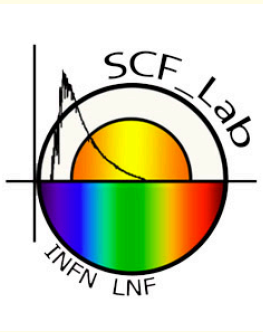
SCF_Lab

Satellite/Lunar/GNSS

laser ranging and altimetry

Characterization **F**acilities **Lab**oratory



SCF_Lab, 2nd part: Gravitational physics

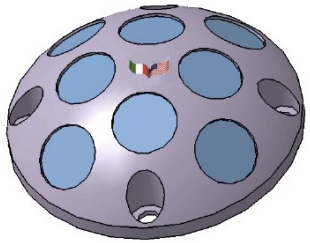
Testing Fundamental Gravity in the Solar System with Laser Ranging

Simone Dell'Agnello, Delle Monache G., Vittori R., Boni A., Cantone C., Ciocci E., Lops C., Martini M., Patrizi G., Tibuzzi M., Maiello M., Currie D., Bianco G. (ASI), March R. (CNR), Bellettini G. (U. Tor Vergata), Tauraso R. (U. Tor Vergata), Intaglietta N., Salvatori L., Contessa S., Porcelli L., Tuscano P., Stecchi A., Mondaini C.
INFN-LNF, Frascati (Rome), Italy

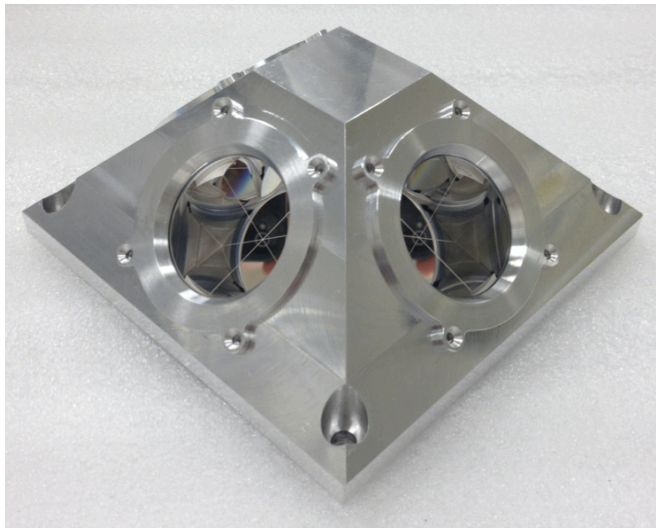
PLUS: Partnership with ASI-CGS, NASA-SSERVI, USA Universities, ILRS

