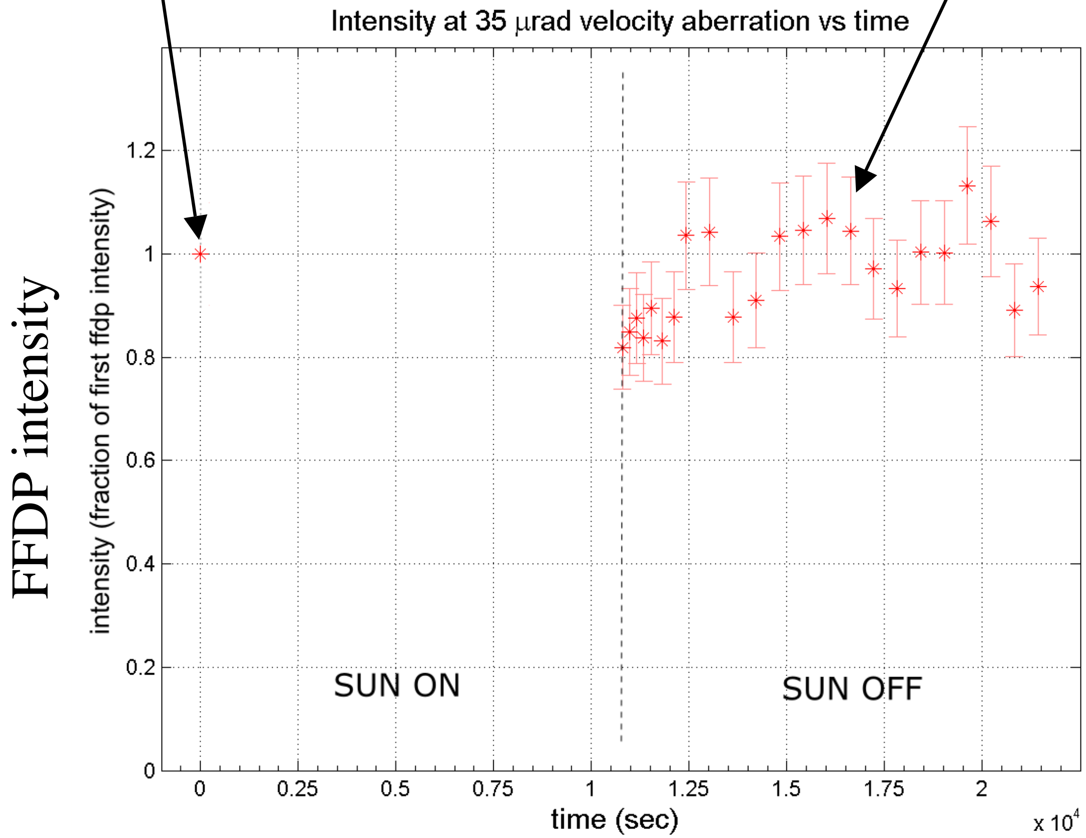
LAGEOS "**Sector**", engineering prototype property of NASA-GSFC,

SCF-Tested at INFN-LNF



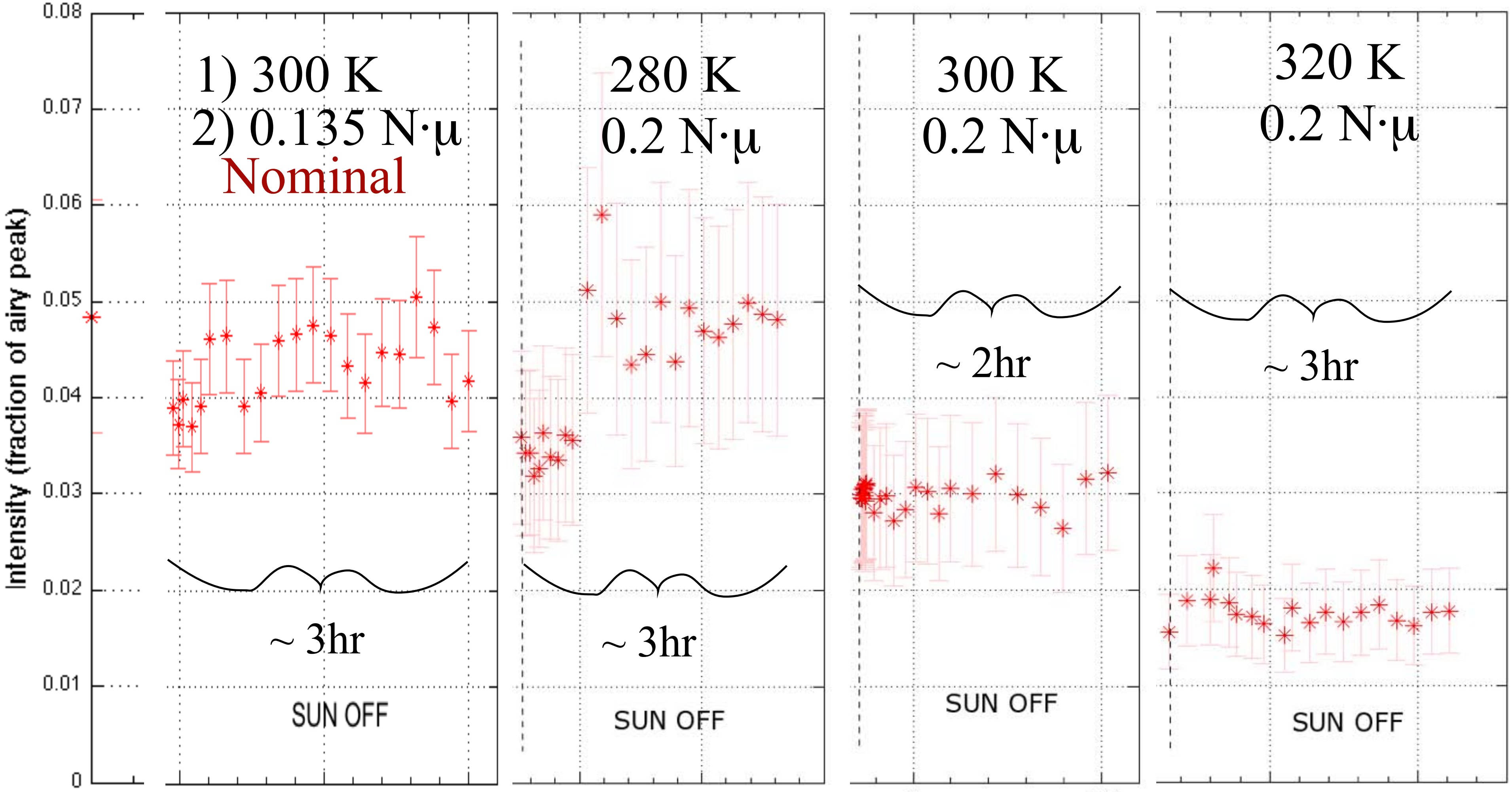
Far Field Diffraction Pattern laser return **intensity nominal, unperturbed value in air**

Very minimal degradation of FFDP



FFDP degradation vs. environment conditions

We varied the Sector 1) temperature and 2) retroreflector mount conductance (screw torque) and measured the FFDP intensity after 3 hours of sun illumination



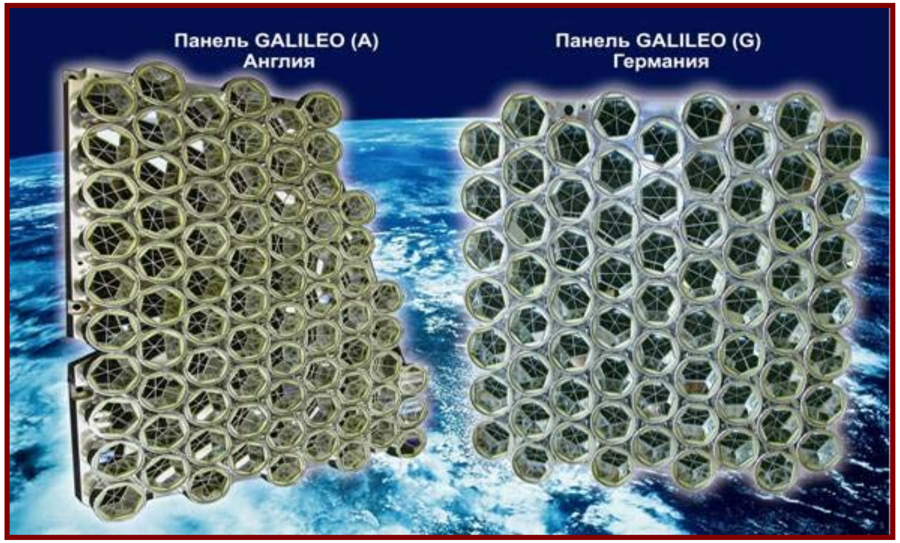
3rd GPS flight LRA made in USSR

Third and last ever made for GPS

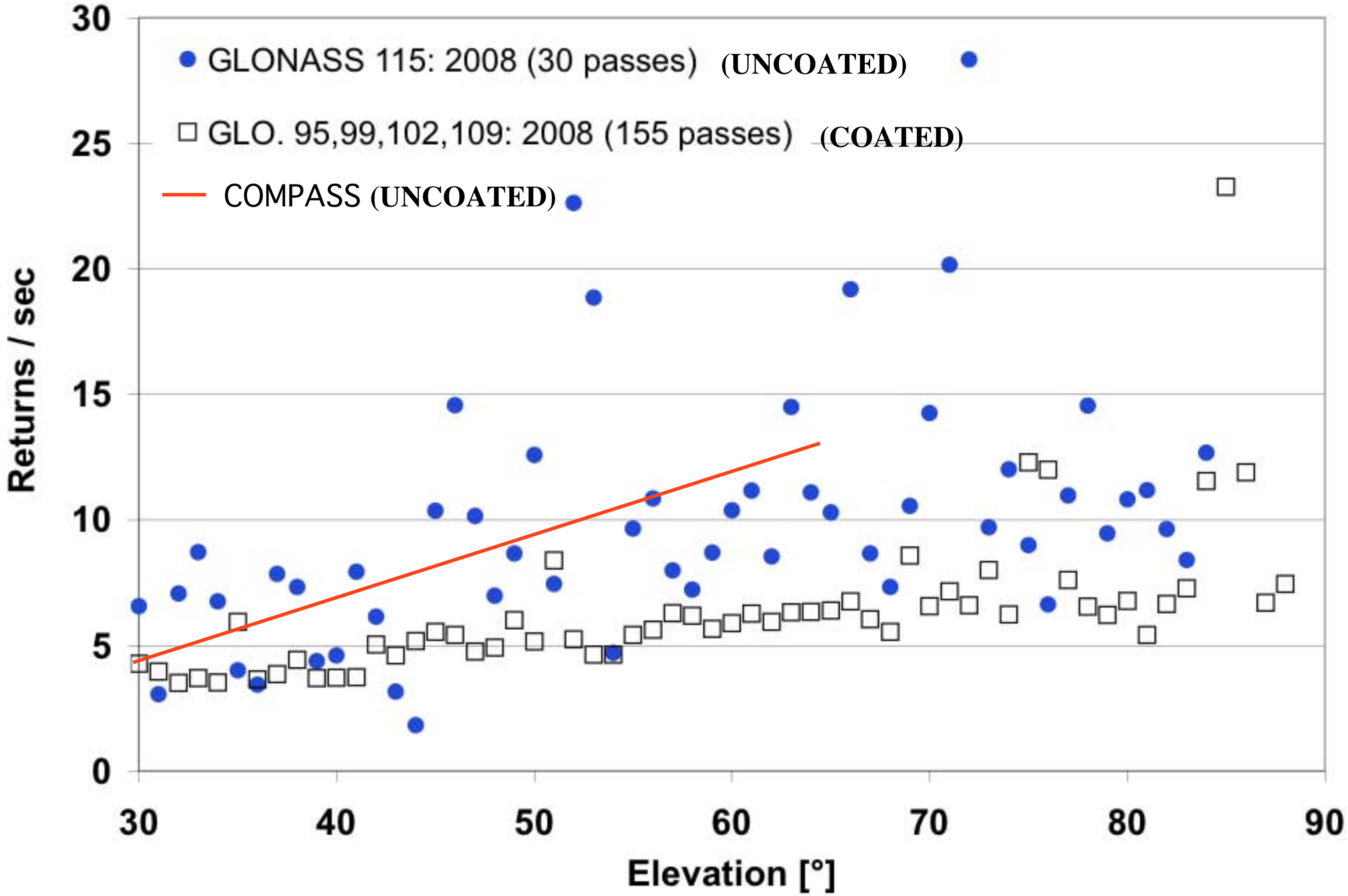
~19 x 24 cm^2, ~1.3 Kg, 32 CCRs.

