Satellite and Lunar Laser Ranging: fundamental physics and applications

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Outline

- **Introduction**
  - Missions Apollo (USA) / Luna (USSR)
  - Satellites LAGEOS (USA-Italy)
- **Space Geodesy, Geodinamics**
- **Investigations of General Relativity. And beyond**
- ***Global Navigation Satellite System* (GNSS)**
  - GPS, GLONASS, Galileo, IRNSS, ...
- **Next frontier**

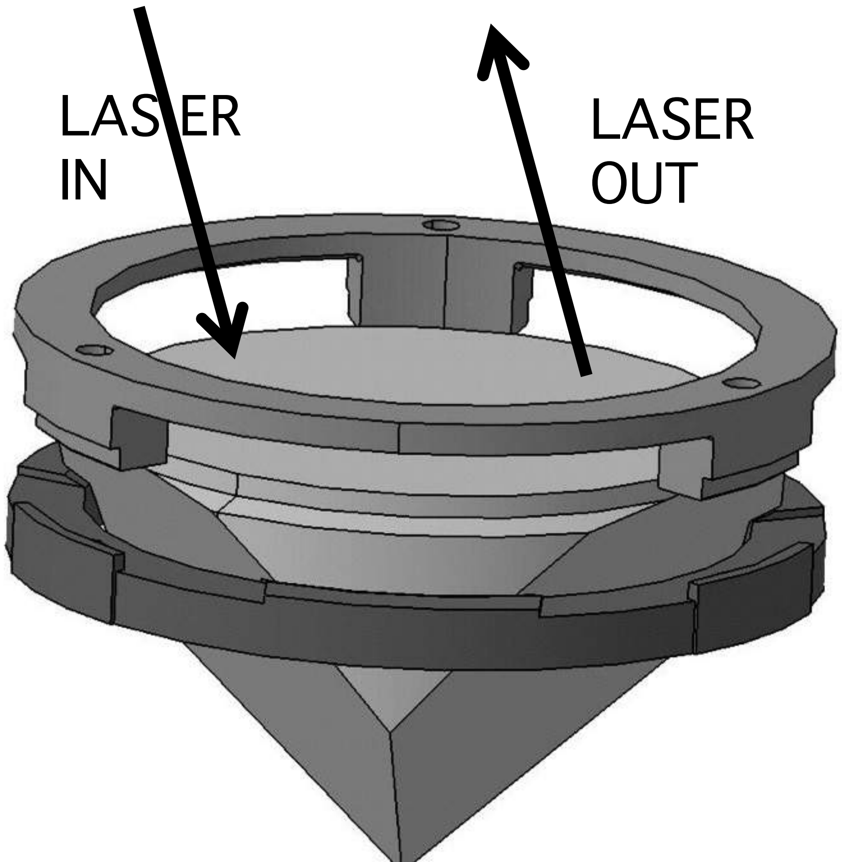
Laser Retroreflectors

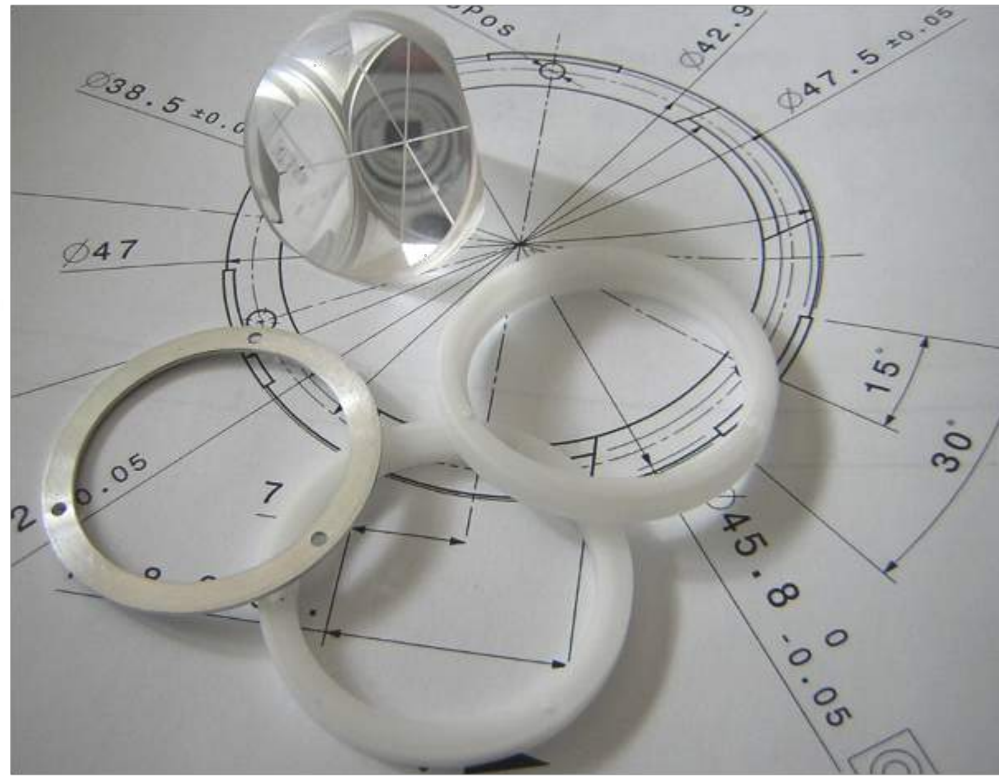
“Prisms for ground surveys”, mounted inside spheres

Taylor-Hobson sphere for angular measurements

Apollo retroreflectors, on the Moon since 1969

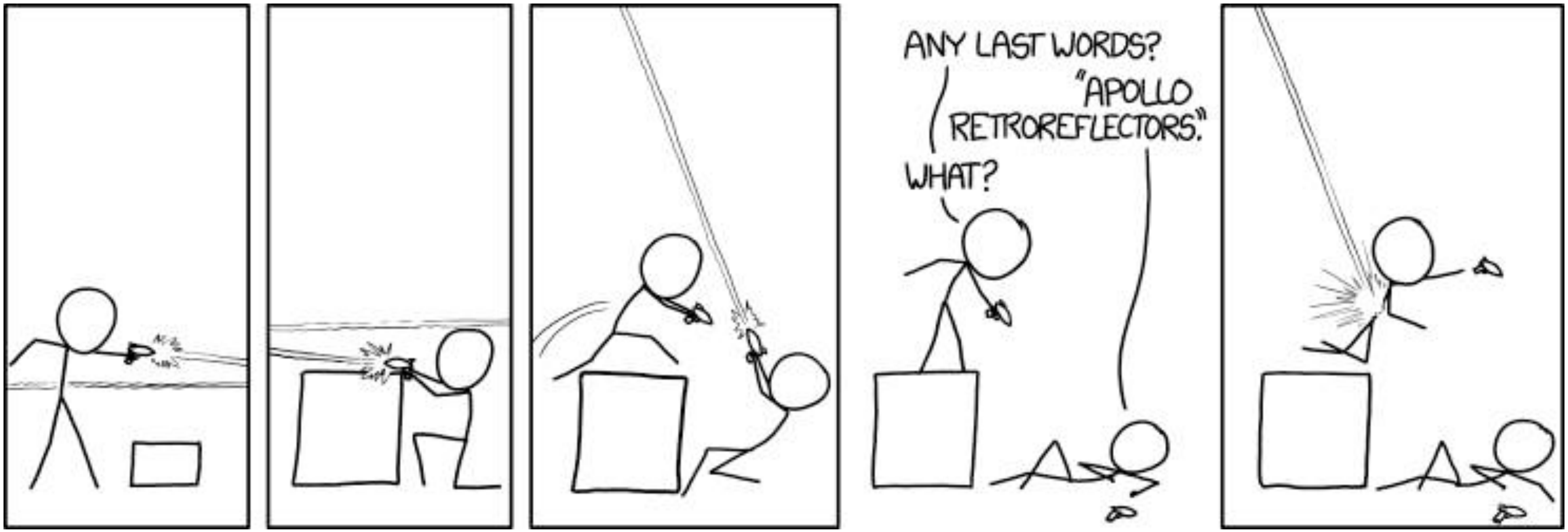
Trick: cube "corners". The triple TIR on back determines an overall retro-reflector IN-OUT