MoonLIGHT, Apollo
100 mm, 38 mm

INRRI
12 mm



CORA
33 mm



SLR/LLR examples

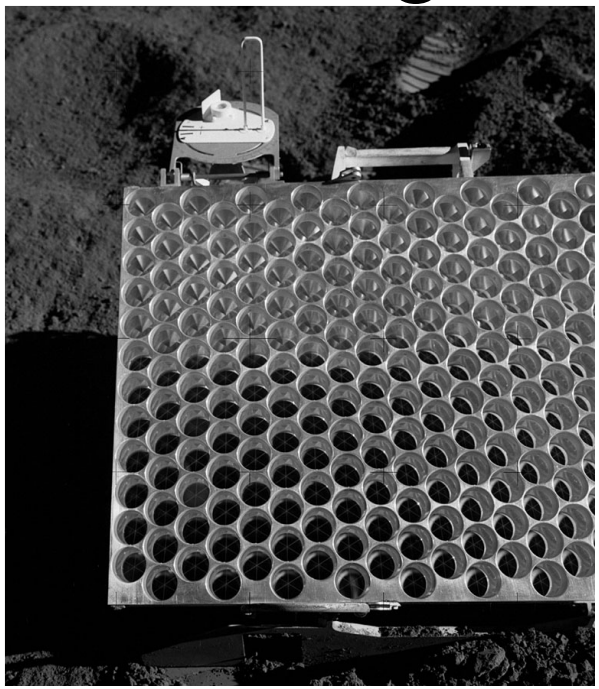
S

L

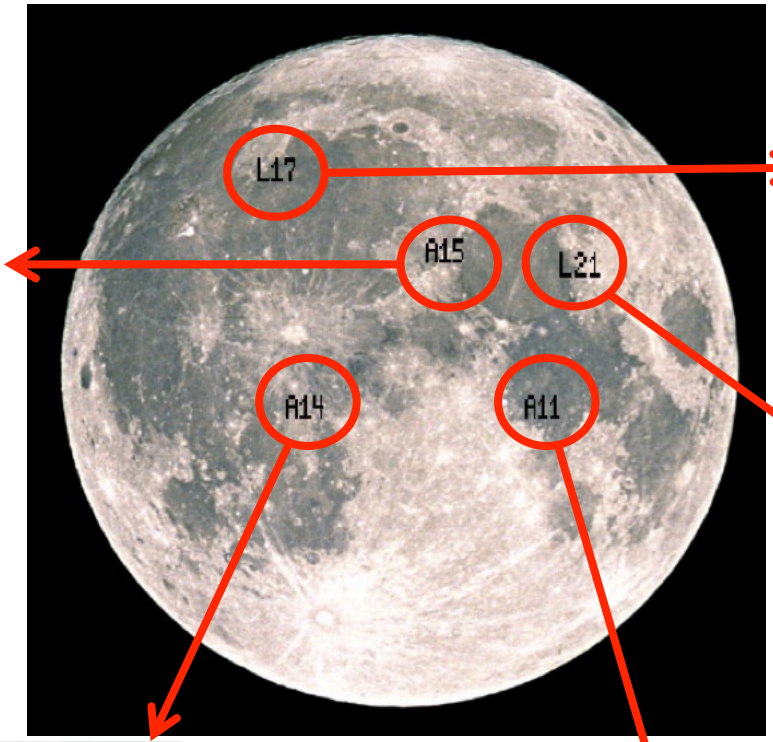
R

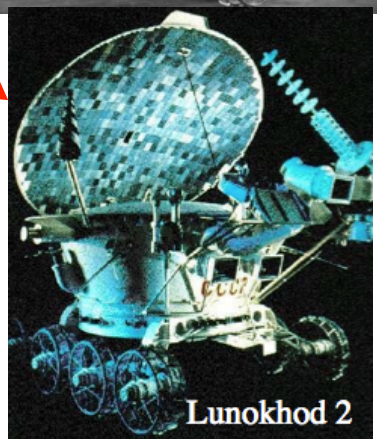
Moon (d ~ 380000 km): ToF ~ 2.5 sec
LAGEOS (h ~ 6000 km): ToF ~ 0.05 sec

1st generation of Lunar Reflector

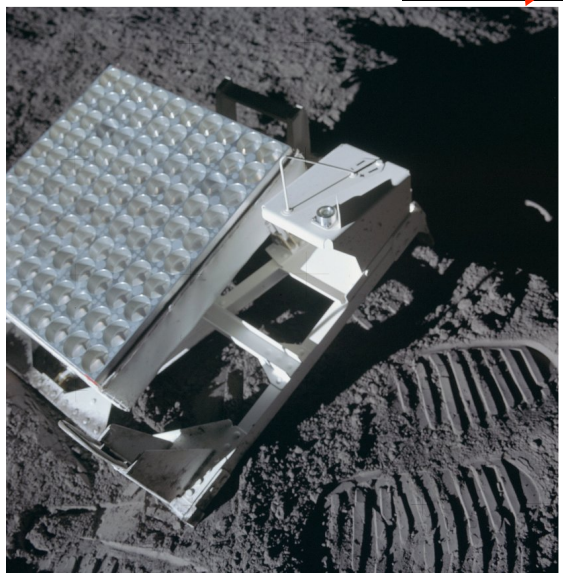


A15 300-element

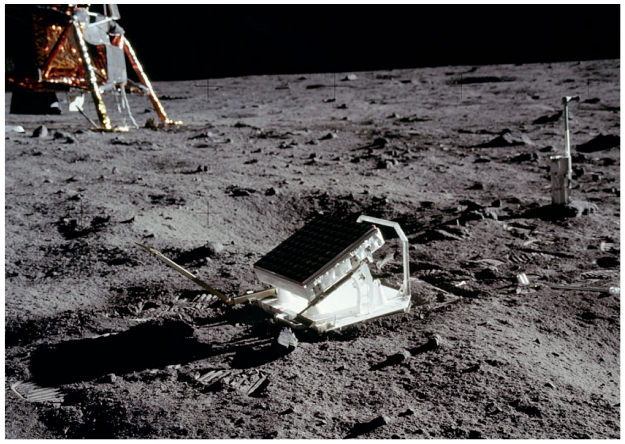




A14
100-element

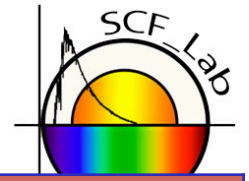


A11 100-element



2 French-built, Soviet-landed reflectors were placed on rovers:
Luna 17 (recently re-discovered!)
Luna 21

LLR tests of General Relativity



Science measurement / Precision test of violation of General Relativity	Time scale	Apollo/Lunokhod few cm accuracy*	MoonLIGHT 1 mm	MoonLIGHT 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	$\lvert\dot{G}/G\rvert<9\times10^{-13}\text{yr}^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	~10 years	$\lvert\alpha\rvert<3\times10^{-11}$	10^{-12}	10^{-13}
Geodetic Precession	Few years	$\lvert K_{gp}\rvert<6.4\times10^{-3}$	6.4×10^{-4}	6.4×10^{-5}