Property of UMD, has been tested at the INFN-LNF SCF.

Design of GLONASS reflectors changed (Al-coating removed) since GLONASS-115, due to ILRS operation experience and results or our SCF-Test (see RD-1)

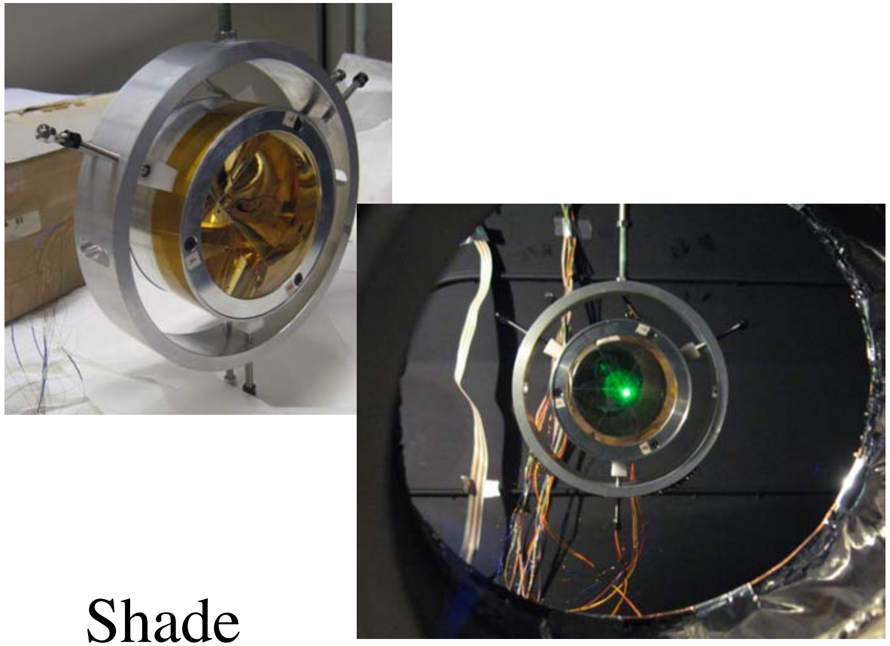


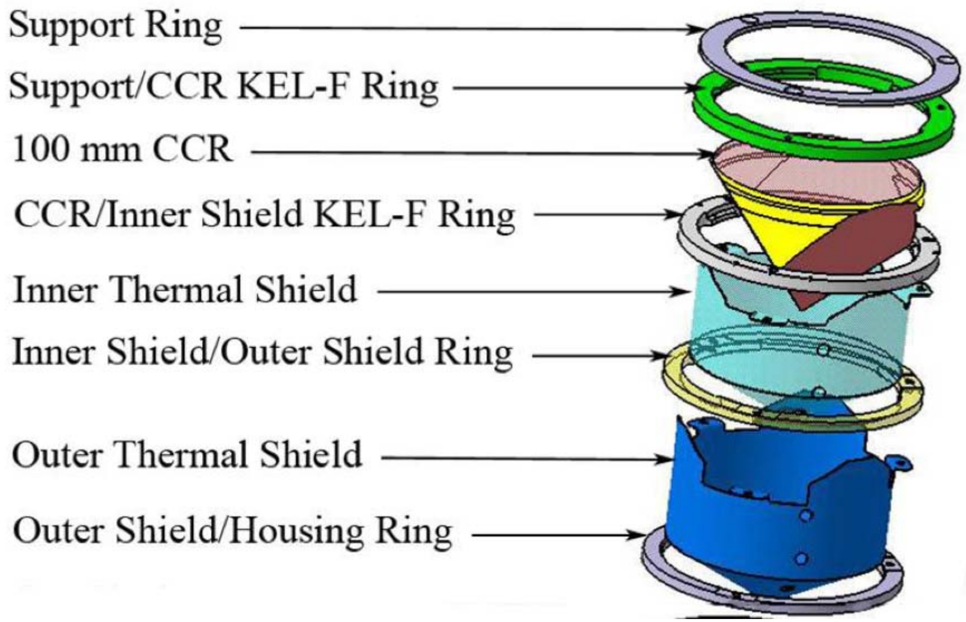
GLO with uncoated (155) vs. coated CCRs



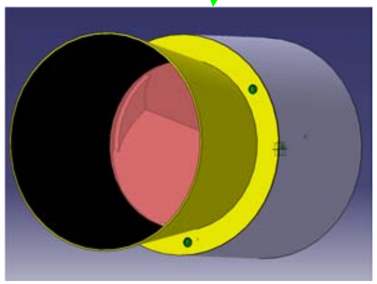
Data courtesy of G. Kirchner (Graz ILRS station)

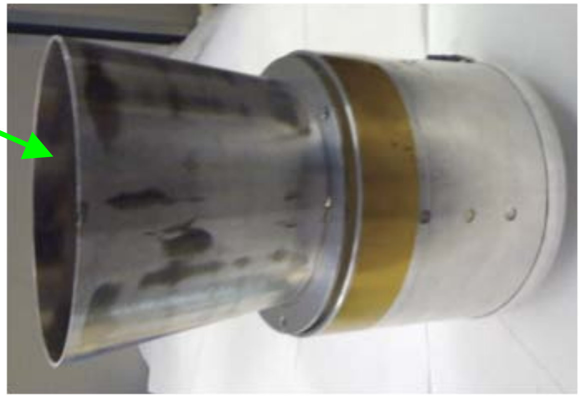
MoonLIGHT/LLRRA21 payload

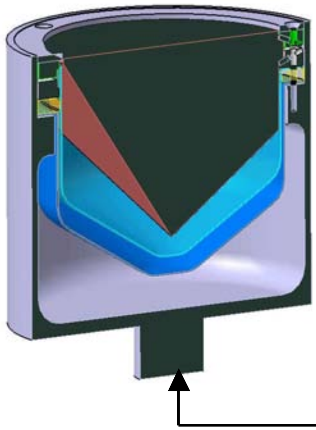




Shade for Sun heat

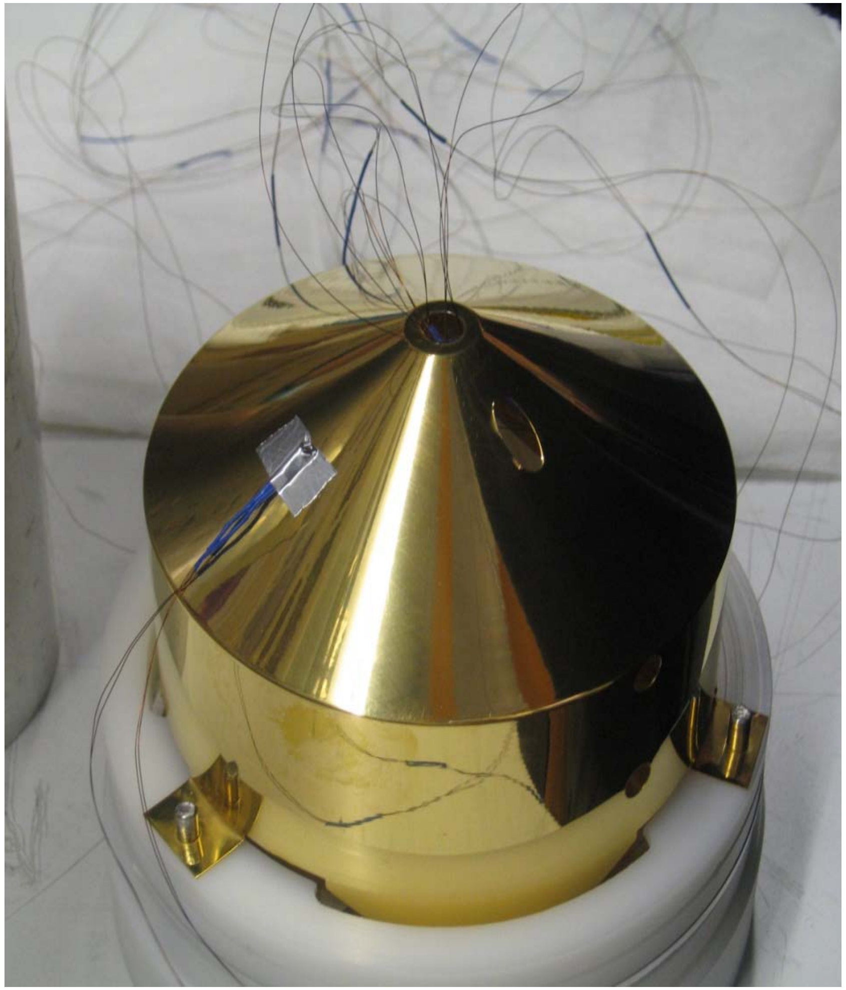


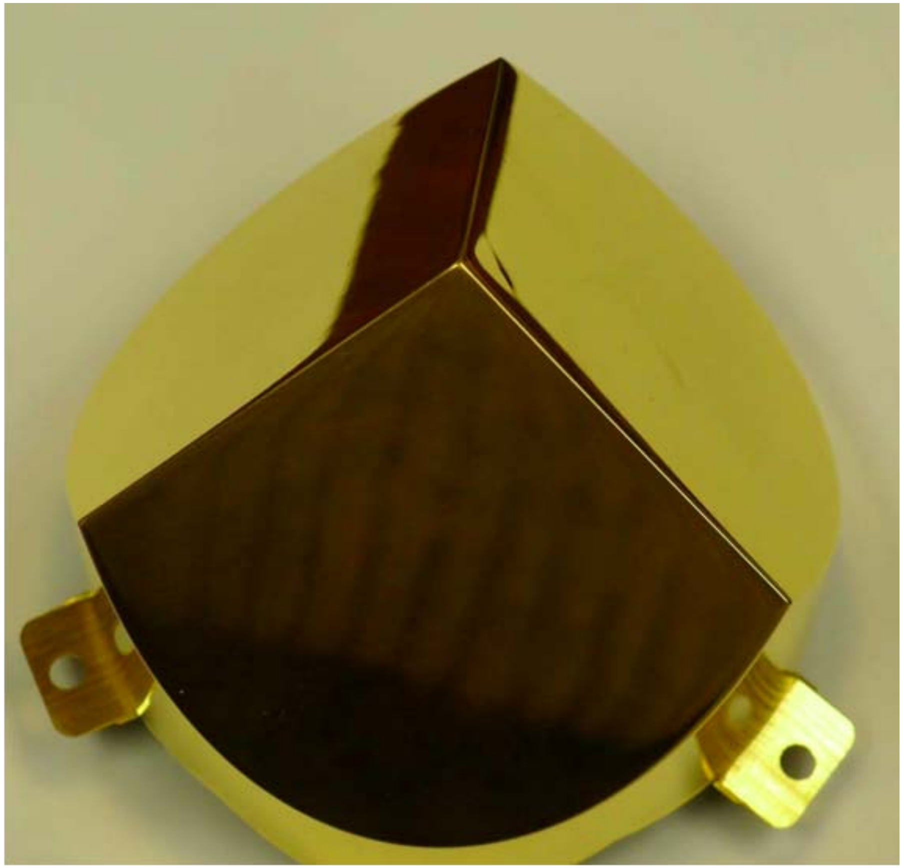




Threaded hole to deploy P/L on lander, rover, orbiter (or drill bore stem, like used by Apollo astronauts)