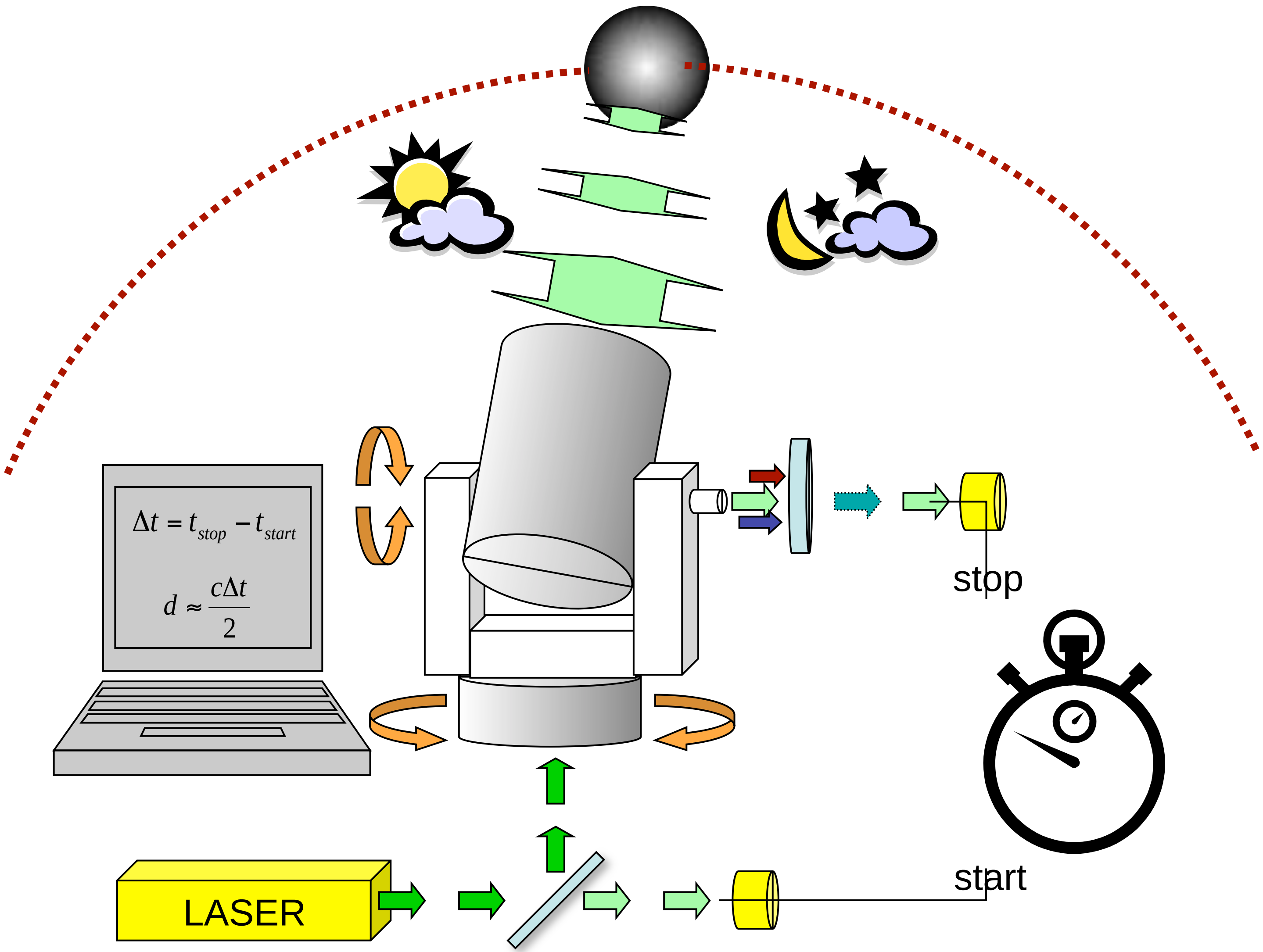


Triple reflection around the corner

Retroreflectors and *lunar laser ranging*

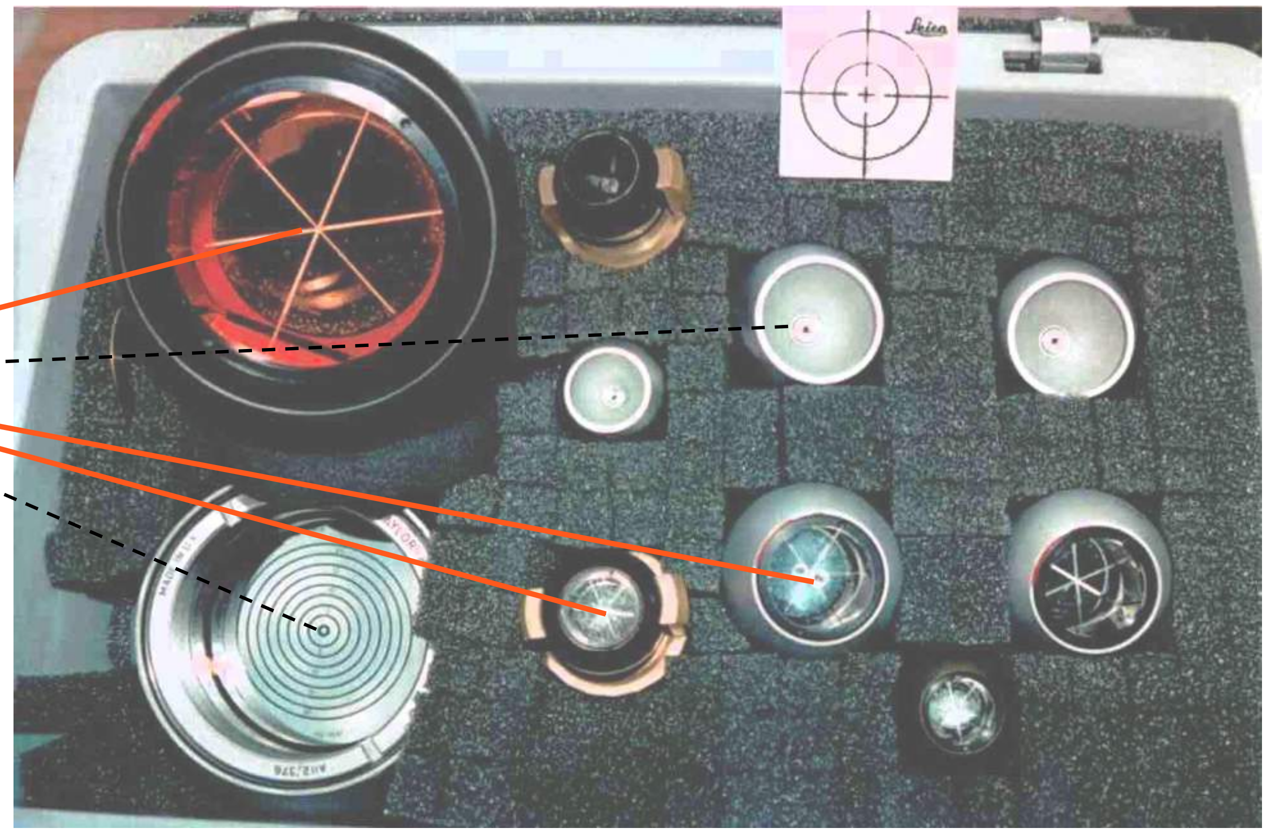


In space: laser pulse, satellite with retroreflectors, receiving telescope/ detector, atomic clock, round trip time of flight (ToF)



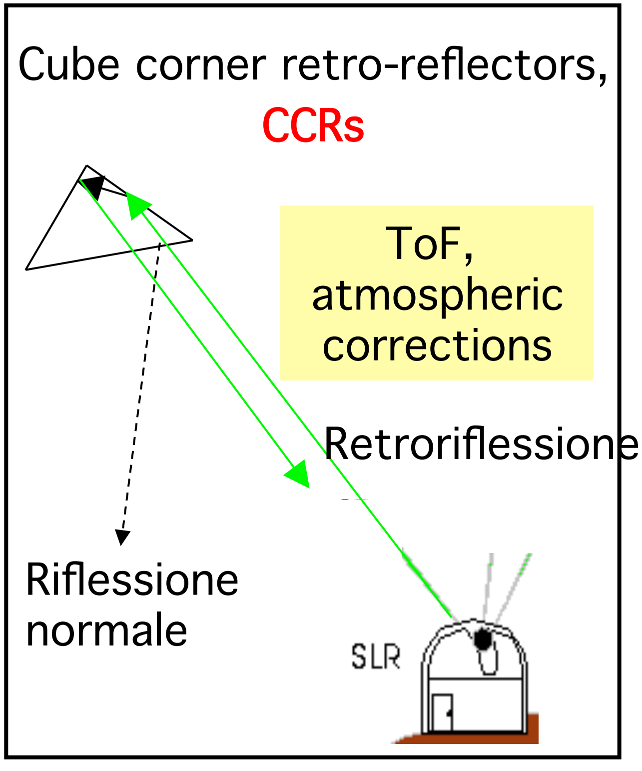
On ground: theodolite (or laser “tracker”), retroreflectors; ToF of laser pulses

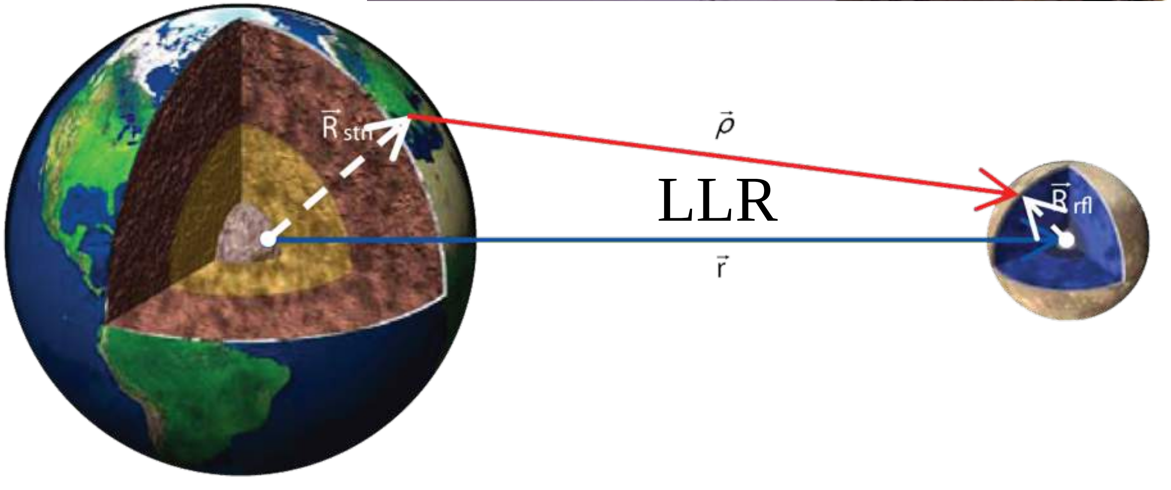
$$d \approx \frac{c\Delta t}{2}$$



Used for positioning metrology of KLOE at DAΦNE,
Here at INFN-LNF

Lunar Laser Ranging (LLR)
Satellite Laser Ranging (SLR)
ToF measurements





Most accurate space positioning. AND. Absolute (next slides)

(mm to cm) .AND. (100K€ to M€)

Laser interferometry more precise but much more expensive and complex/difficult

Principle

- Ground station send laser pulses to satellite
- Telescopio next to laser measures retroreflected pulses
- LAGEOS satellite spherical satellite, a point-like mass: metal => massa, CCRs => laser “traceability”

S

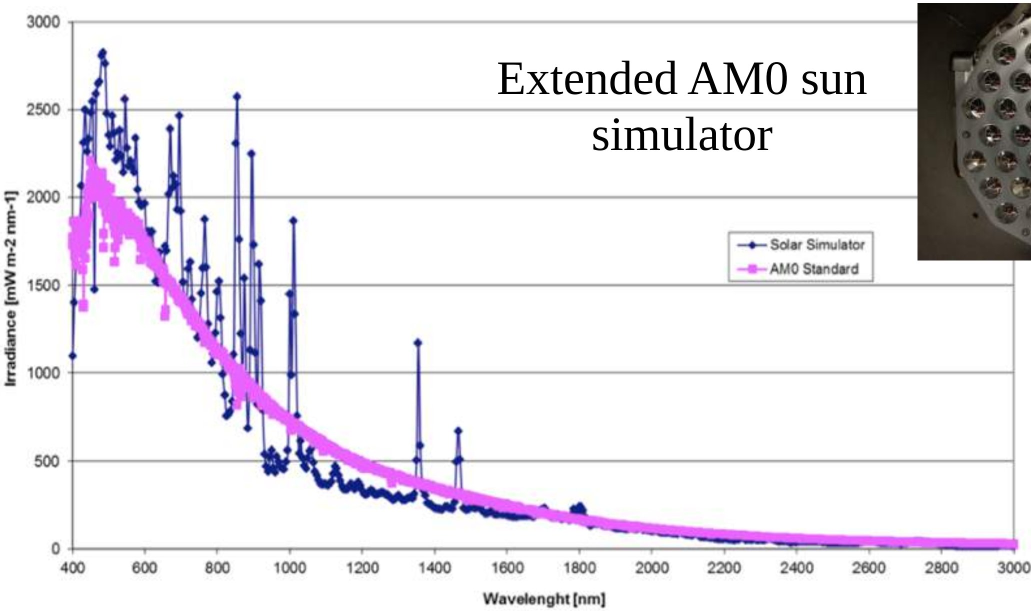
L

R

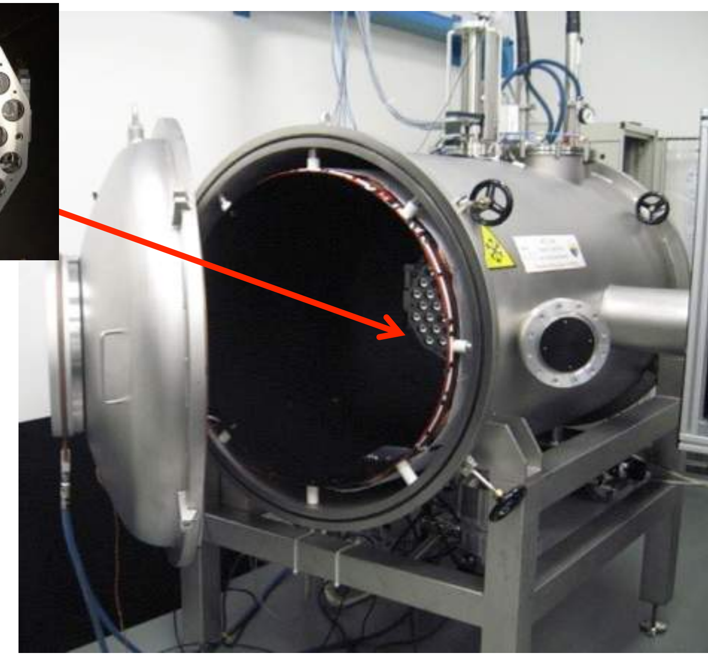
Lunar laser ranging (LLR)

ASI-INFN *Joint Lab* on *laser retroreflectors & ranging*

- **SCF_Lab** @ INFN-Frascati
  - Unique characterization of CCR performance
- **MLRO** @ ASI-CGS, Matera Laser Ranging Observatory
  - SLR/LLR
  - Space Geodesy Center

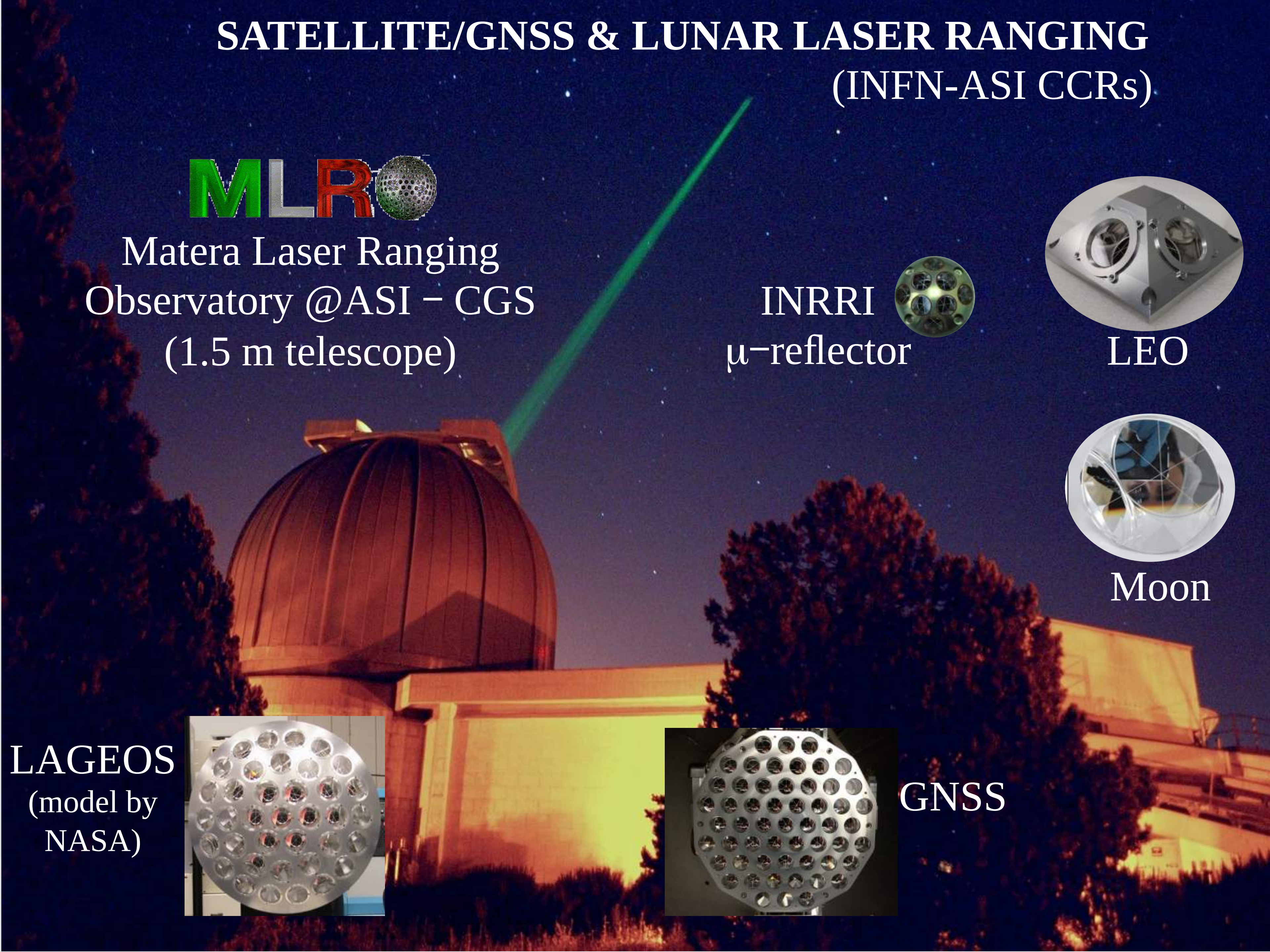


Extended AM0 sun simulator



www.lnf.infn.it/esperimenti/etrusco/

SATELLITE/GNSS & LUNAR LASER RANGING
(INFN-ASI CCRs)