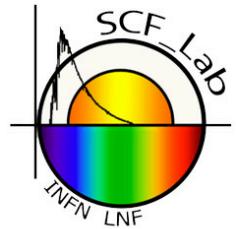
* J. G. Williams, S. G. Turyshev,and D. H. Boggs, PRL 93, 261101 (2004)

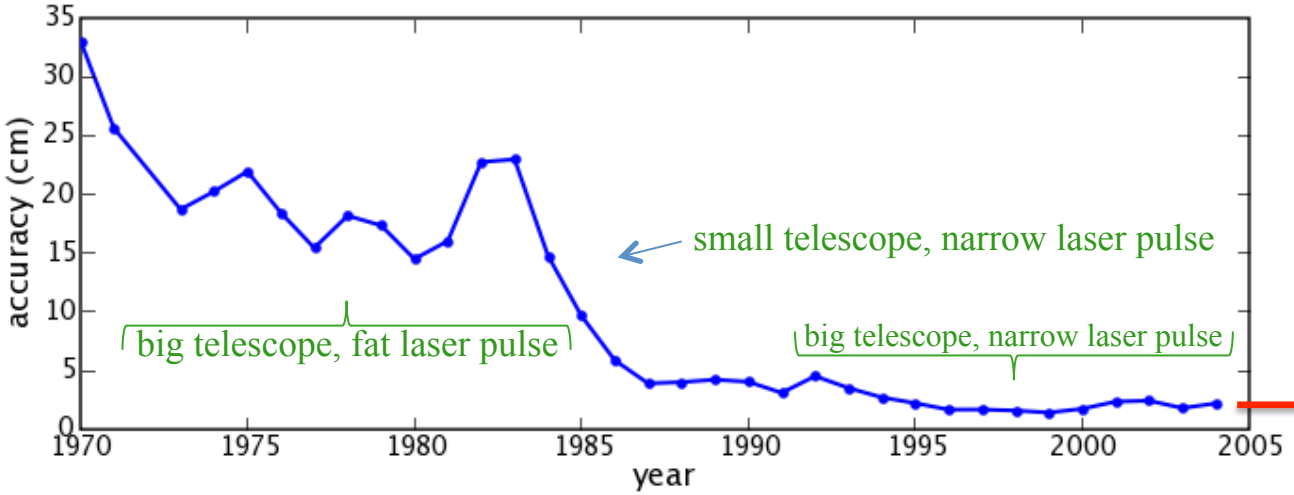
LNF measurement of the Geodetic Precession with Apollo/Lunokohd, including new APOLLO station, with Planetary Ephemeris Program (PEP) by CfA: **~1% accuracy**

Number of laser returns to make a "standard" ~2-cm LLR range:

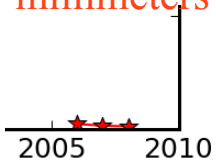
- **MoonLIGHT single, large reflector**: ~1
- Apollo/Lunokhod/Luna-Glob multi-reflector array: thousands