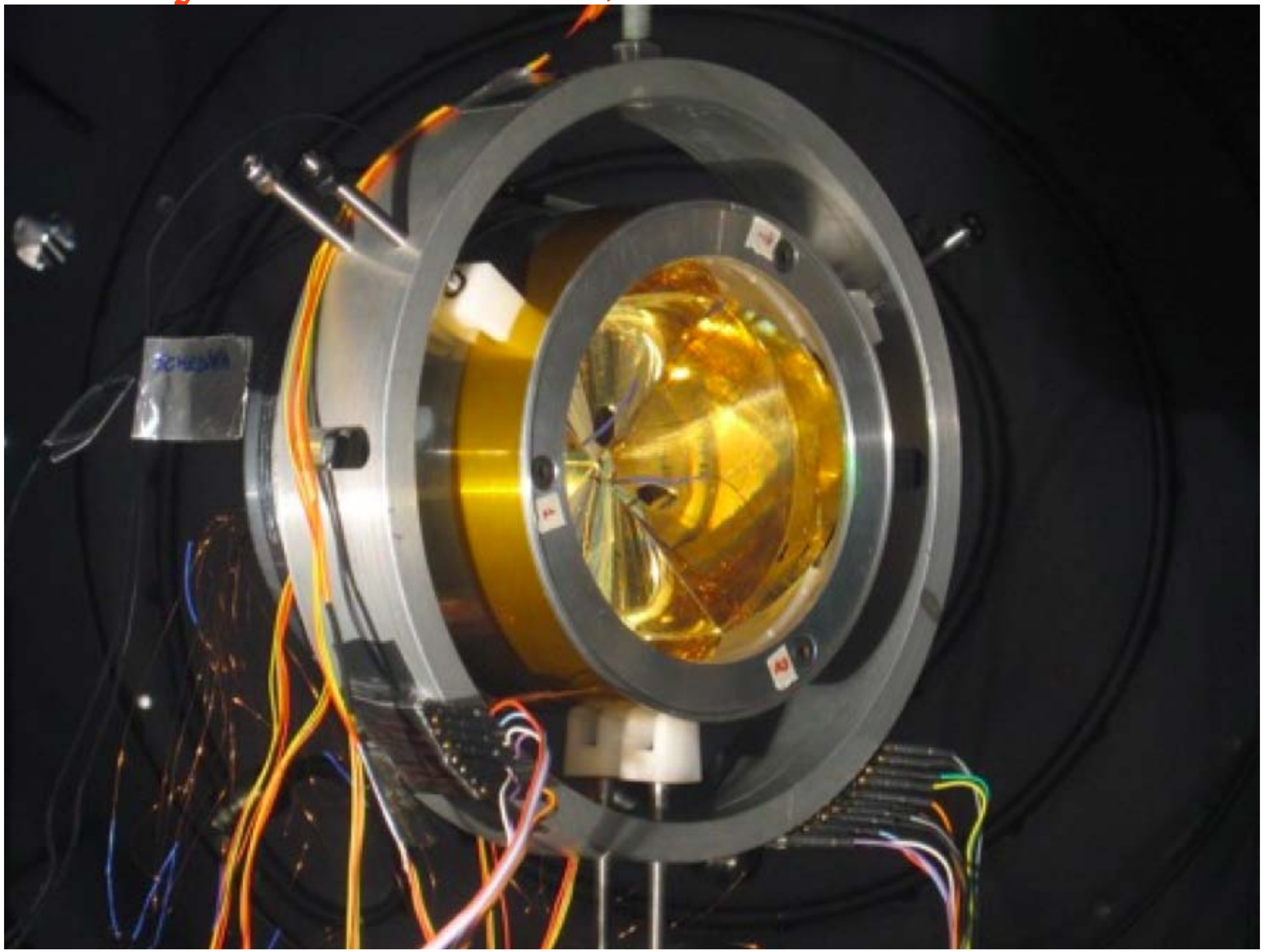
Inner and outer thermal shields of reflector



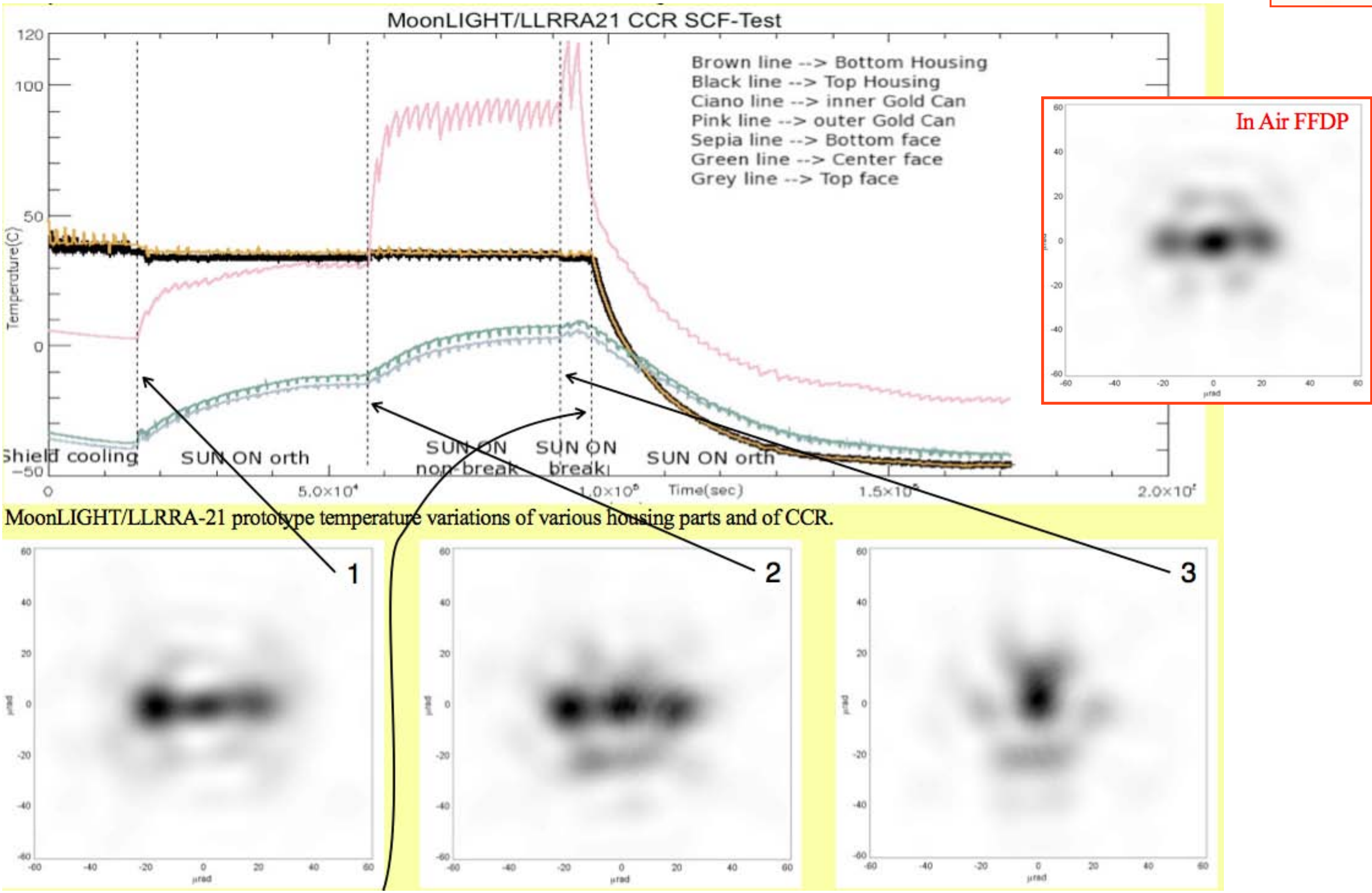


SCF-Test of MoonLIGHT/LLRRA21

during lunar day (Sun illumination): very unfavorable, hot conditions

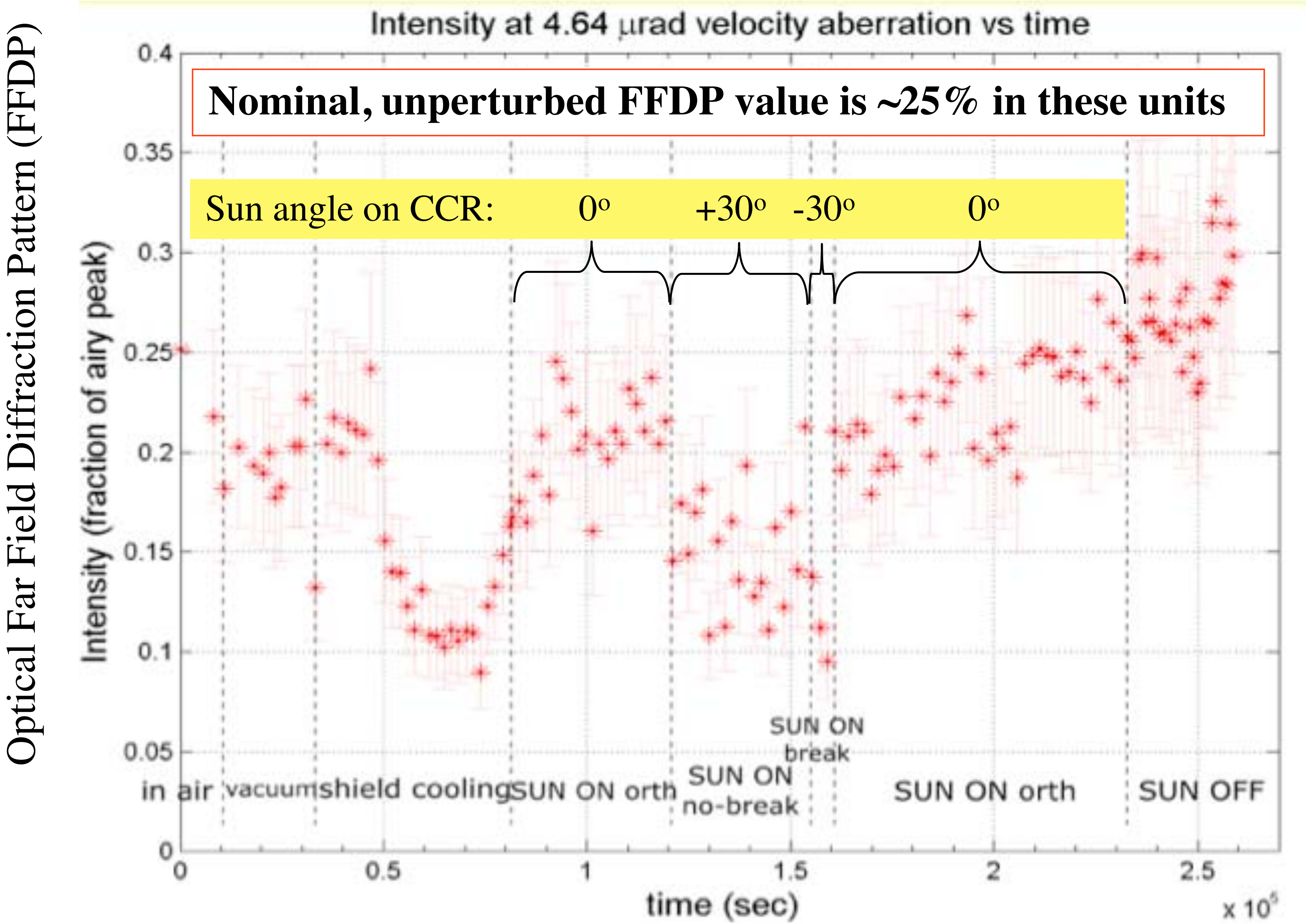


Temperatures of MoonLIGHT under the Sun



MoonLIGHT/LLRRA-21 prototype temperature variations of various housing parts and of CCR.