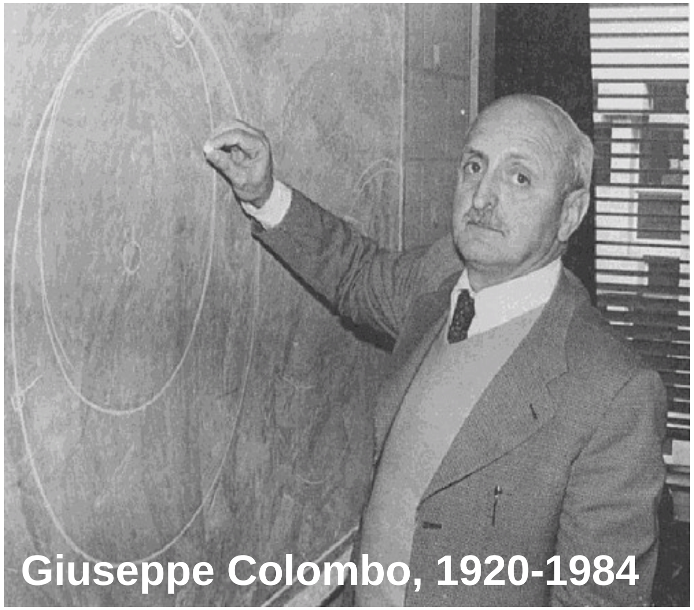
Centro di Geodesia Spaziale *Giuseppe Colombo*
Matera, Italy
Un sito la cui posizione è misurata col laser, radio e navigazione satellitare

Direttore: Dr. Giuseppe Bianco

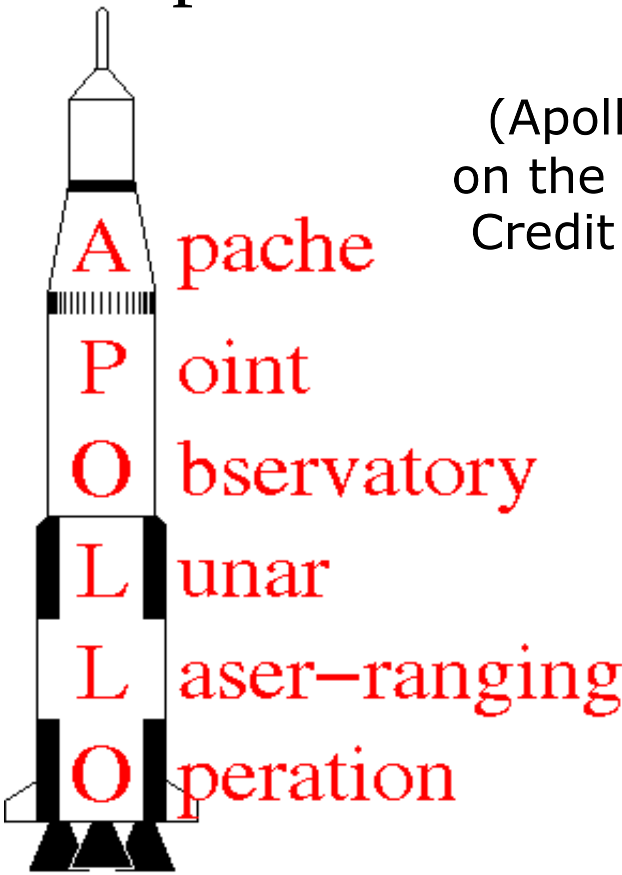
MLRO,
Matera Laser Ranging Observatory
Ha fatto il primo LLR il 25 Marzo 2010

MLRO

agenzia spaziale italiana


Giuseppe Colombo, 1920-1984

mm precision / orbit segment (normal point)



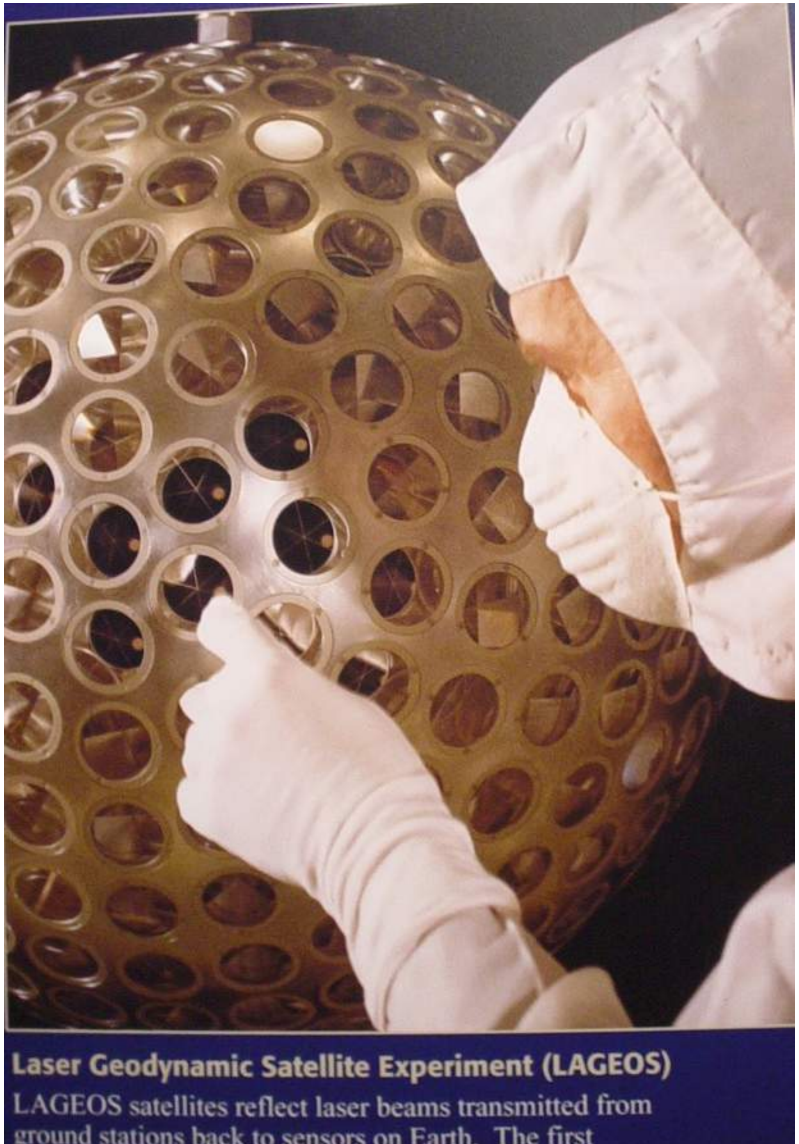
New Mexico, USA
(Apollo) Laser beams are sent to reflectors on the moon from a telescope in New Mexico.
Credit: Dan Long, Apache Point Observatory

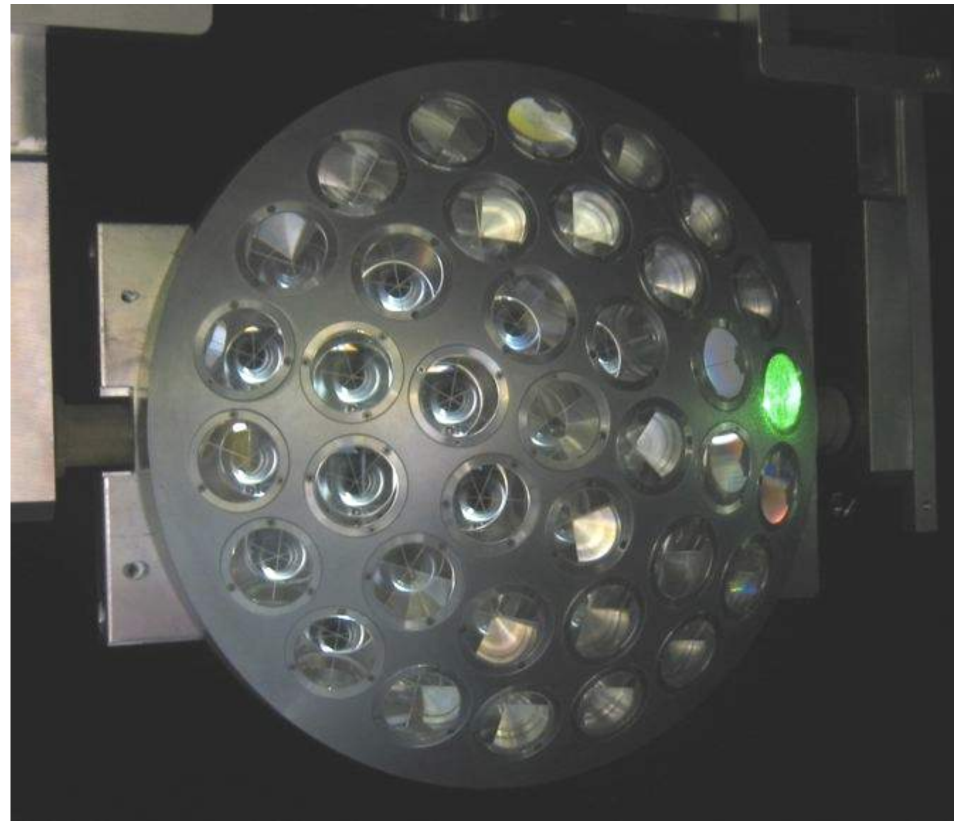
Leader: Tom Murphy,
Univ. of California at San Diego

3 stations in France, OCA-CERGA, Obs. du Calern

Laser Geodynamics Satellites (LAGEOS)

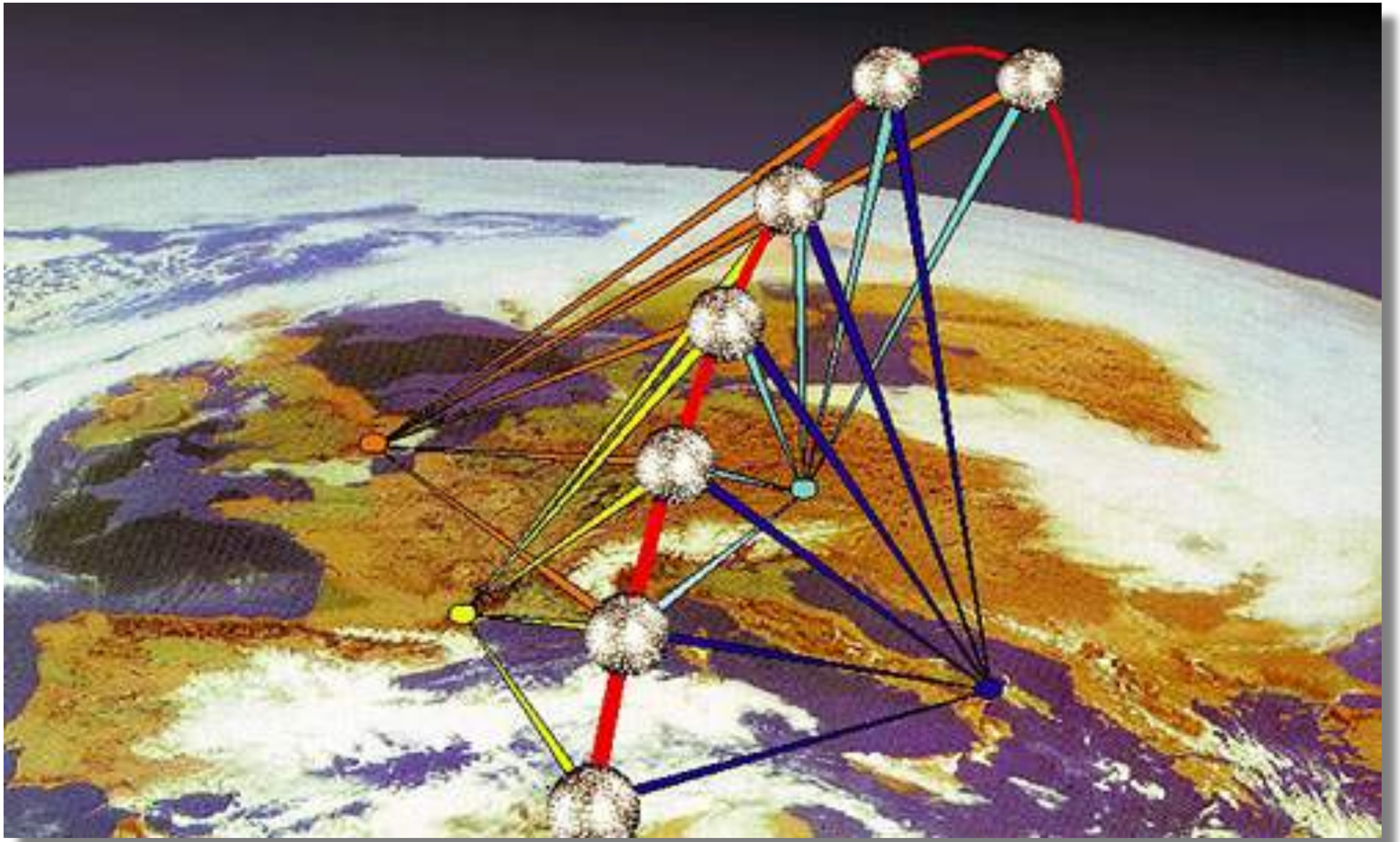
LAGEOS I (1976; NASA), LAGEOS II (1992; NASA/ASI)