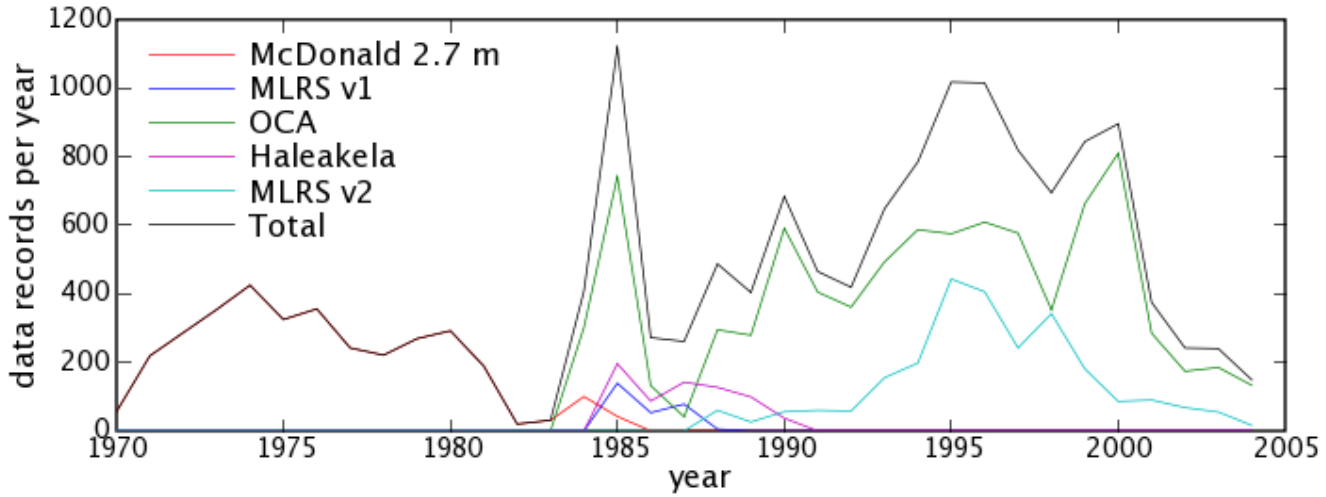
Historic LLR Range Precision

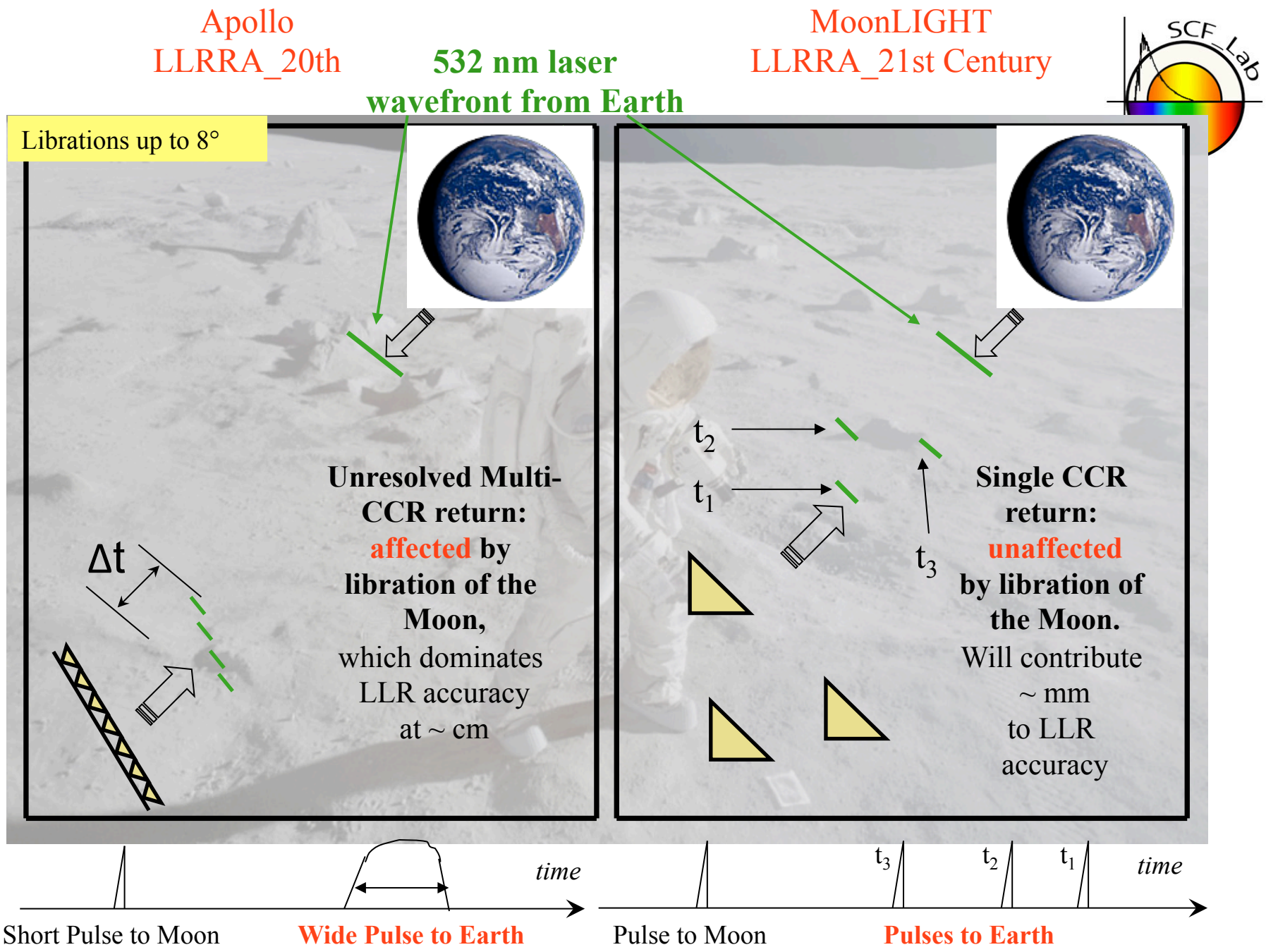




With APOLLO, "Apache Point Observatory Lunar Laser Operation", In New Mexico: few millimeters






Apollo
LLRRA_20th
532 nm laser
wavefront from Earth
MoonLIGHT
LLRRA_21st Century
SCF_Lab
Librations up to 8°
Δt
Unresolved Multi-CCR return: affected by libration of the Moon, which dominates LLR accuracy at ~ cm
t2
t1
t3
Single CCR return: unaffected by libration of the Moon. Will contribute ~ mm to LLR accuracy
time
Short Pulse to Moon
Wide Pulse to Earth
t3
t2
t1
time
Pulse to Moon
Pulses to Earth