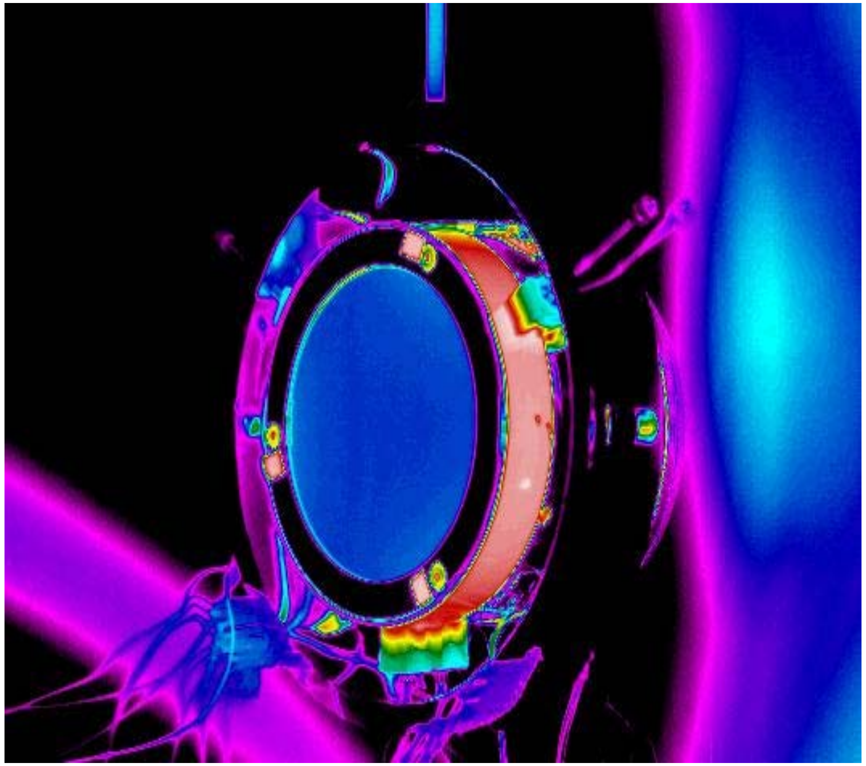
SCF-Test of MoonLIGHT/LLRRA21



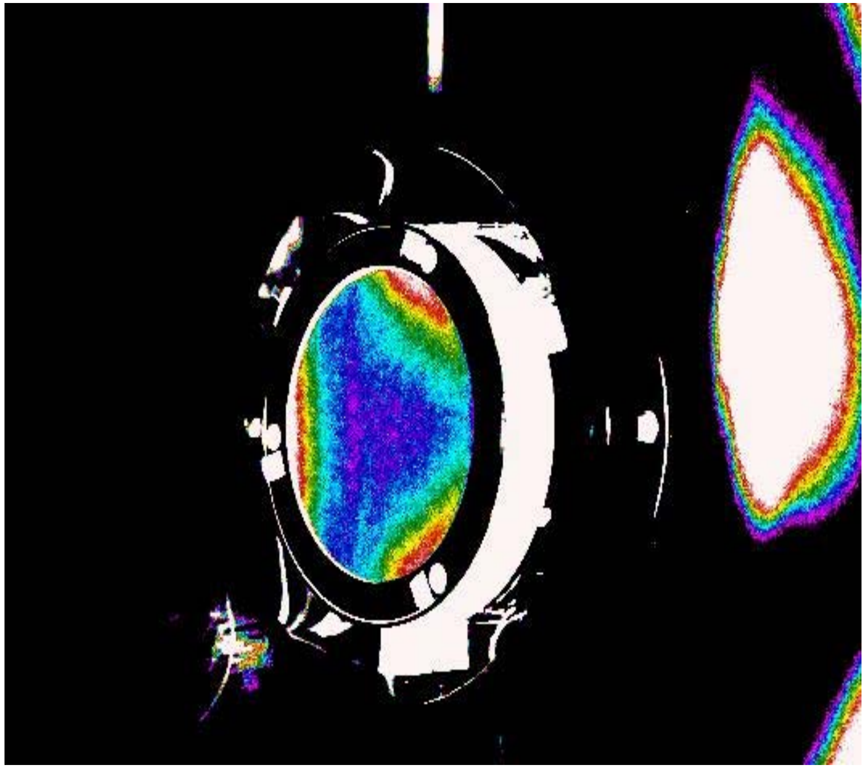
SCF Thermal Vacuum Test Infrared Imager

The SCF is sensitive to subtle thermal effect, like the mount conductance (as measured for the LAGEOS Sector)

Full Dynamic Range



Heat Flow Due to Tab Supports



International Lunar Network (ILN) concept

http://iln.arc.nasa.gov/ Nine Countries

Lunar Geophysics Network (LGN) of multi-site simultaneously operating instruments:

- –Seismometer
- –**Lunar Laser Ranging payload**
- –Thermal heat flow probe
- –E&M Sounder

40 years of 'LLR' test of General Relativity

(Logo by NASA)

Main Reference Documents

- [RD-1] Dell'Agnello, S., et al, Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS, J. Adv. Space Res. **47** (2011) 822–842.
- [RD-2] P. Willis, Preface, Scientific applications of Galileo and other Global Navigation Satellite Systems (II), J. Adv. Space Res., **47** (2011) 769.
- [RD-3] D. Currie, S. Dell'Agnello, G. Delle Monache, A Lunar Laser Ranging Array for the 21st Century, Acta Astron. **68** (2011) 667-680.
- [RD-4] Dell'Agnello, S., et al, Fundamental physics and absolute positioning metrology with the MAGIA lunar orbiter, Exp Astron DOI 10.1007/s10686-010-9195-0. ASI Phase A study. Work under Contract INAF-RHI n. 20080508-1 for the Phase A Study of the ASI Small Mission MAGIA
- [RD-5] Dell'Agnello, S. et al, A Lunar Laser Ranging Retro-Reflector Array for NASA's Manned Landings, the International Lunar Network and the Proposed ASI Lunar Mission MAGIA, Proceedings of the 16th International Workshop on Laser Ranging, Space Research Centre, Polish Academy of Sciences Warsaw, Poland, 2008.
- [RD-5] March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., Constraining spacetime torsion with the Moon and Mercury, Physical Review D **83**, 104008 (2011)
- [RD-7] March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., Constraining spacetime torsion with LAGEOS, arxiv:1101.2791v2 [gr-qc], 24 Feb 2011.
- [RD-8] International Lunar Network (http://iln.arc.nasa.gov/), Core Instrument and Communications Working Group Final Reports:

  http://iln.arc.nasa.gov/sites/iln.arc.nasa.gov/files/ILN_Core_Instruments_WG_v6.pdf

  http://iln.arc.nasa.gov/sites/iln.arc.nasa.gov/files/WorkingGroups/WorkingGroups2.pdf

Conclusions and proposal of collaboration

- Efficient LLR instruments Luna-Glob/Resurs will help for
  - Testing gravitational science
  - Exploration and Selenodesy (IMRF)
  - Service to the two mission goals (absolute, accurate positioning)
- SCF: unique capabilities; in use by ASI, NASA (for the Moon), ASI and ESA (for GNSS)
- We are interested in collaborating in Luna-Glob/Resurs on LLR activities. Especially SCF-Testing.
  - INFN has a Memorandum of Understanding with Russian Academy of Science since many years
  - INFN has very good ties with ASI, the Italian Space Agency, which promotes and coordinates space activities in Italy

INFN (brief and partial overview)

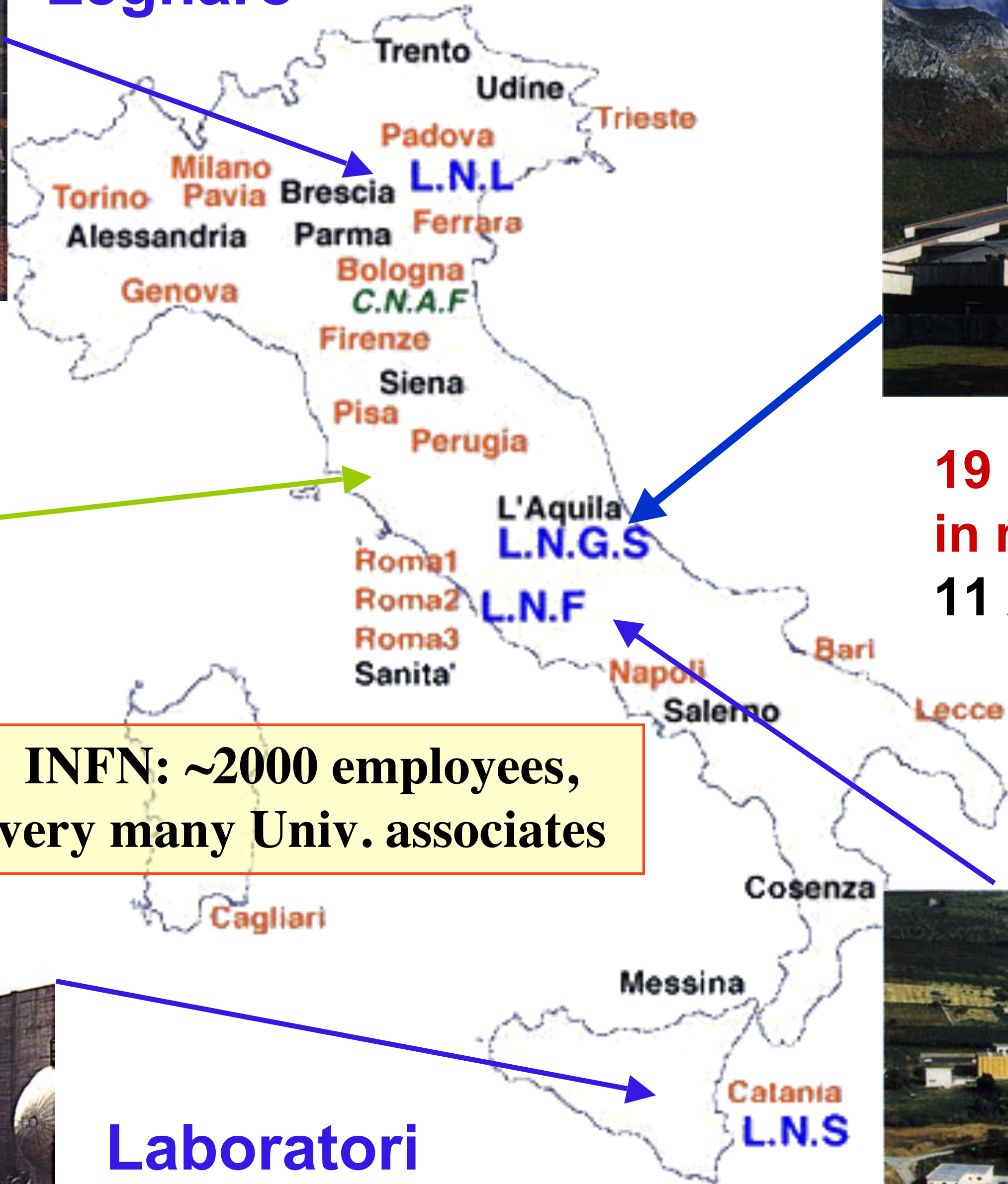
- Public research institute. Main mission: study of
  - fundamental forces (including gravity), particle, nuclear and astroparticle physics and of its
  - technological and industrial applications (SLR, LLR, GNSS)
- Prominent participation in major astroparticle physics missions:
  - FERMI, PAMELA, AGILE (all launched)
  - **AMS-02**, launched by **STS-134 Endeavor to the International Space Station (ISS)** on May 16, 2011
- VIRGO, gravitational wave interferometer (teamed up with LIGO)
- …. More, see http://www.infn.it

INFN-LNF (brief and partial overview)

- Located in Frascati, near Rome, next to ESA-ESRIN (which includes the ASI Science Data Center, ASDC), and to INAF-IFSI. Well connected to Rome airports and train stations
- Large-scale Infrastructure of the "European Research Framework Programme (FP)"
- Largest physics national lab in Italy
  - Several particle accelerator facilities and experiments
  - Gravitational bar antenna
  - Space facility **SCF: SLR/LLR Characterization Facility**
  - … More, see http://www.lnf.infn.it

Legnaro

Gran Sasso (underground lab)