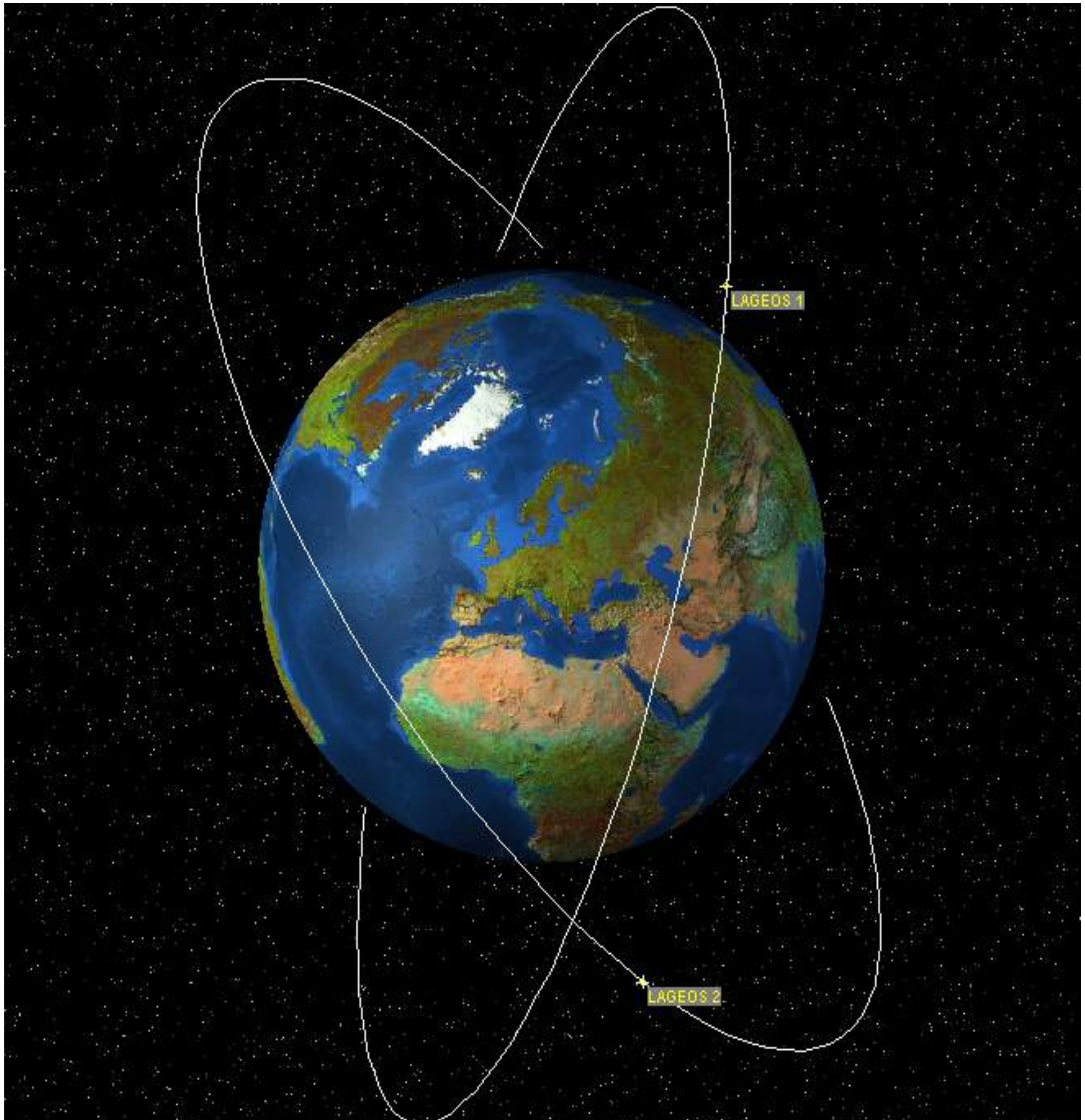


LAGEOS “Sector”, EM of NASA-GSFC, at LNF for space tests

LAGEOS tracked by stations at Matera (IT), Herstmonceux (UK), Graz (AT), OCR (FR)



Lunga vita ai LAGEOS (~1 Milione di anni)



International Terrestrial Reference System (ITRS) Cartesian frame:

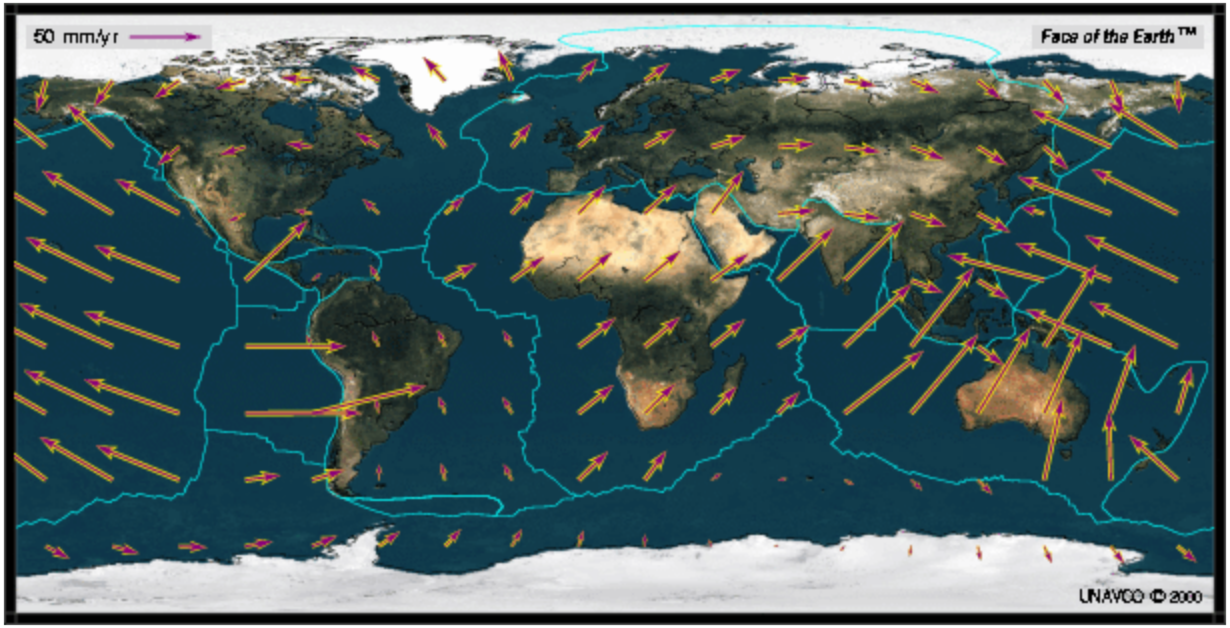
- **Origin = Geocenter** = centro of mass of the Earth = focii of LAGEOS orbits
- **Meter, or scale of length = semi-axis of** LAGEOS orbit
- **Angles**, or orientation of axes = radio-measurement of quasars (“fixed stars”)
- **Cartesian coordinates of laser stations**
- Distribution of the frame: GPS, Galileo ...

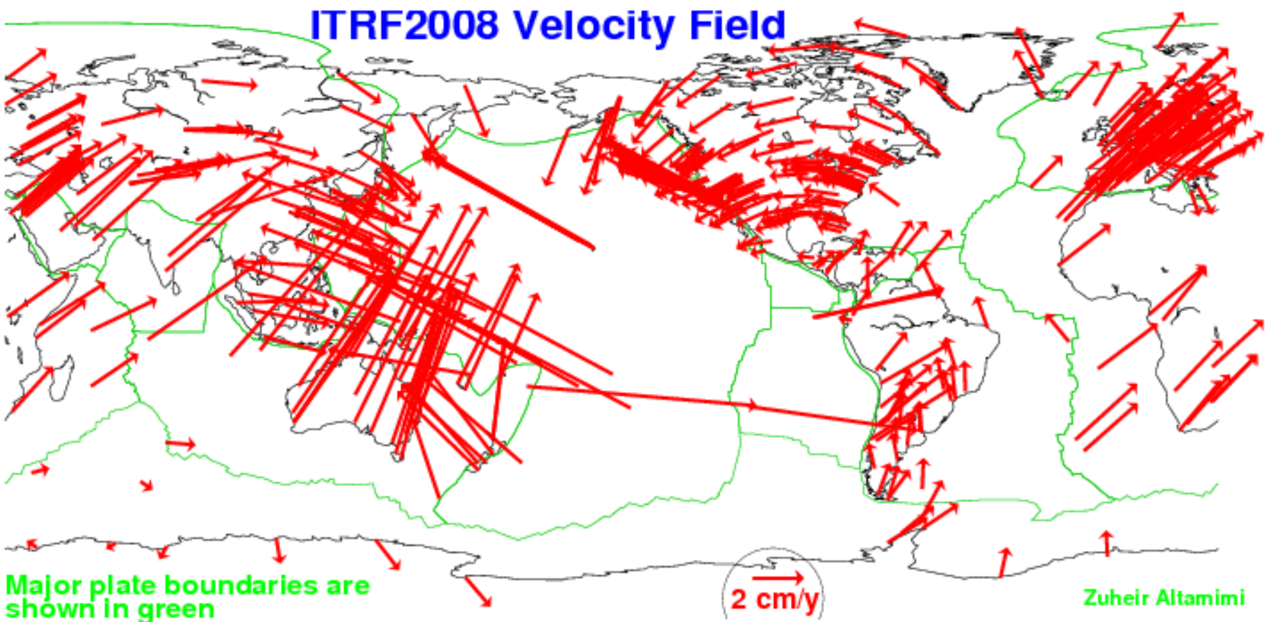
ILRS = SLR/geodesy international Service