Experiment of INFN National Scientific Committee 2 (CSN2) **MoonLIGHT** ended and its continuation for **2013-2018**:

MoonLIGHT-2

Moon Laser Instrumentation for General relativity High accuracy Tests – Phase 2

MoonLIGHT, Apollo

100 mm, 38 mm

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

SCF_Lab

Satellite/Lunar/GNSS

laser ranging and altimetry

Characterization **F**acilities **Lab**oratory

SCF_Lab
INFN LNF

SCF-Test: thermal-optical-vacuum measurements

SCF-Test concept: reproduce the passage of a satellite equipped with an LRA, into the Earth shadow and sun illumination.

Exposure of CCR/LRA:

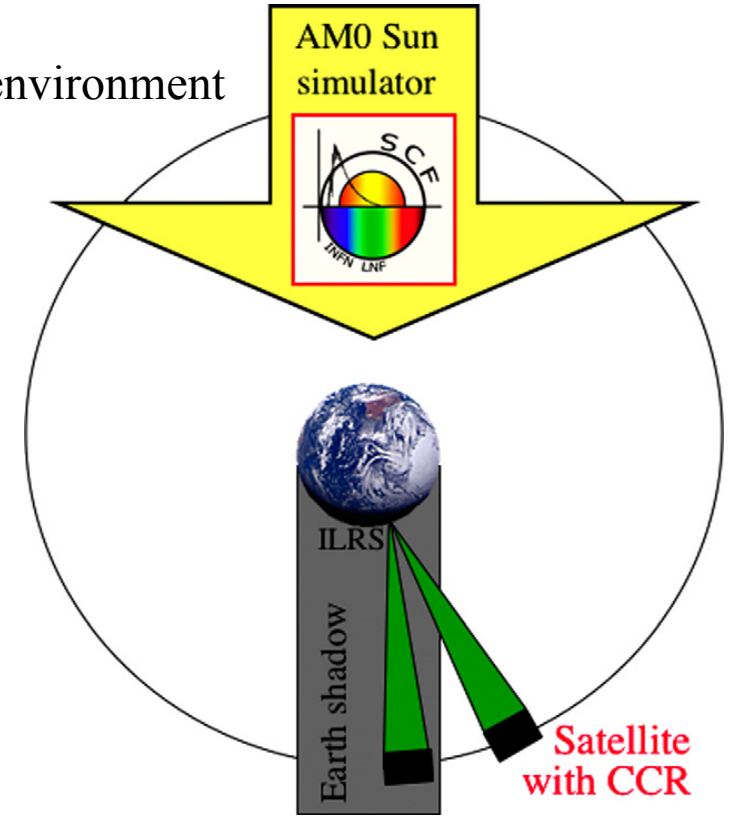
- Low temperature (77K) and vacuum (10^{-6} mbar) of the environment

- Hold the average temperature, T_{AVG}, of the CCR/LRA
→ reached stationary state, FFDP taken

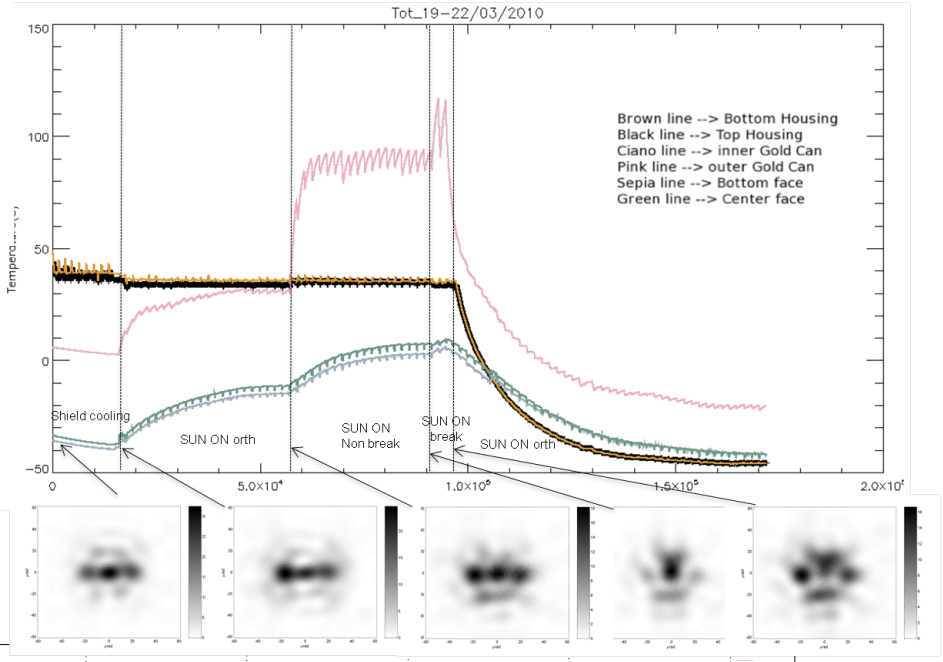
- Sun Simulator (SS) illumination → thermogram taken