19 Sites (“Sezioni”) in major cities

11 Associated sites

4 National Labs

VIRGO-EGO

European
Gravitational
Observatory

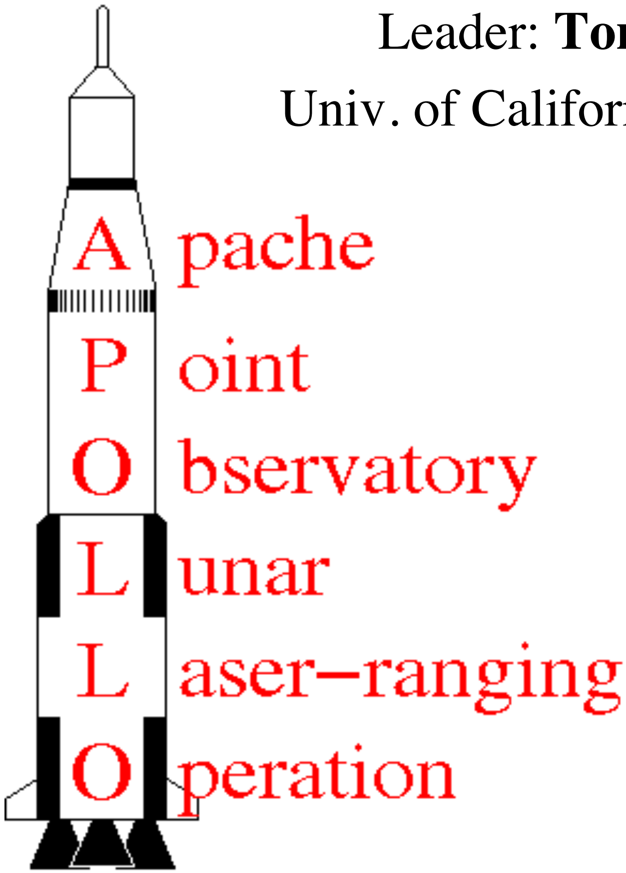
INFN: ~2000 employees, very many Univ. associates

Laboratori del Sud (Catania)

Lunakhod 1 rediscovered by LRO/APOLLO

New 'APOLLO' LLR station, active since 2007

Leader: **Tom Murphy**,
Univ. of California at San Diego



(Apollo) Laser beams are sent to reflectors on the moon from a telescope in New Mexico.
Credit: Dan Long, Apache Point Observatory

Centro di Geodesia Spaziale (CGS) *Giuseppe Colombo*
Matera, Italy
Tri-colocated within ITRF by SLR, VLBI, GNSS

MLRO,
Matera Laser Ranging Observatory
LLR capability restarted in March 2010


Giuseppe Colombo, 1920-1984

SLR/LLR work by the SCF Team

- **First-ever** SCF-Test of:
  - GPS-II retroreflector array **flight model** property of UMD
  - GLONASS and Galileo's GIOVE-A and -B retroreflector prototype by V. Vasiliev
  - LAGEOS Sector **engineering model** property of NASA-GSFC
  - **Hollow** retroreflector prototype provided by GSFC
  - **Galileo IOV** retroreflector prototype property of ESA
  - New generation LLR retroreflector, for:
    - First manned landing - 2006 NASA LSSO Program (the beginning of U. of Maryland and INFN-LNF collaboration LLRRA21/MoonLIGHT)
    - Two ASI studies, including MAGIA for Phase A
    - NLSI "CAN" Project (LUNAR, Directed by J. Burns)
- Response to NASA's ILN anchor nodes Request For Info (RFI)
- Response to ESA's RFI for lunar lander

Current SCF research activities

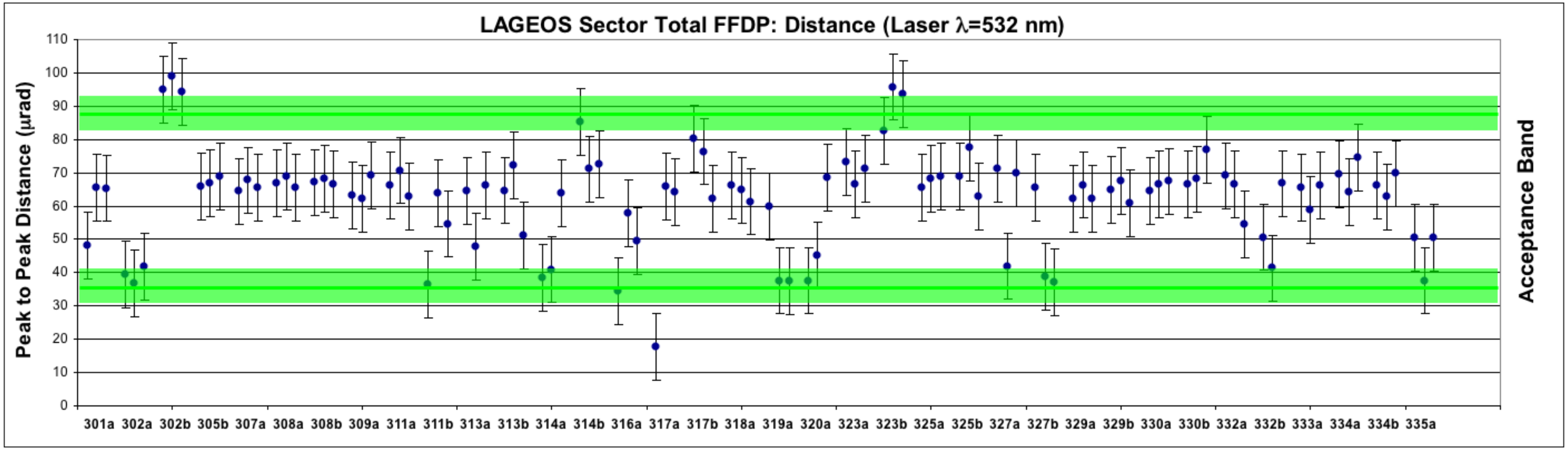
- Our approved projects:
  - **MoonLIGHT-ILN** (INFN; LLR)
    - LLR analysis effort using CfA's Planetary Ephemeris Program (PEP)
  - **ETRUSCO-2** (Asi-INFN; SLR of GNSS and LAGEOS)
- Study of new gravitational physics theories: theoretical predictions and experimental test
- We collaborate with:
  - Italian Air Force, ASI-CGS@Matera, University of Maryland, Harvard-Smithsonian Center for Astrophysics (CfA), NASA-GSFC, NASA Lunar Science Institute (NLSI), UCSD, International Lunar Network (ILN) …

One past activity for ASI by INFN-LNF (not an SCF-Test)

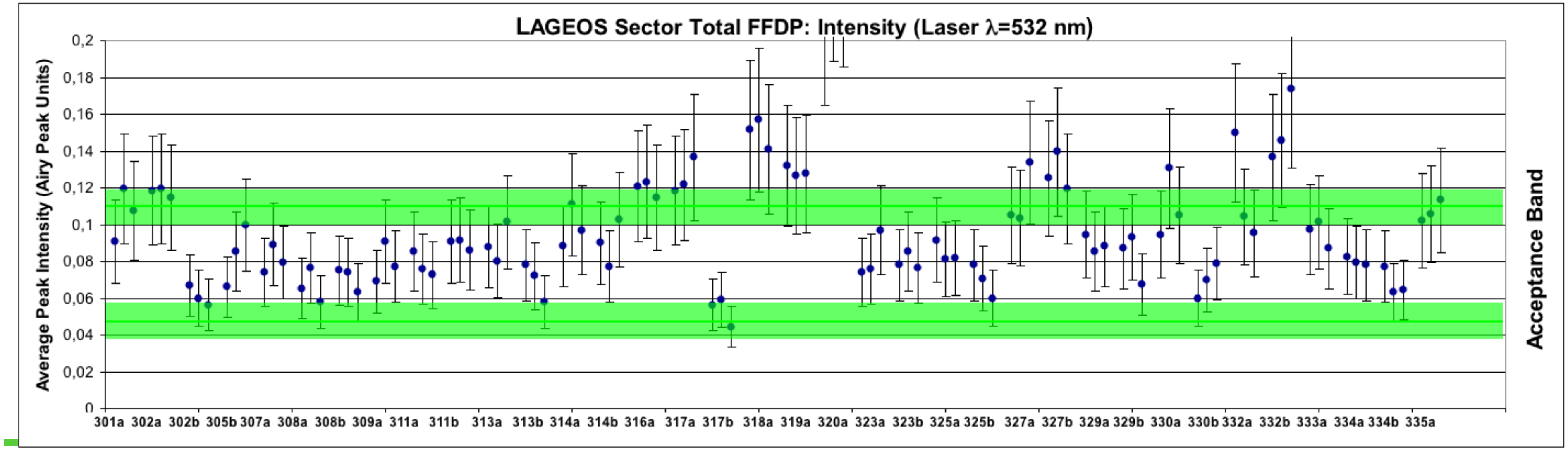
- Industrial optical FFDP acceptance test, in-air and isothermal conditions, of 110 flight reflectors manufactured by Zeiss for the LARES mission
  - Accomplished by INFN-LNF in 3 working weeks before Christmas 2008:
    - At the optics lab with 633 nm wavelength
    - 15 days, enormous amount of retroreflector handling by LNF team, no casualty, completely successful
  - 110 retroreflectors accepted and paid by ASI, on the basis of this test activity by INFN-LNF
  - THIS WAS ONLY AN FFDP TEST IN AIR AND ISOTHERMAL CONDITIONS; NOT AN SCF-TEST
  - ASI reference document: DC-OSU-2009-012