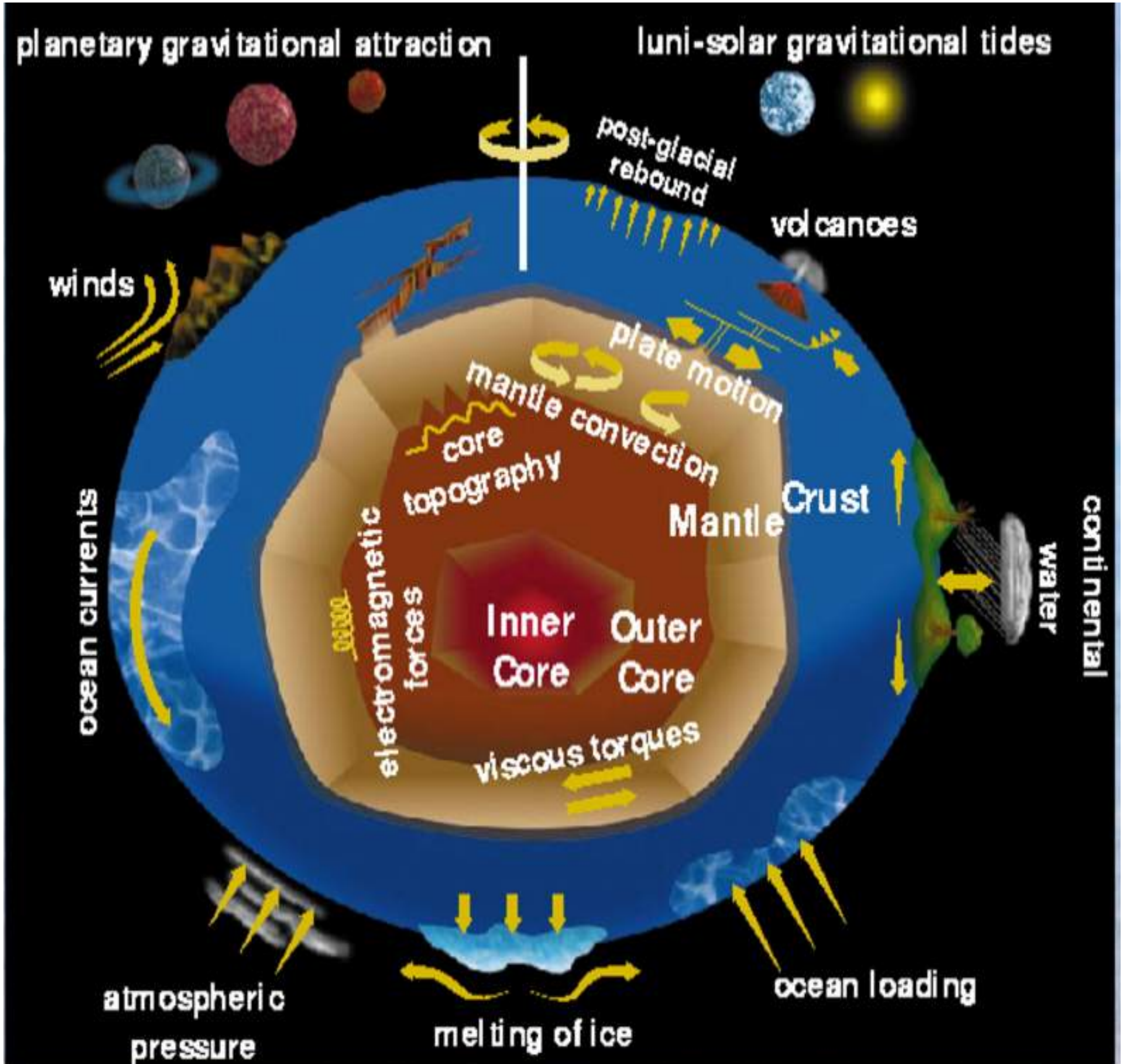
LAGEOS

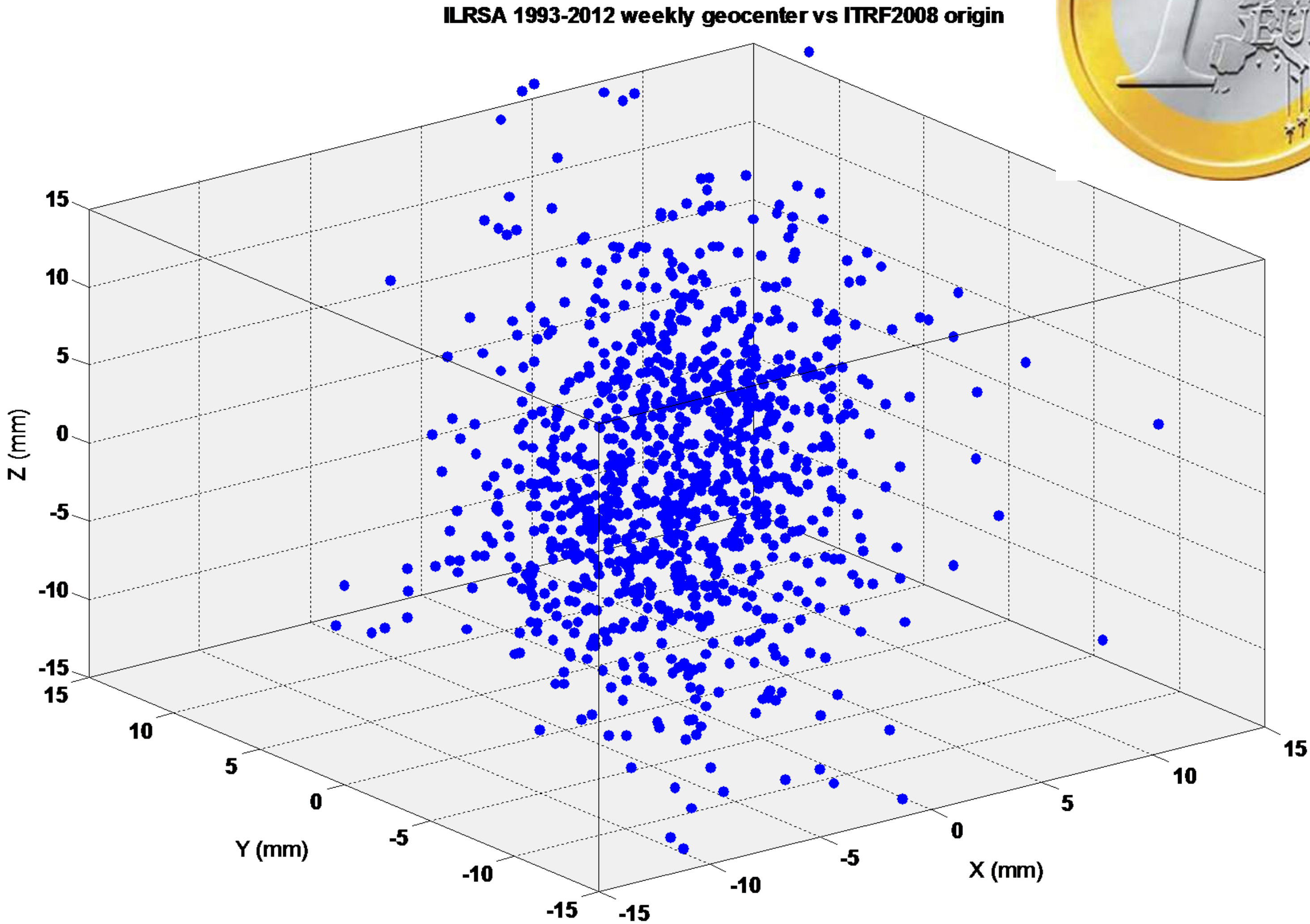
International Laser Ranging Service

Geodinamics
Plate tectonics


50 mm/yr
Face of the Earth™
UNAVCO © 2000

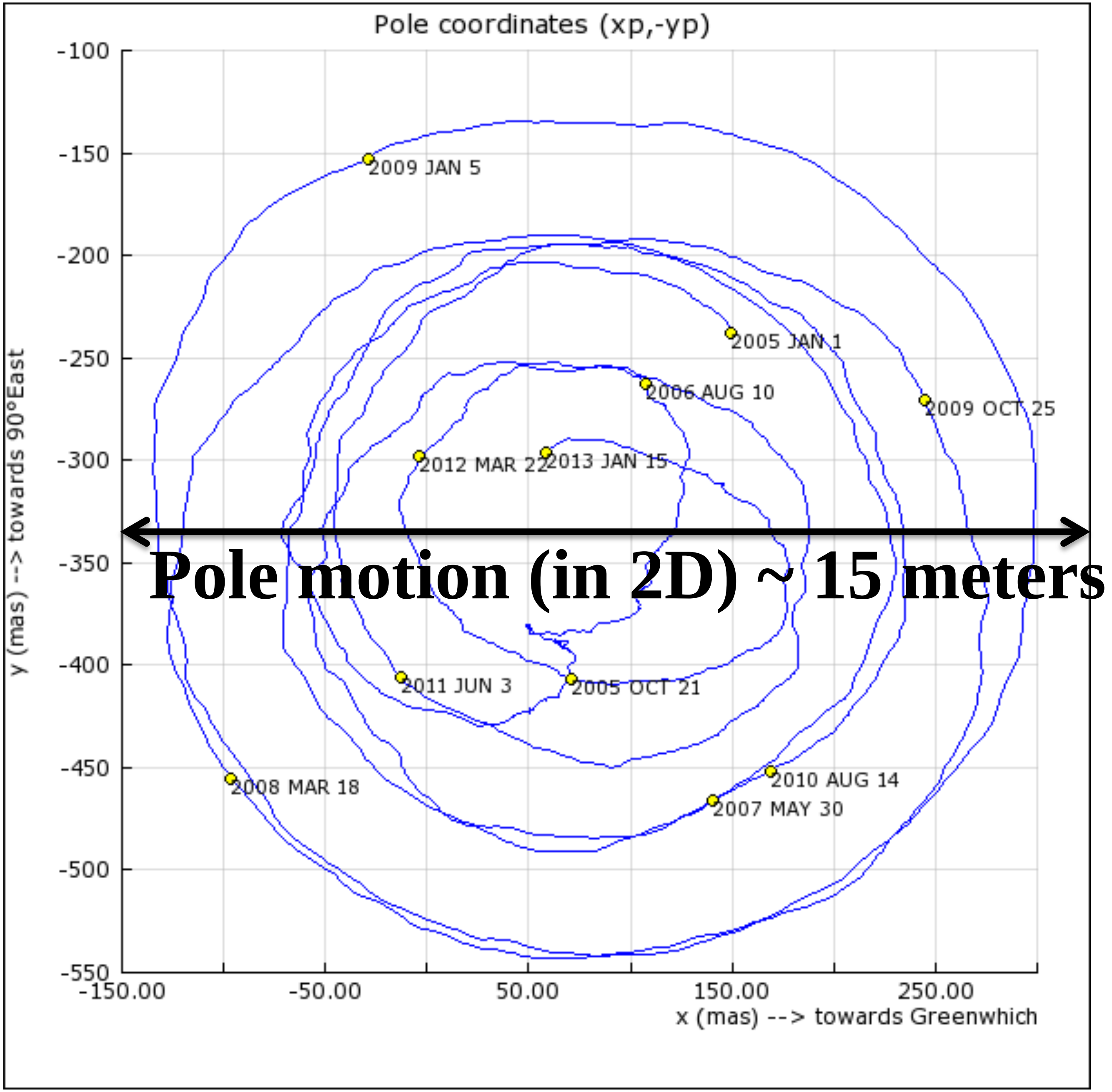

ITRF2008 Velocity Field
Major plate boundaries are shown in green
2 cm/y
Zuheir Altamimi


planetary gravitational attraction
luni-solar gravitational tides
post-glacial rebound
volcanoes
winds
plate motion
mantle convection
core topography
Crust
Mantle
continental water
ocean currents
electromagnetic forces
Inner Core
Outer Core
viscous torques
atmospheric pressure
melting of ice
ocean loading

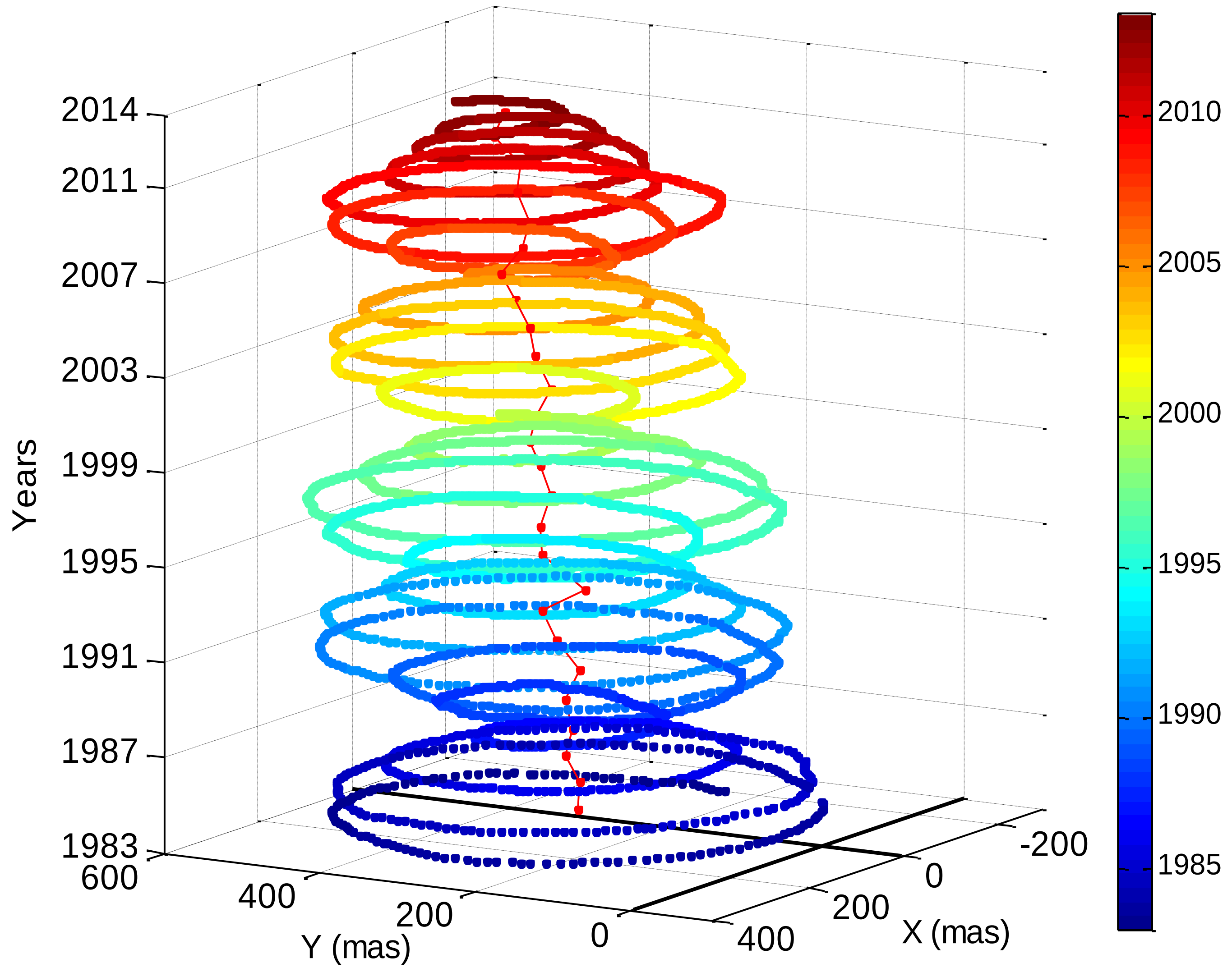


ILRSA 1993-2012 weekly geocenter vs ITRF2008 origin
Z (mm)
15
10
5
0
-5
-10
-15
Y (mm)
15
10
5
0
-5
-10
-15
X (mm)
-15
-10
-5
0
5
10
15