- Cool down → FFDP acquired

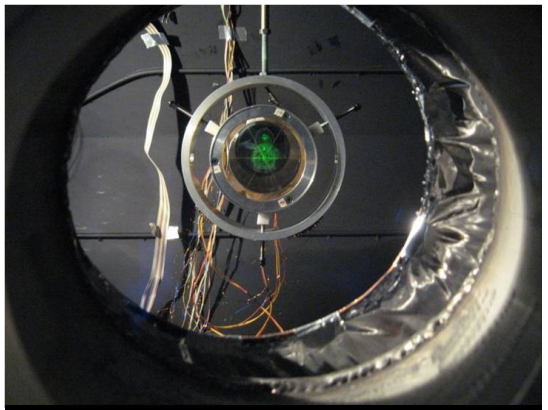
- Repeat the above measurement for different:
  - Temperature: $T \neq T_{AVG}$
  - SS illumination angles



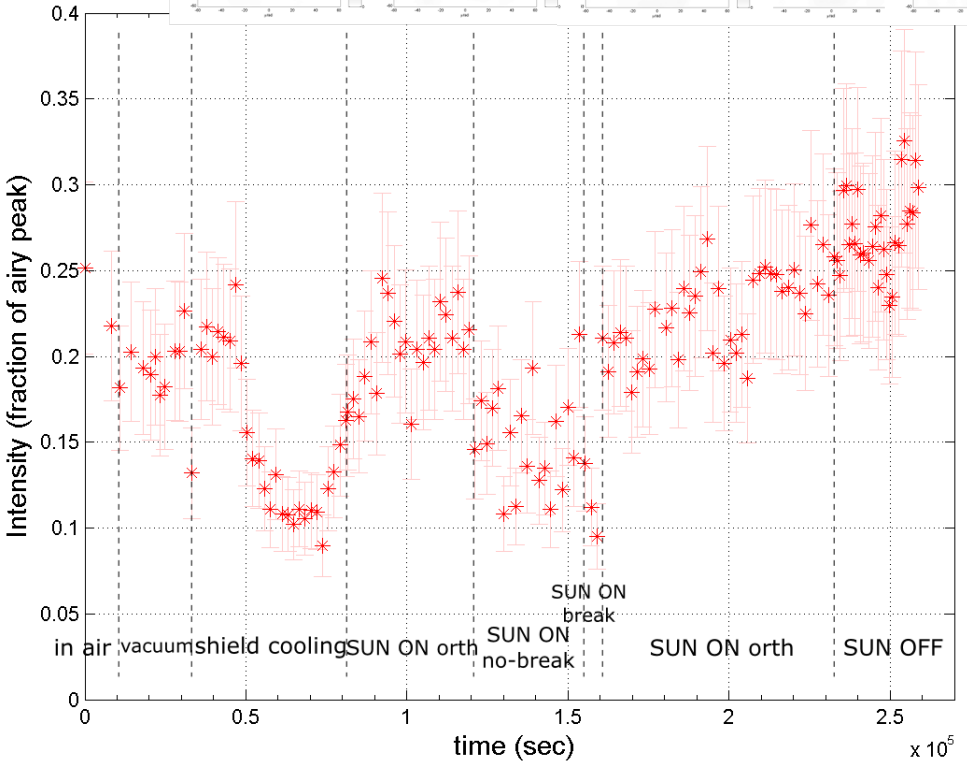
1st SCF-Test of MoonLIGHT



temperature variations of various housing parts and of CCR

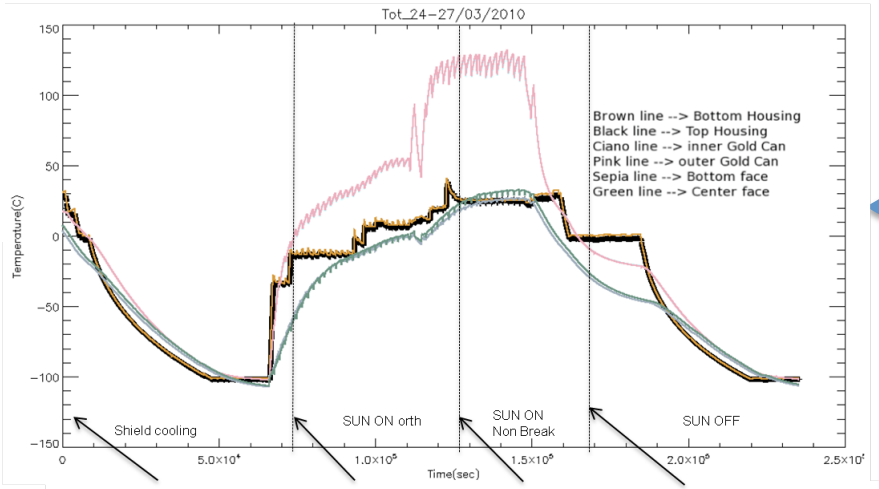


MoonLIGHT inside SCF

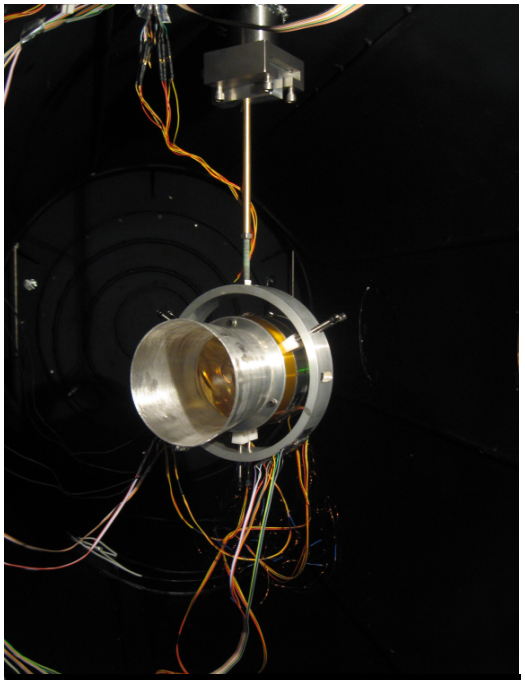


average FFDP intensity variation at Moon velocity aberration. Error on intensity is ± 20% relative.