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

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

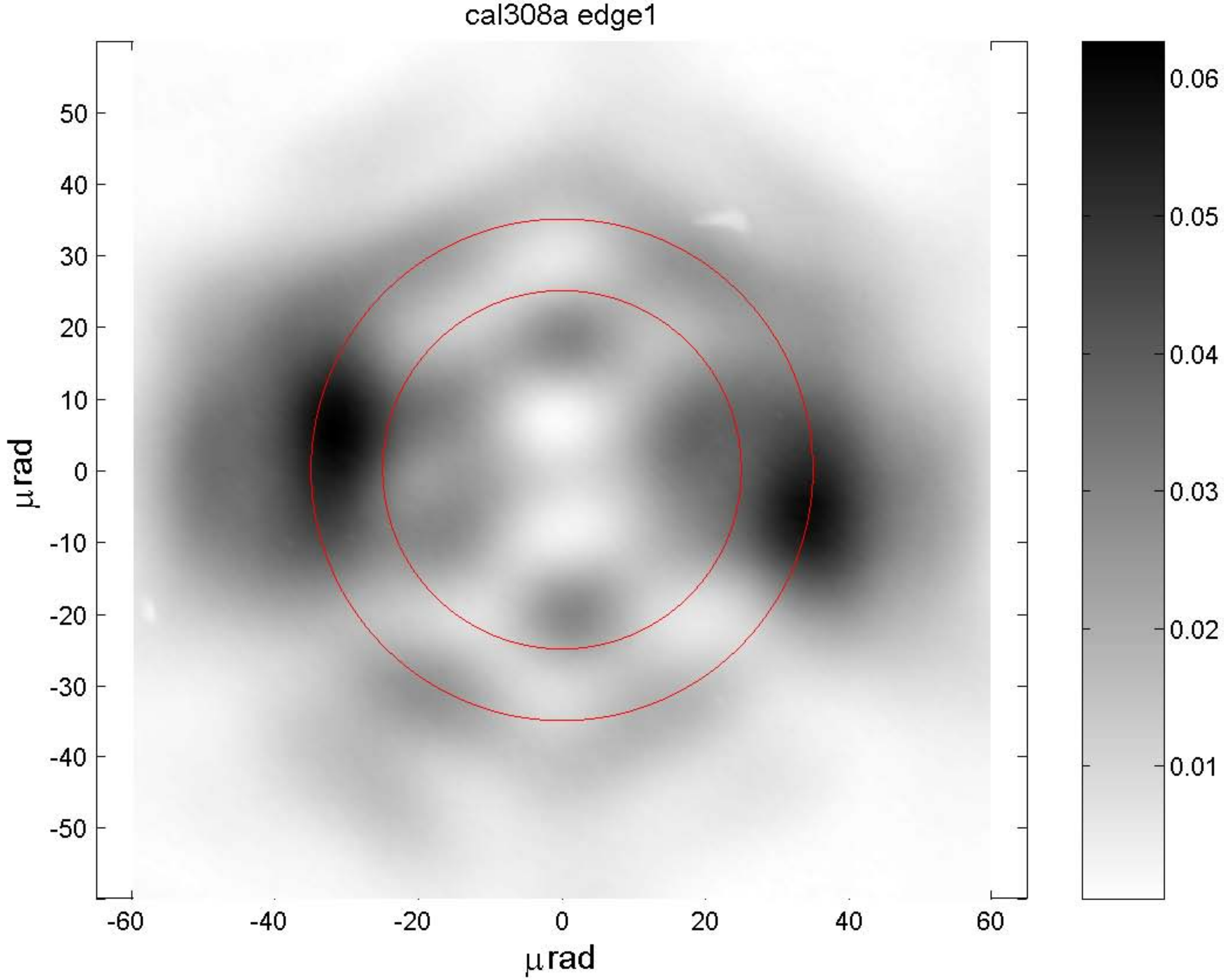


Preliminary



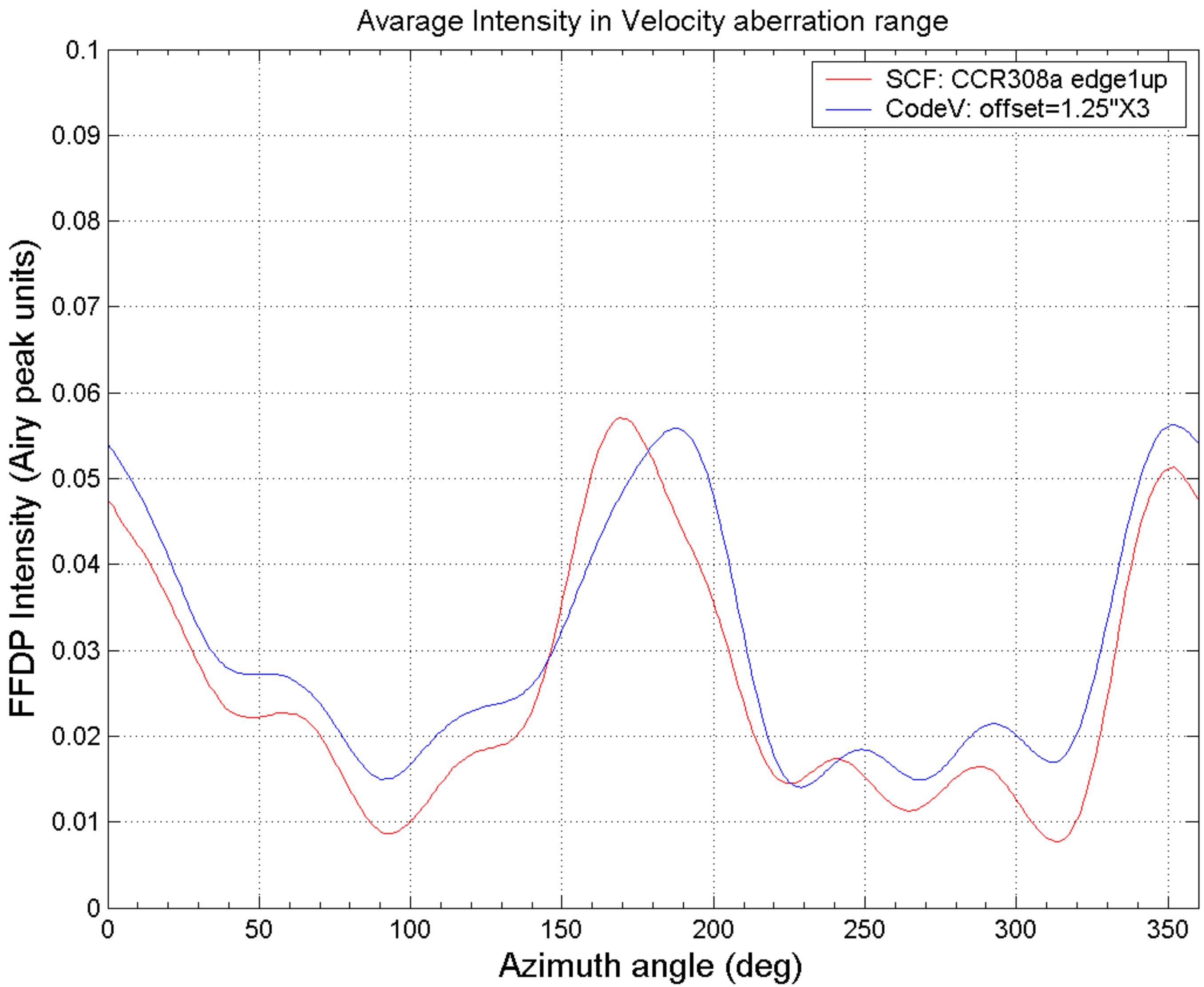
Full measured FFDPs info (not just the “peaks”)

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



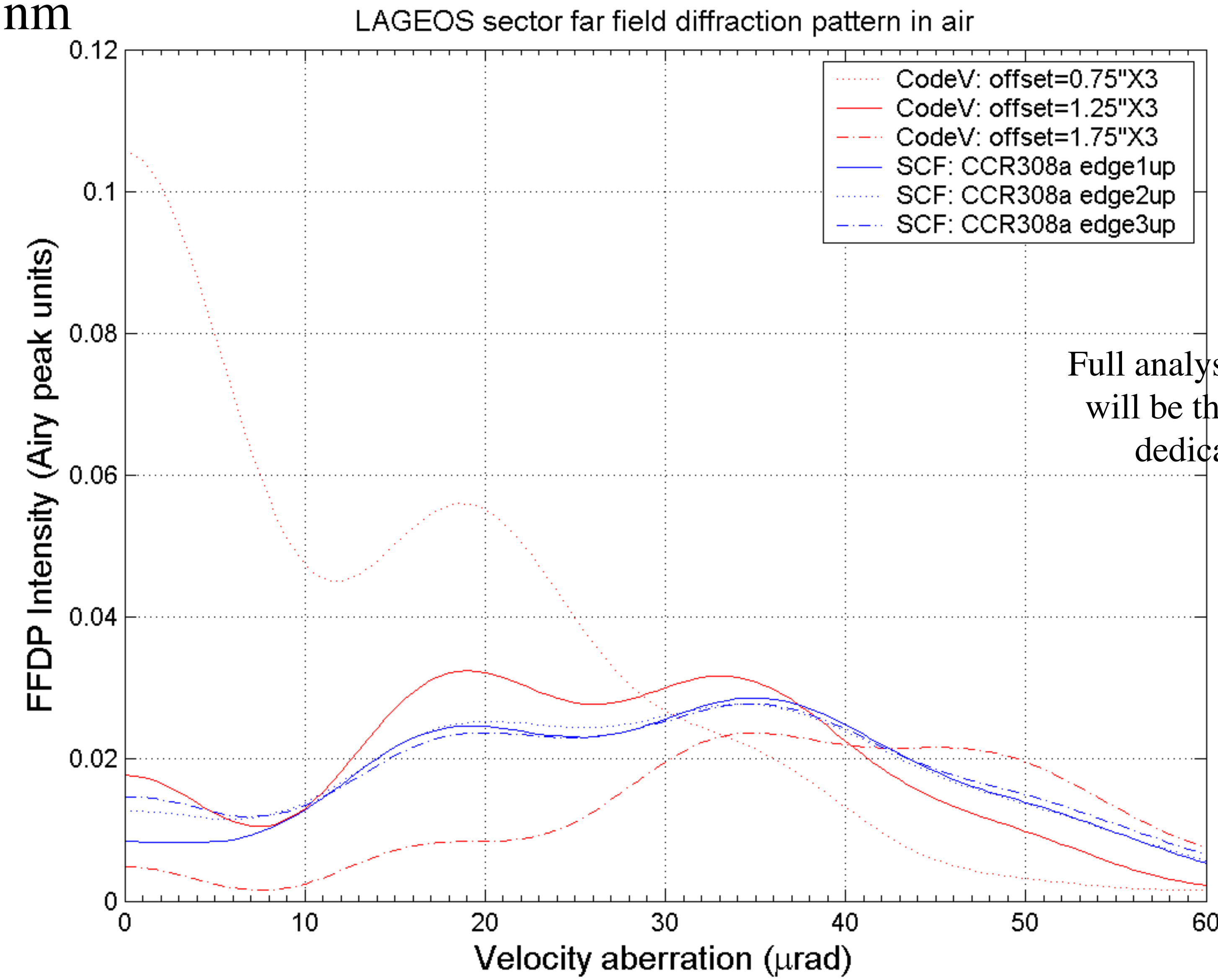
Full FFDPs info (not just the “peaks”)

532 nm



FFDPs contain more info than just the "peaks"