1
EURO


Pole coordinates (xp,-yp)
-100
-150
-200
-250
-300
-350
-400
-450
-500
-550
y (mas) --> towards 90°East
-150.00
-50.00
50.00
150.00
250.00
x (mas) --> towards Greenwhich
2009 JAN 5
2005 JAN 1
2006 AUG 10
2009 OCT 25
2012 MAR 22
2013 JAN 15
2011 JUN 3
2005 OCT 21
2008 MAR 18
2010 AUG 14
2007 MAY 30
Pole motion (in 2D) ~ 15 meters

Pole motion in 3D (tens of meters)

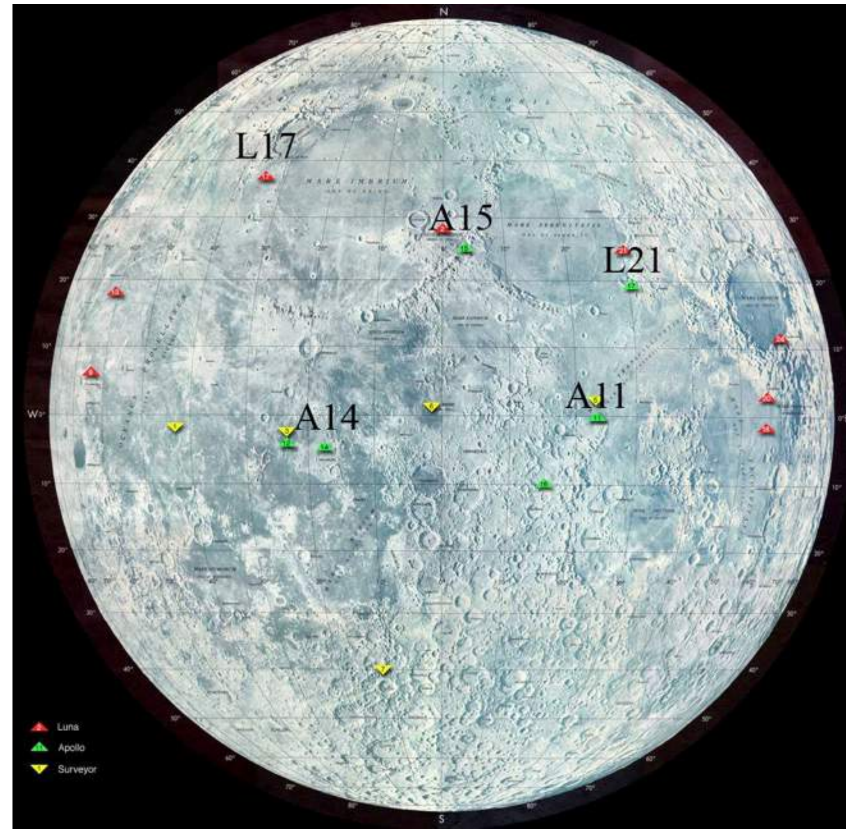


ASI/CGS

All started with LLR

- R. H. Dicke et: precision tracking of satelliti using conventional light pulses to test gravity in the 50s
- Laser invented ~1960

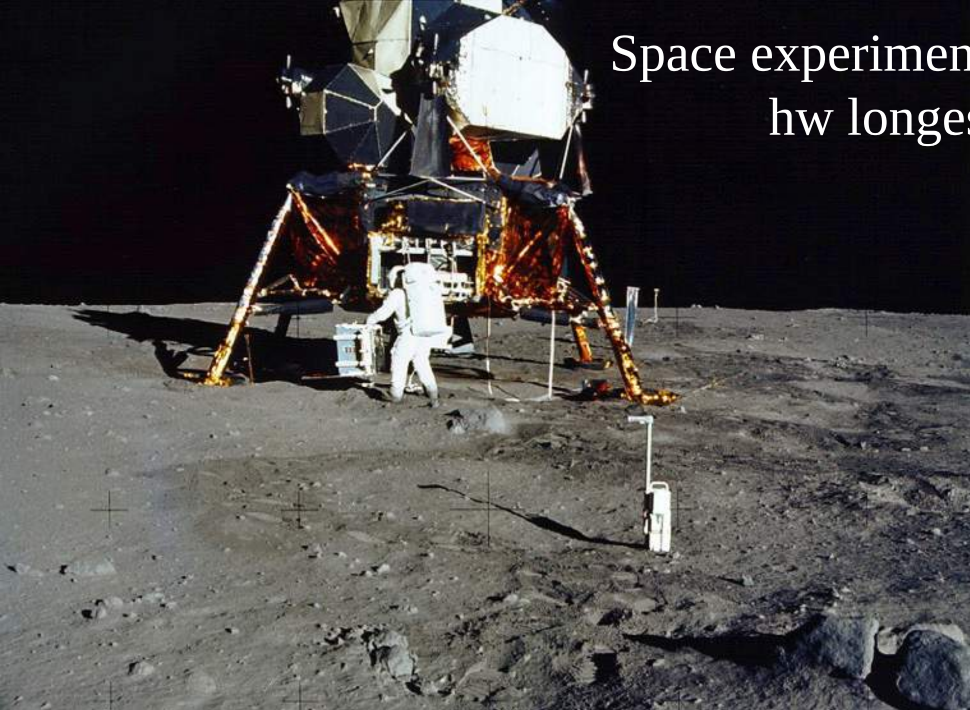
- MIT & URSS shoot lasers on lunar surface in the 60s
- CCRs deployed by Apollo missions 11, 14, 15



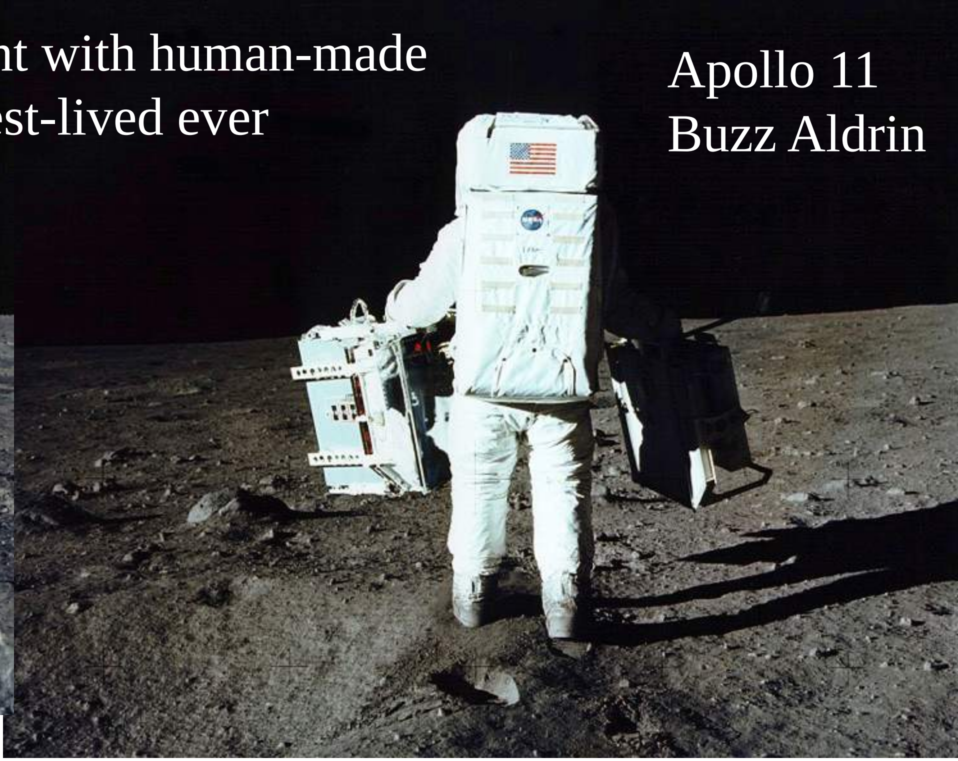
  - Apollo: arrays of CCRs of fused silica, circular aperture 3.8 cm each
  - Apollo 11 e 14: used 100 CCR
  - Apollo 15: 300 CCR

Slide courtesy of S. Merkowitz (NASA-GSFC)

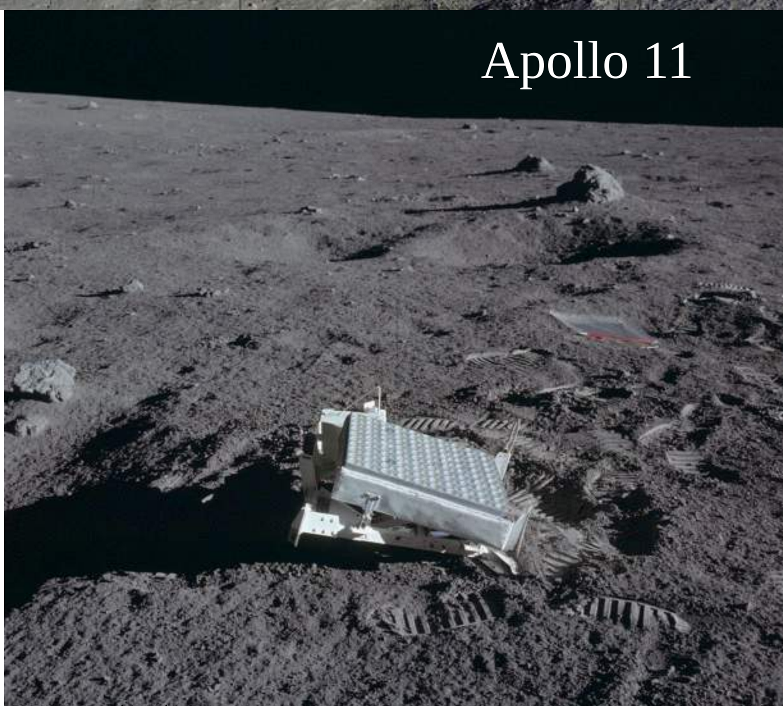
Space experiment with human-made hw longest-lived ever