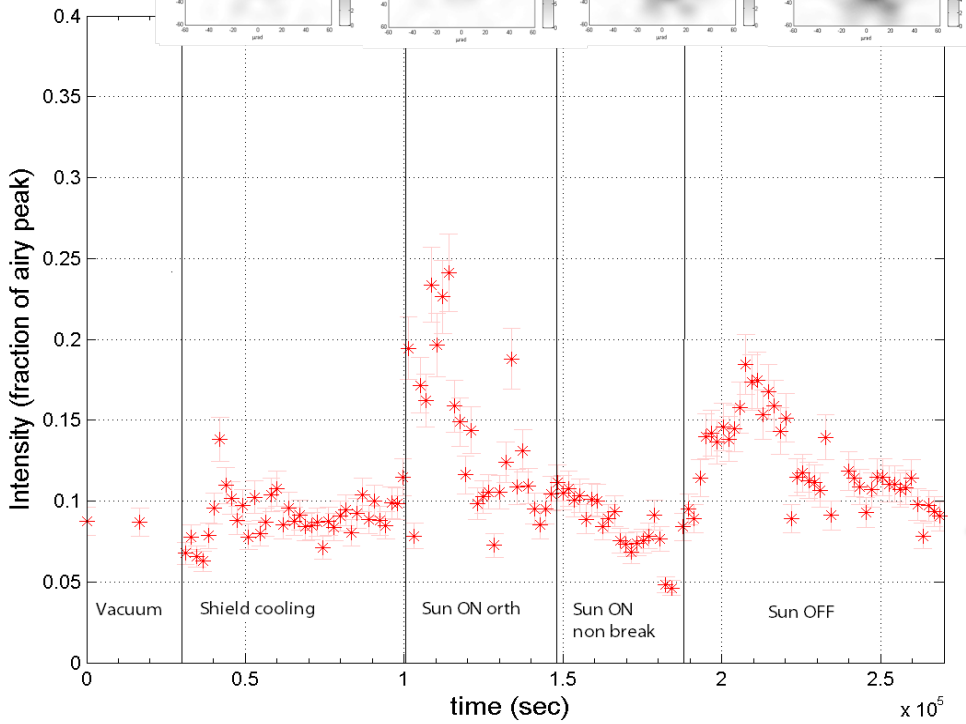
2nd SCF-Test of MoonLIGHT



temperature variations of various housing parts and of CCR

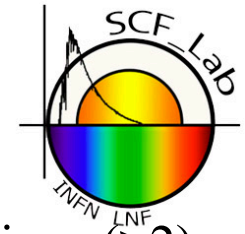


MoonLIGHT with sun shade



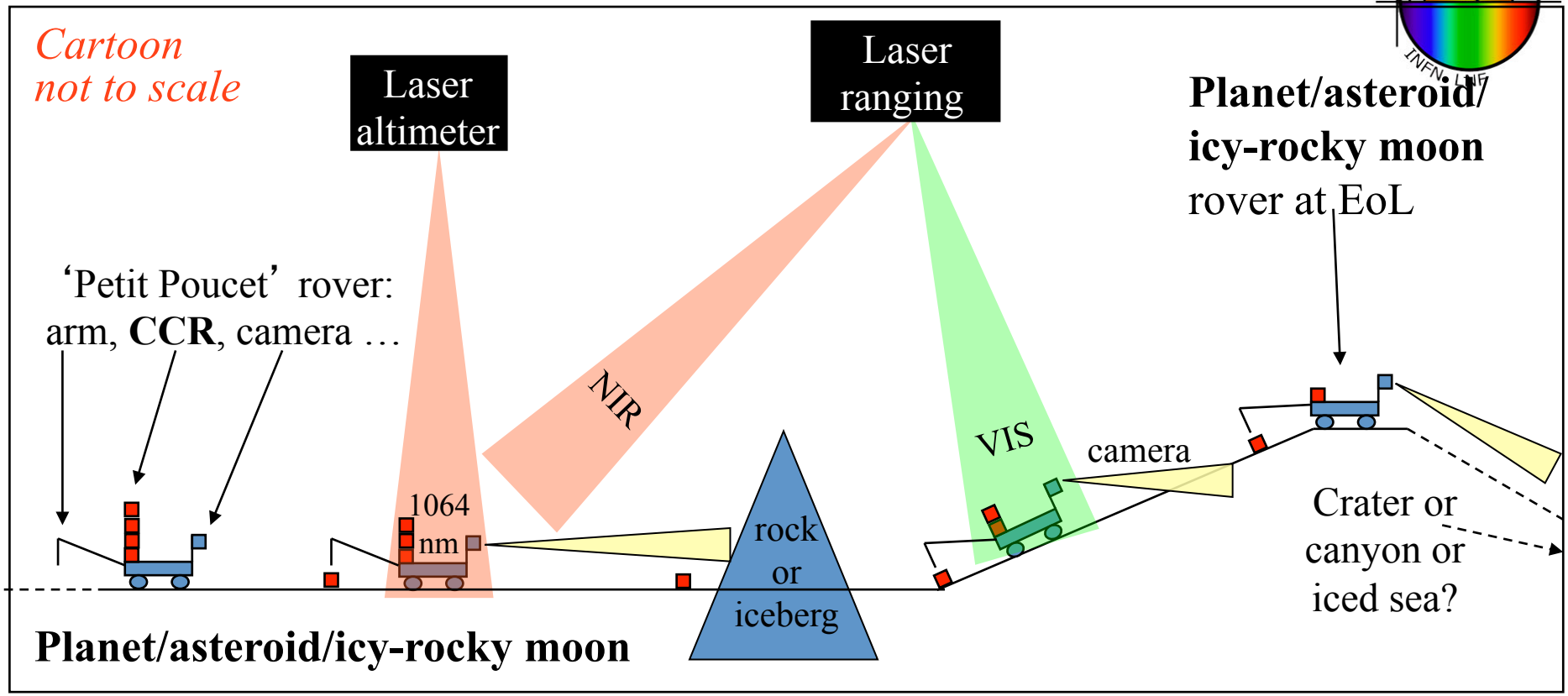
average FFDP intensity variation at Moon velocity aberration.
Error on intensity is ± 20% relative.

Moon & Mars



- Lunar Laser Ranging (Sun-Earth-Moon gravity)
  - Existing reflectors (5 **Apollo/Lunokhod**), existing (4) & **new** stations (>2)
  - New big reflector by INFN/Maryland, **MoonLIGHT**. Improved tests of General Relativity and New Gravity theories up to x100
  - New solar system small reflector by INFN, **INRRI** (**IN**strument for landing-**R**oving laser ranging/altimetry **R**etroreflector **I**nvestigations). Ranged by orbiters
  - Approved missions: Luna-27 (Rosc.-ESA), Astrobotic, Moon Express
  - Proposed: SELENE-2 (Jaxa), Chang'e 4+ (CSA), LGN (NASA)
- Mars/Phobos/Deimos Laser Ranging (Sun-Mars-Jupiter)
  - **INRRI** and medium-size reflector, **CORA** (COsmo Retroreflector Array), by INFN & Ministry of Defense
  - Approved missions: Mars 2020 (NASA), ExoMars 2018 (ESA-Roscosmos)
  - Proposed: GETEMME (ESA, DLR, …), gravity mission on Phobos/Deimos
- Data laser-communications, esp. for Mars exploration, will be great opportunity for laser ranging experiments

INRRIs at: Moon; Mars, Jupiter/Saturn moons



- Selenolocate rover activity from orbiters thanks to CCR (reflector):
  - Laser altimetry at nadir (LRO-like) to rovers at poles of moons
  - Laser ranging with pointing capability to CCRs anywhere (GETEMME-like)
- **Deploy CCR networks**! Also on far side of Earth's Moon

SCF_Lab

Satellite/Lunar/GNSS laser ranging and altimetry Characterization Facilities Laboratory