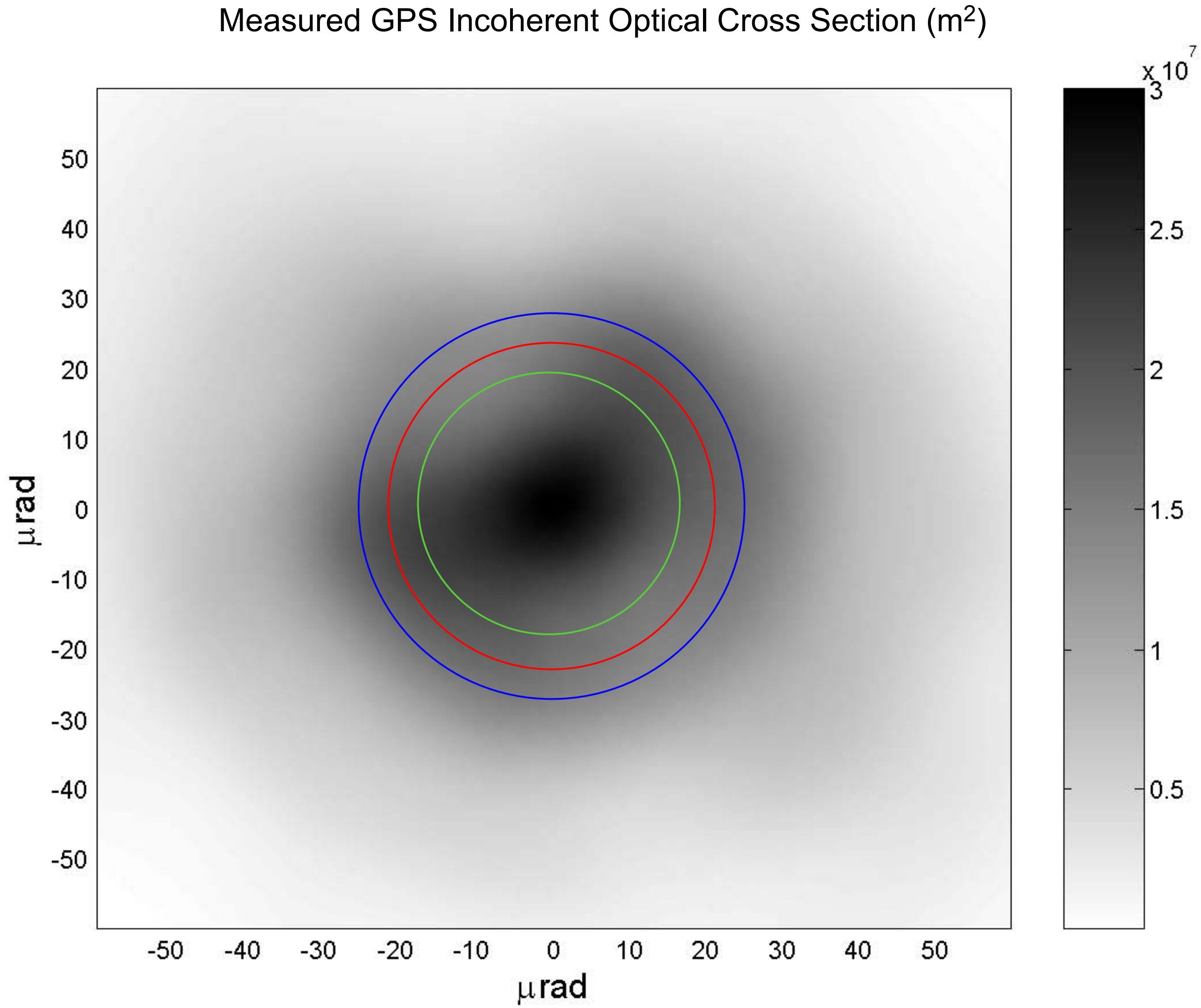
532 nm



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

3^{rd} GPS flight LRA measured optical cross section

in air at λ=532 nm



σ_0 in the 2D velocity aberration plane

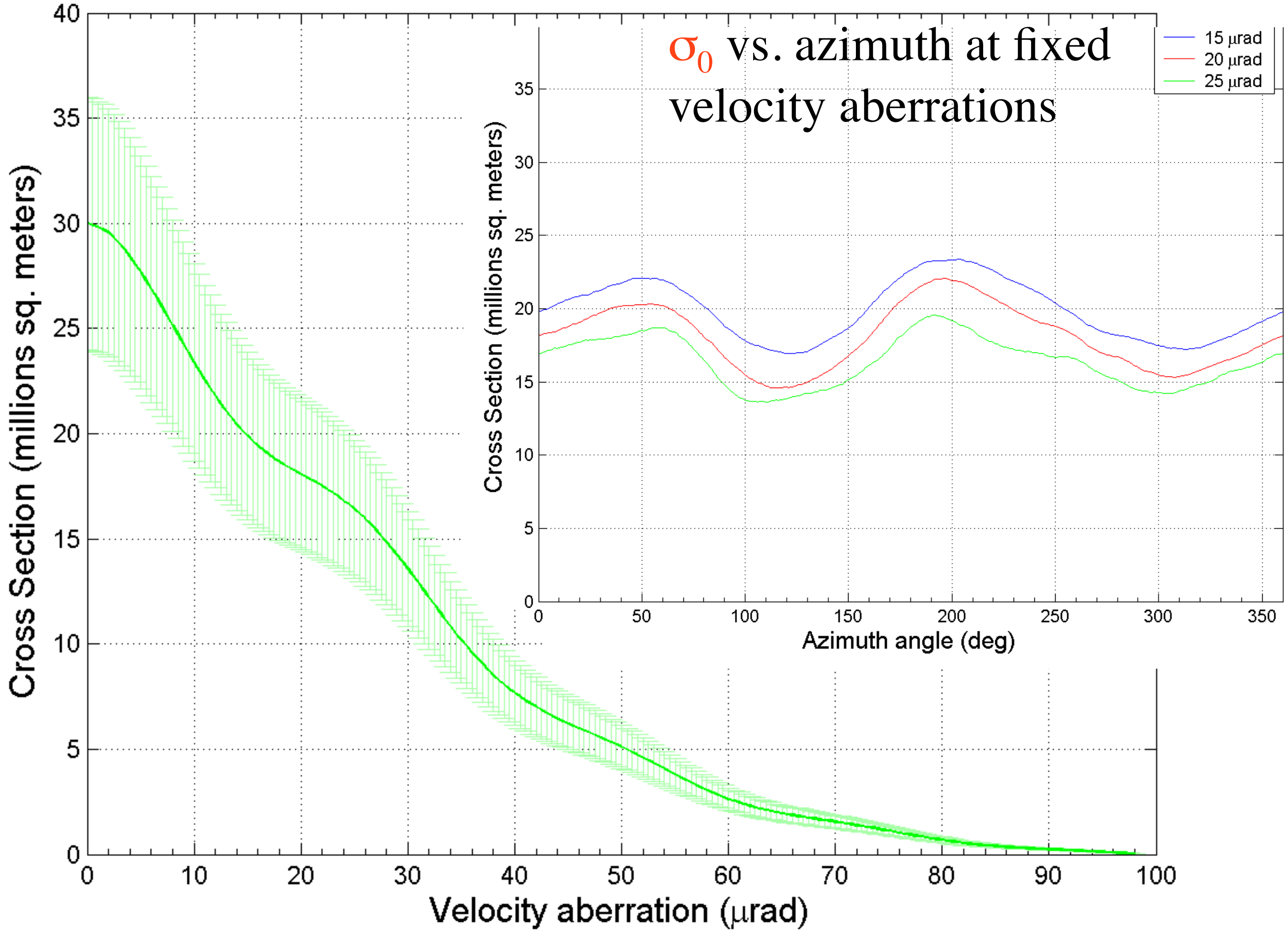
σ_0 = measured on-axis (0° laser incidence), in-air, isothermal optical cross section vs. bi-dimensional velocity aberration in the two absolute units

Based on CCR FFDPs and scale normalizations

σ_0 vs. velocity aberration (2D radius and azimuth)

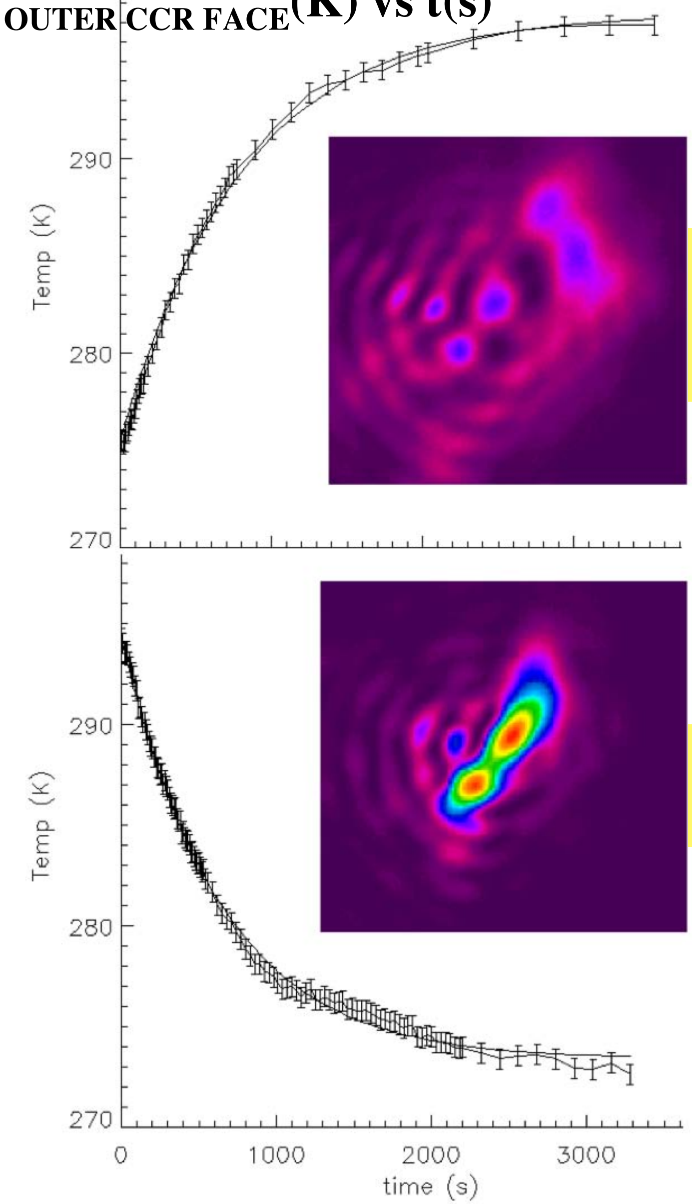
Compare with ILRS requirement of **100 million m² at 25 μrad for GPS**

SCF-Test: showed that in space can get x8 further reduction of this in-air cross section



(Default) SCF-Test of GPS flight CCR

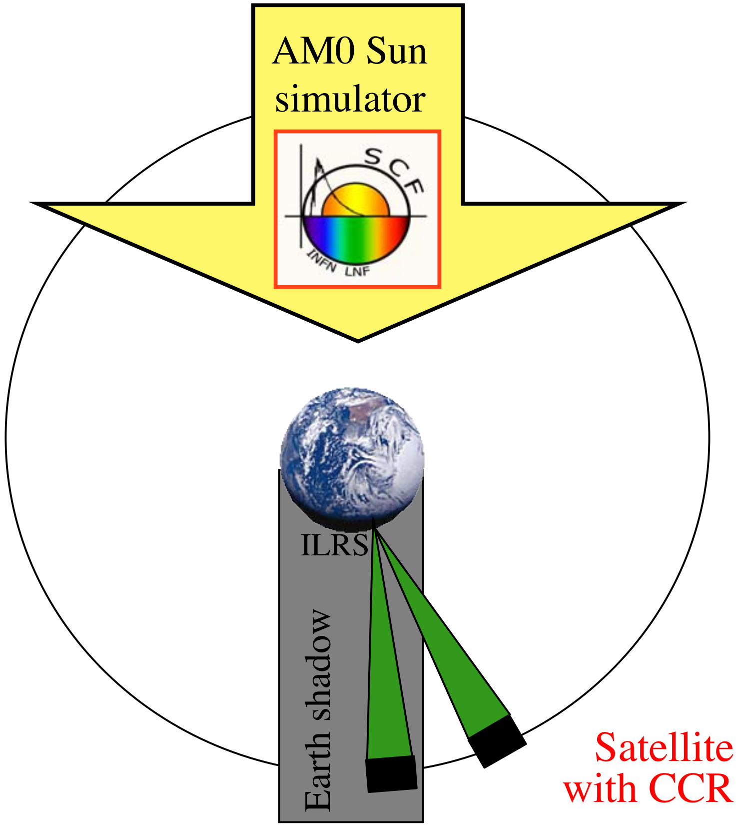
$T_{OUTER\ CCR\ FACE}$(K) vs t(s)



FFDP laser return peaks severely degraded

FFDP laser return peaks restored

Factor ~7 reduction of FFDP

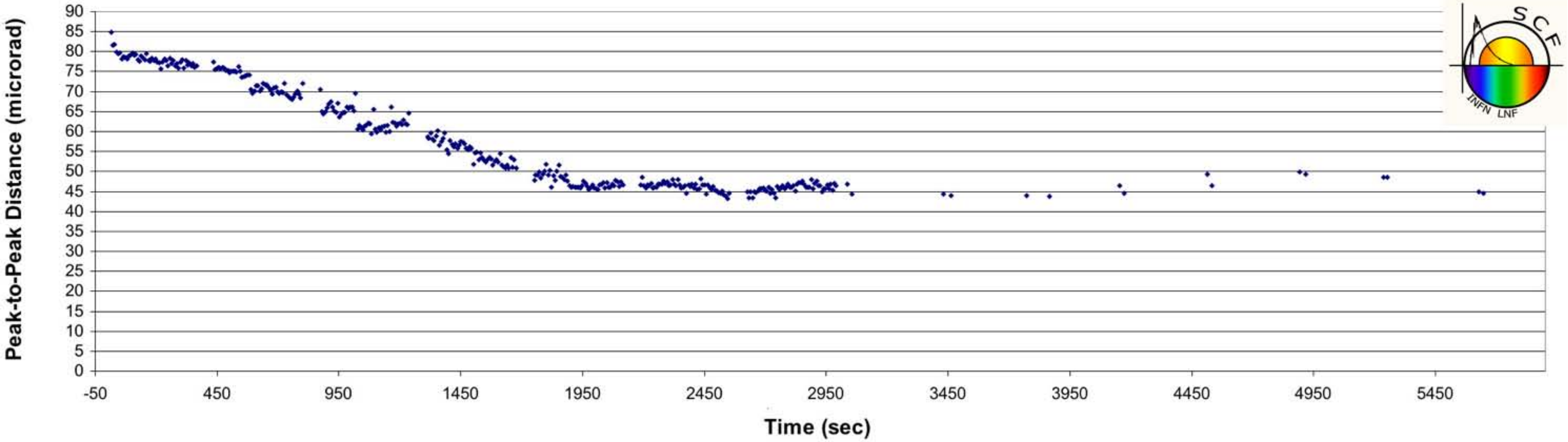


(Default) SCF-Test of GPS flight CCR

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

Time constants

- quick conductive cooldown (**coating** on CCR back faces)
- slow radiative cooldown (**non-insulating** CCR mounting)