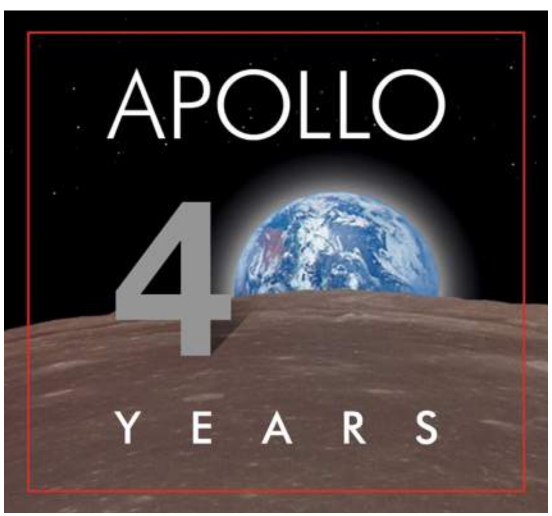
Apollo 11
Buzz Aldrin



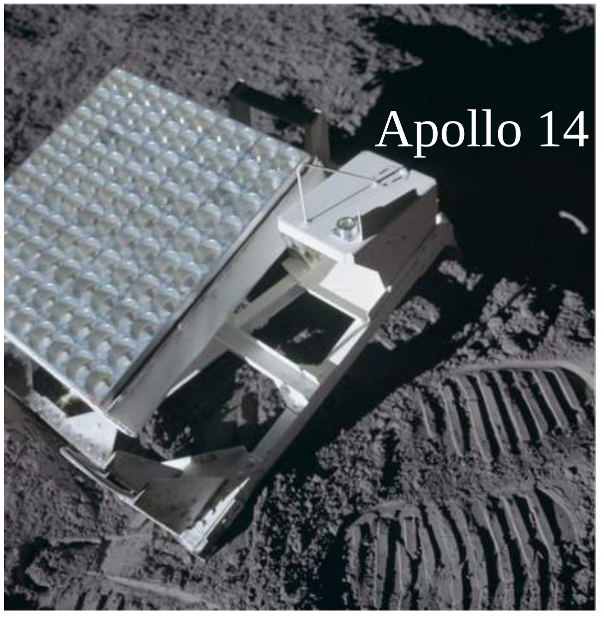
Apollo 11

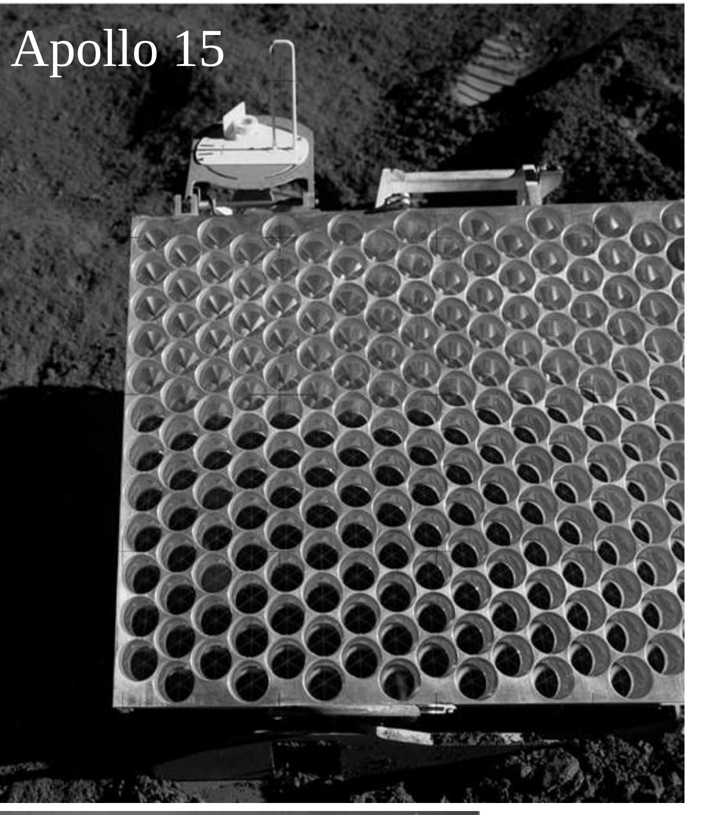


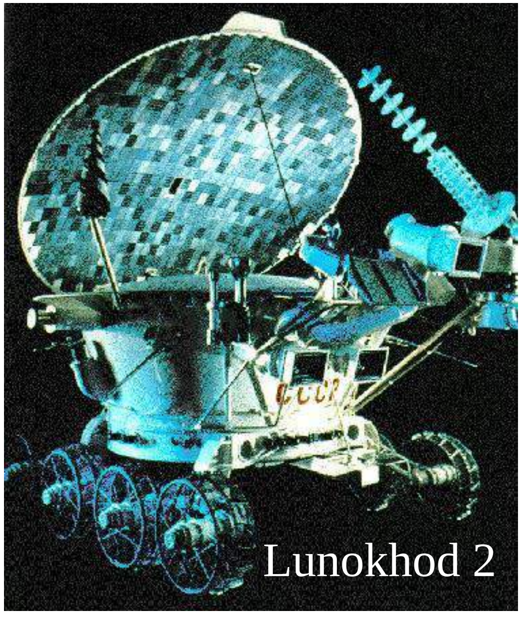
LLR: only Apollo experiment still giving data. 2009 logo

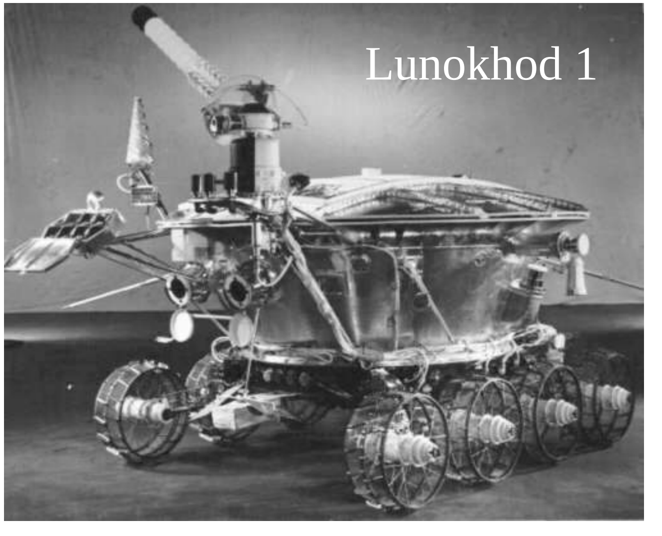


1st generation CCRs

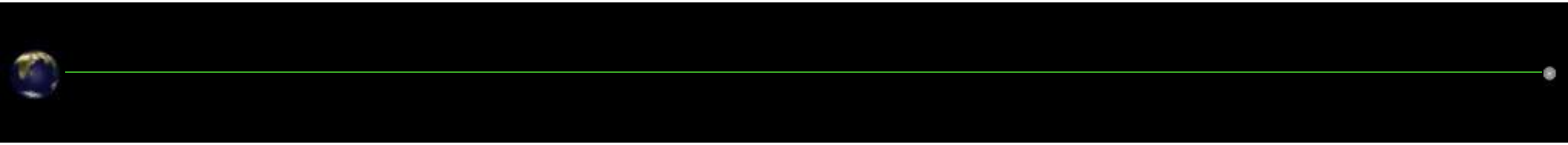








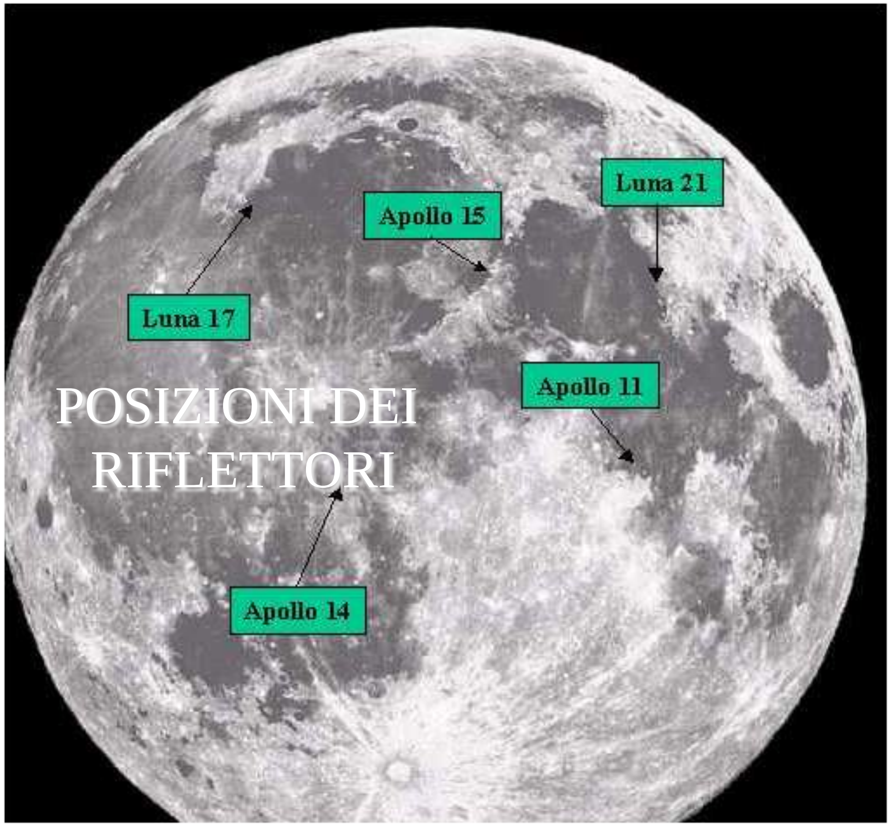
Precision: ~2 cm ~ 5×10^{-11} of Earth-Moon distance