SCF-Test of GPS flight CCR

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

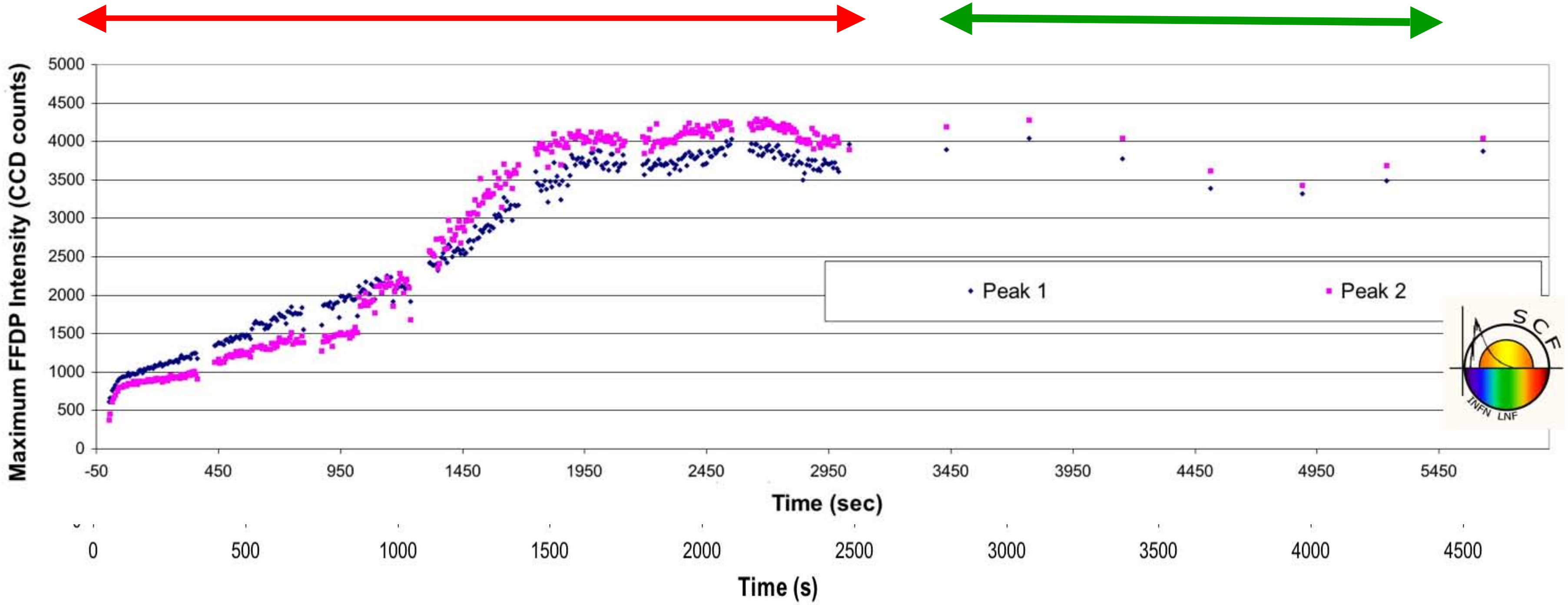
~3 hours of Sun illumination, then Sun=off and FFDP measurement

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

Effect measured for the 1st time in the laboratory

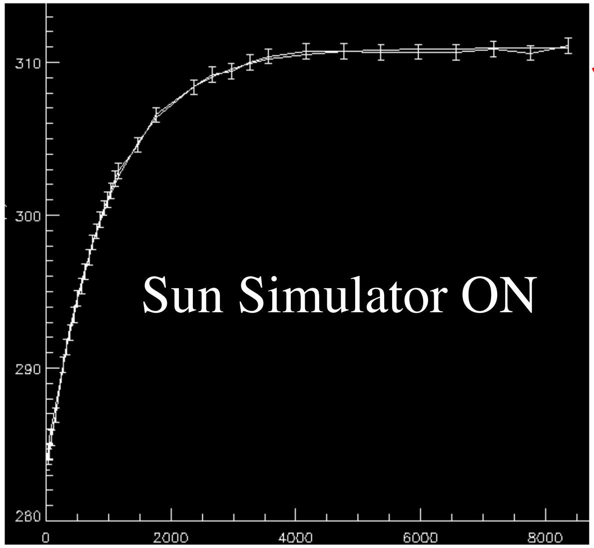
CCR non-isothermal: strong reduction of FFDP peak intensity

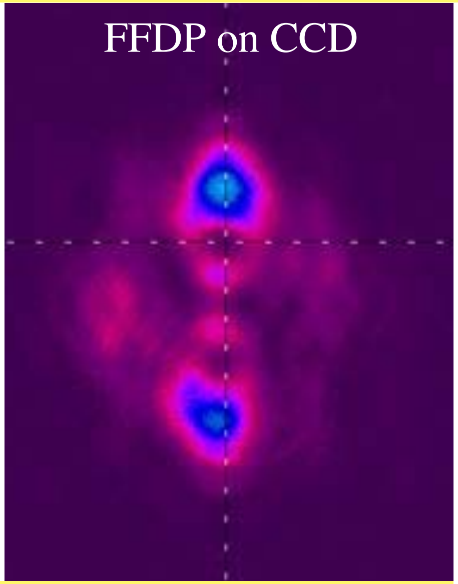
CCR more isothermal: Peak intensity restored



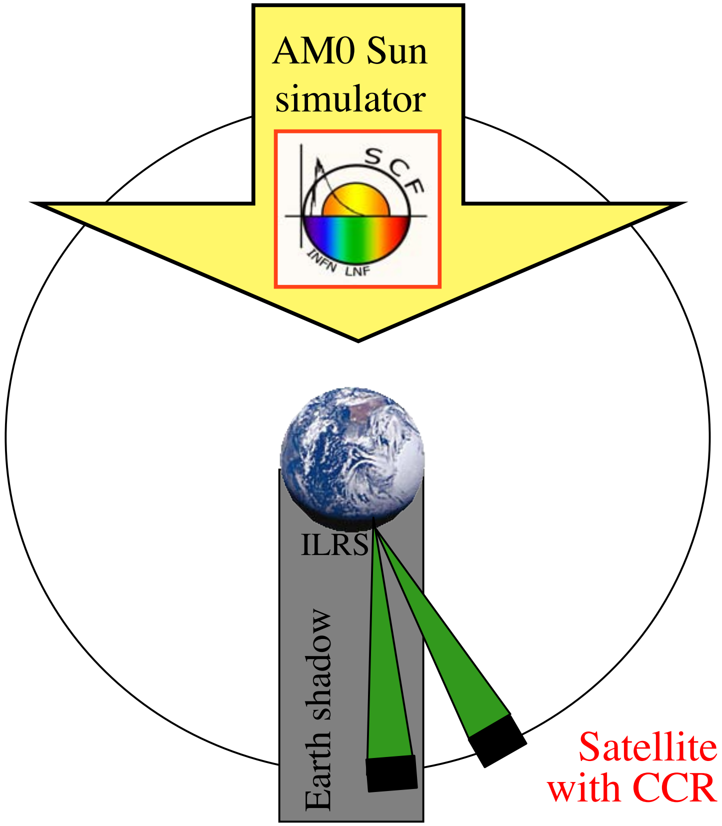
SCF-Test of GPS/GLONASS/GIOVE made in 2007

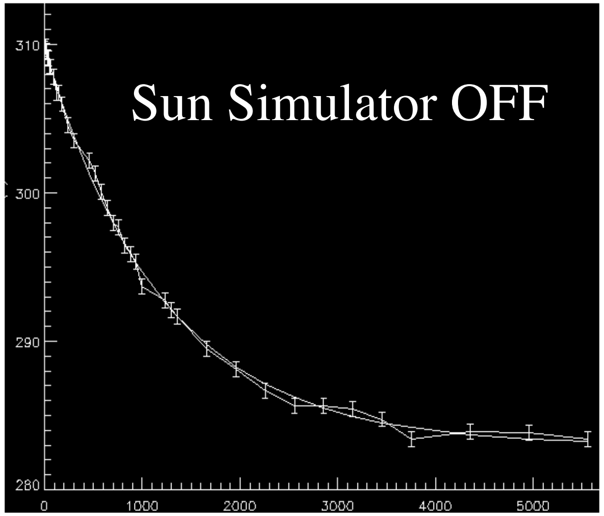
Laser return peaks reduced by factor 2, their distance increased to 2 Km



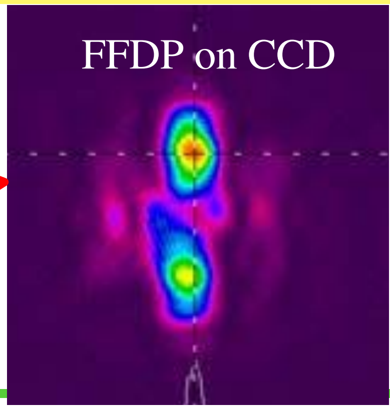


Factor ~7 reduction of FFDP





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



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

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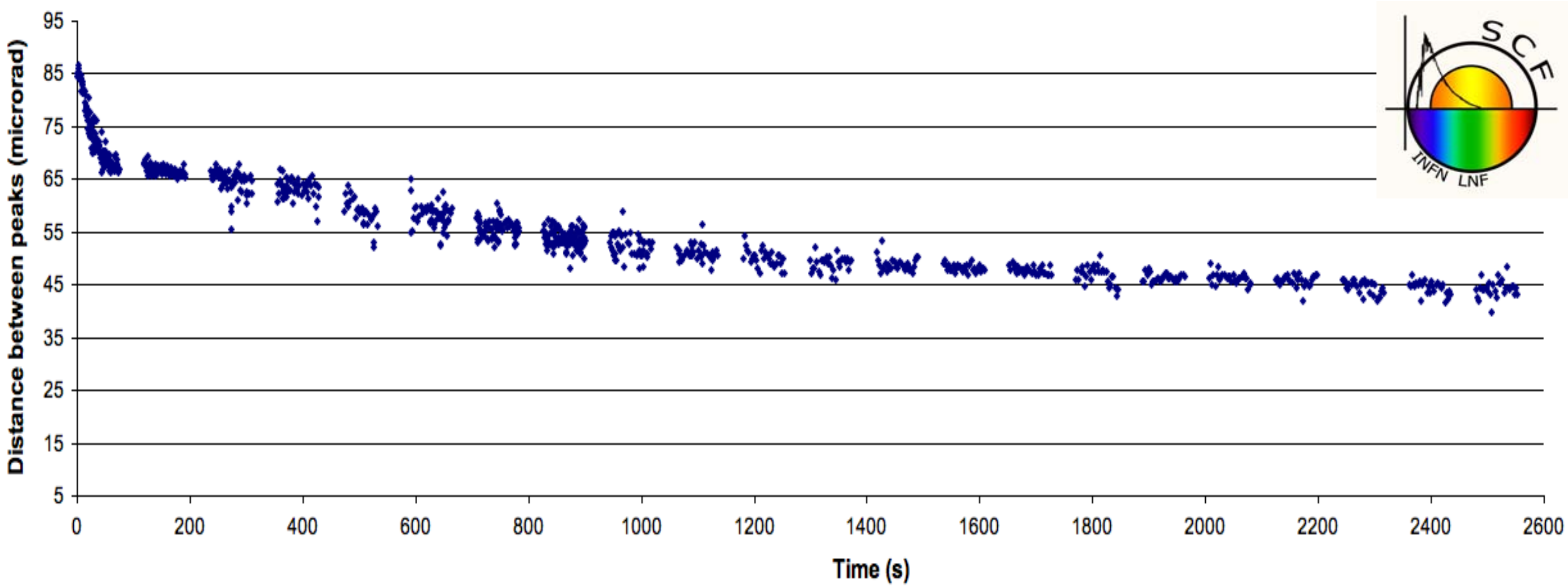
- slow radiative cooldown (CCR mounting: non-insulating)



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