GIF: relative sizes, distances, times

ToF ~ 2.6 sec

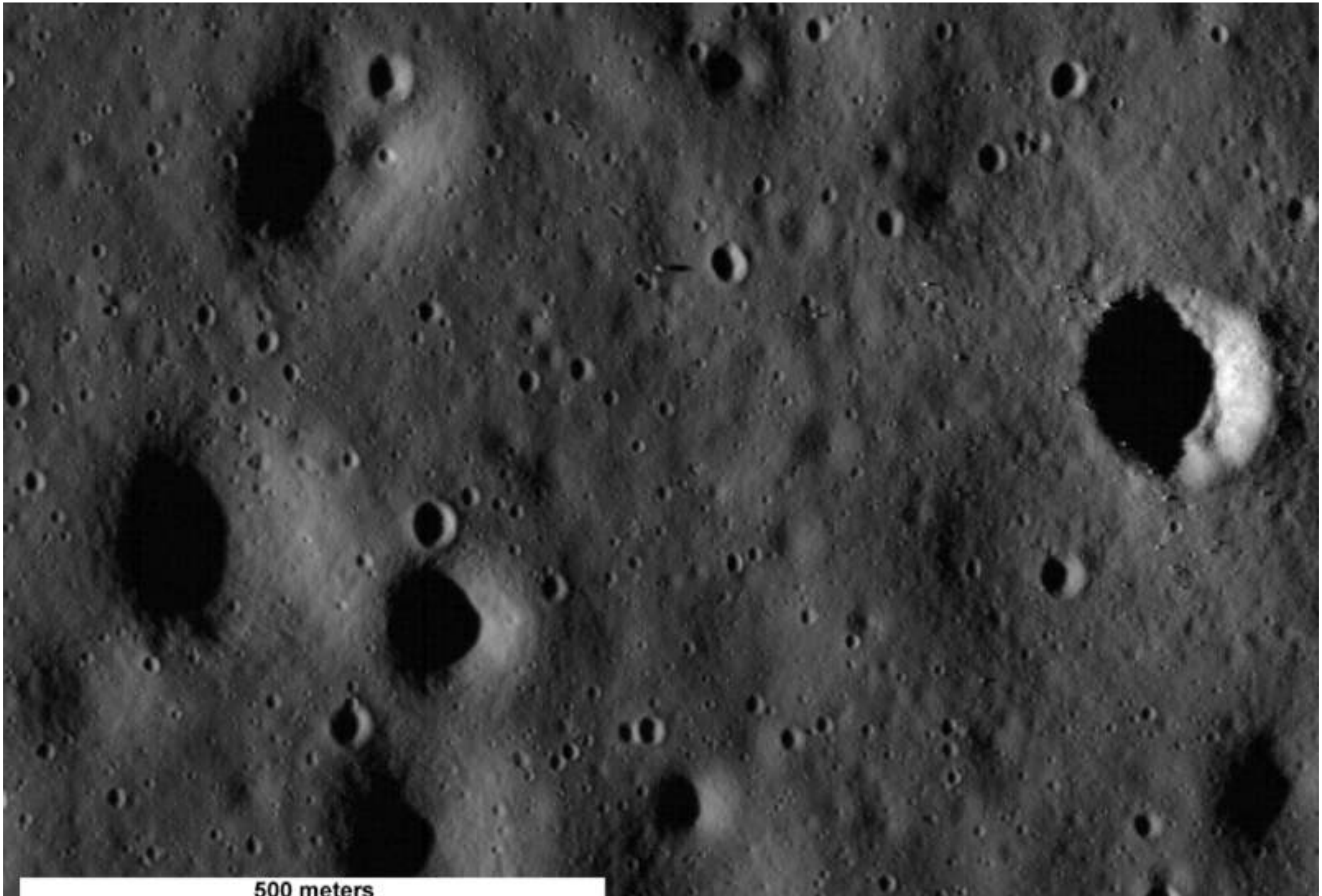
Distance ~ 384,000 km



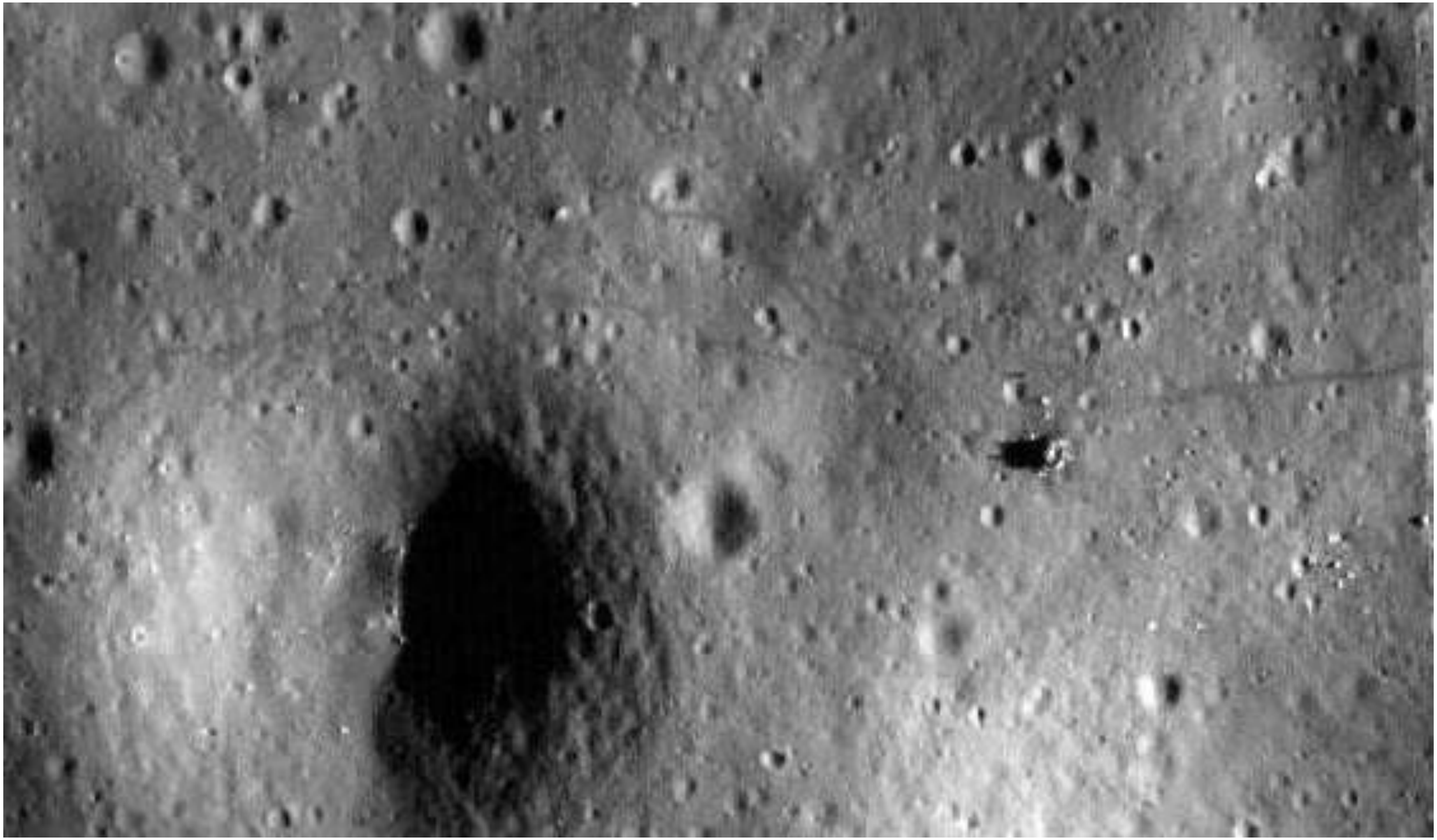
Humanity landed on the Moon?

Witnessed since ~48 years by lunar CCRs. Not enough?

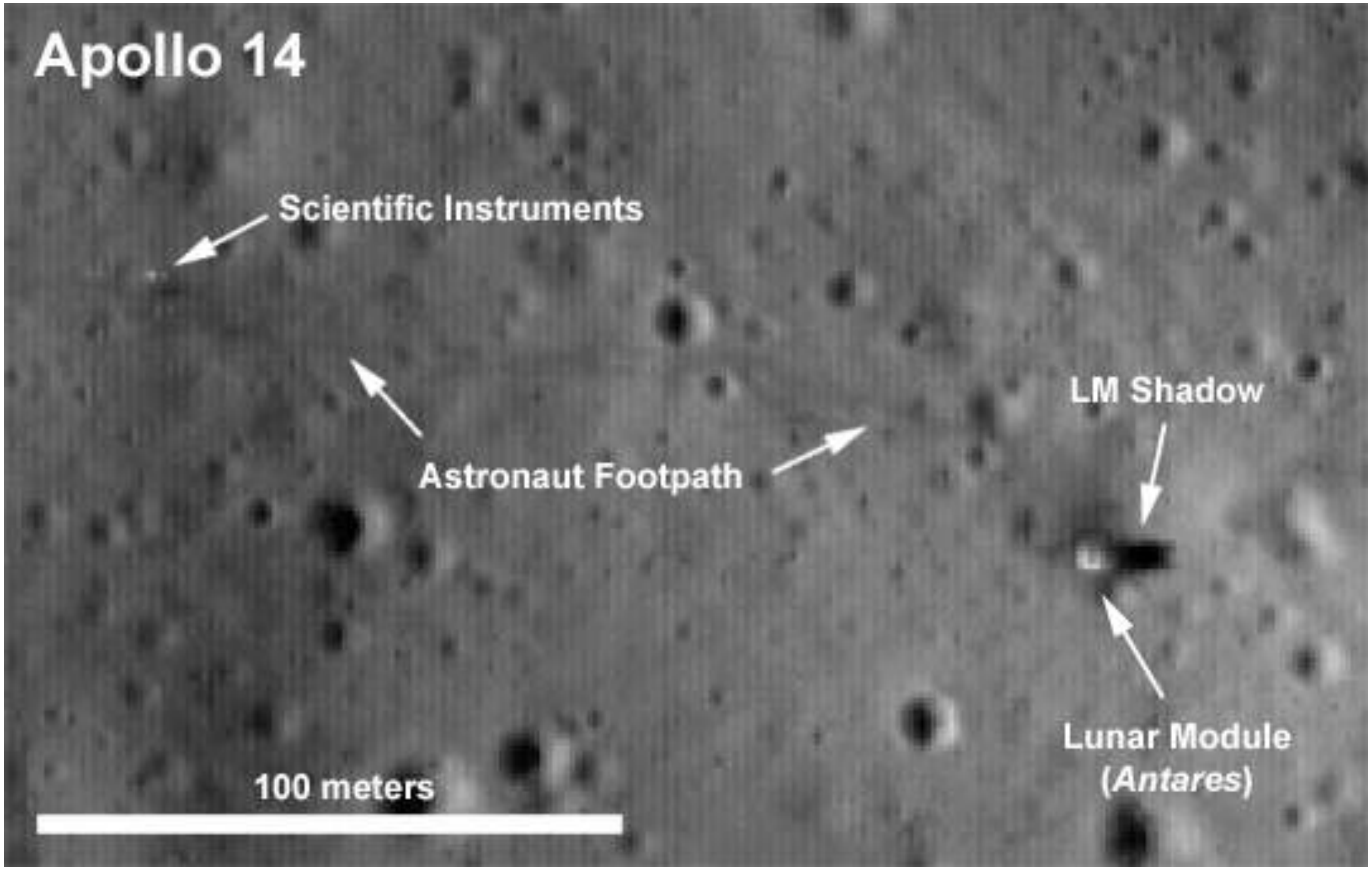
Apollo 11 seen by LROC, digital camera of Lunar Reconnaissance Orbiter (NASA)



Apollo 12, Lunar Reconnaissance Orbiter Narrow Angle Camera (LROC NAC)

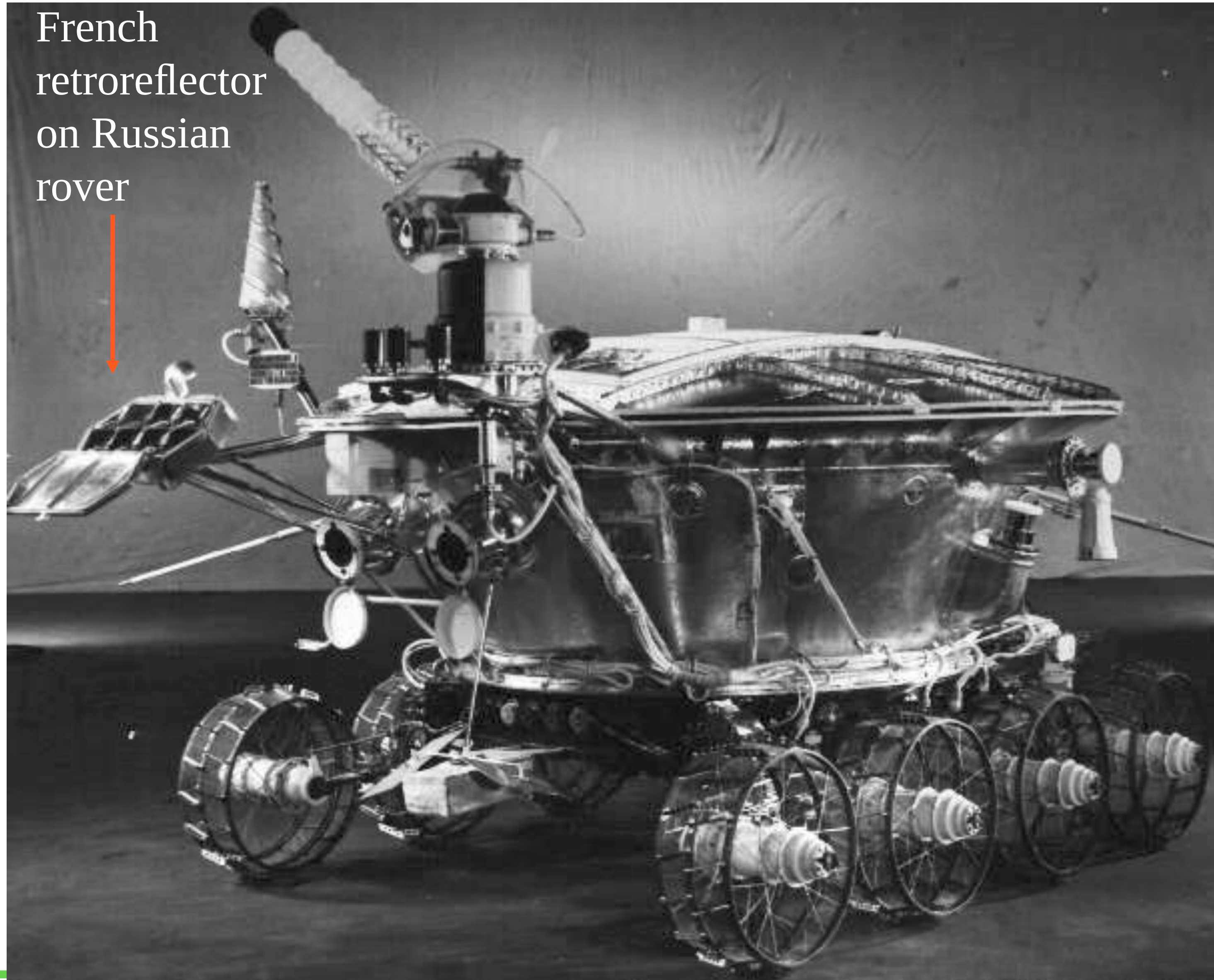


Apollo 14 from orbit. Armstrong statement



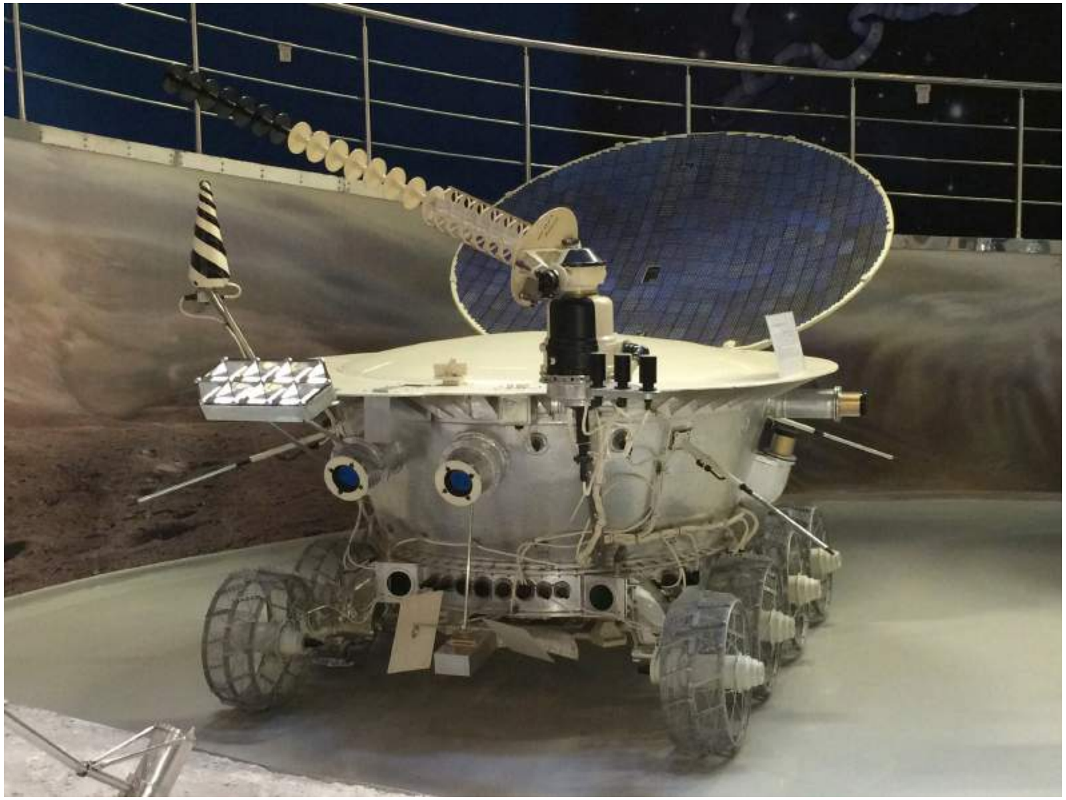
About half million people worked on the Apollo program.
Neil Armstrong: “**it would have been more difficult to fake it than to do it**”

Rover Lunakhod 1, rediscovered by LRO and then by laser stations

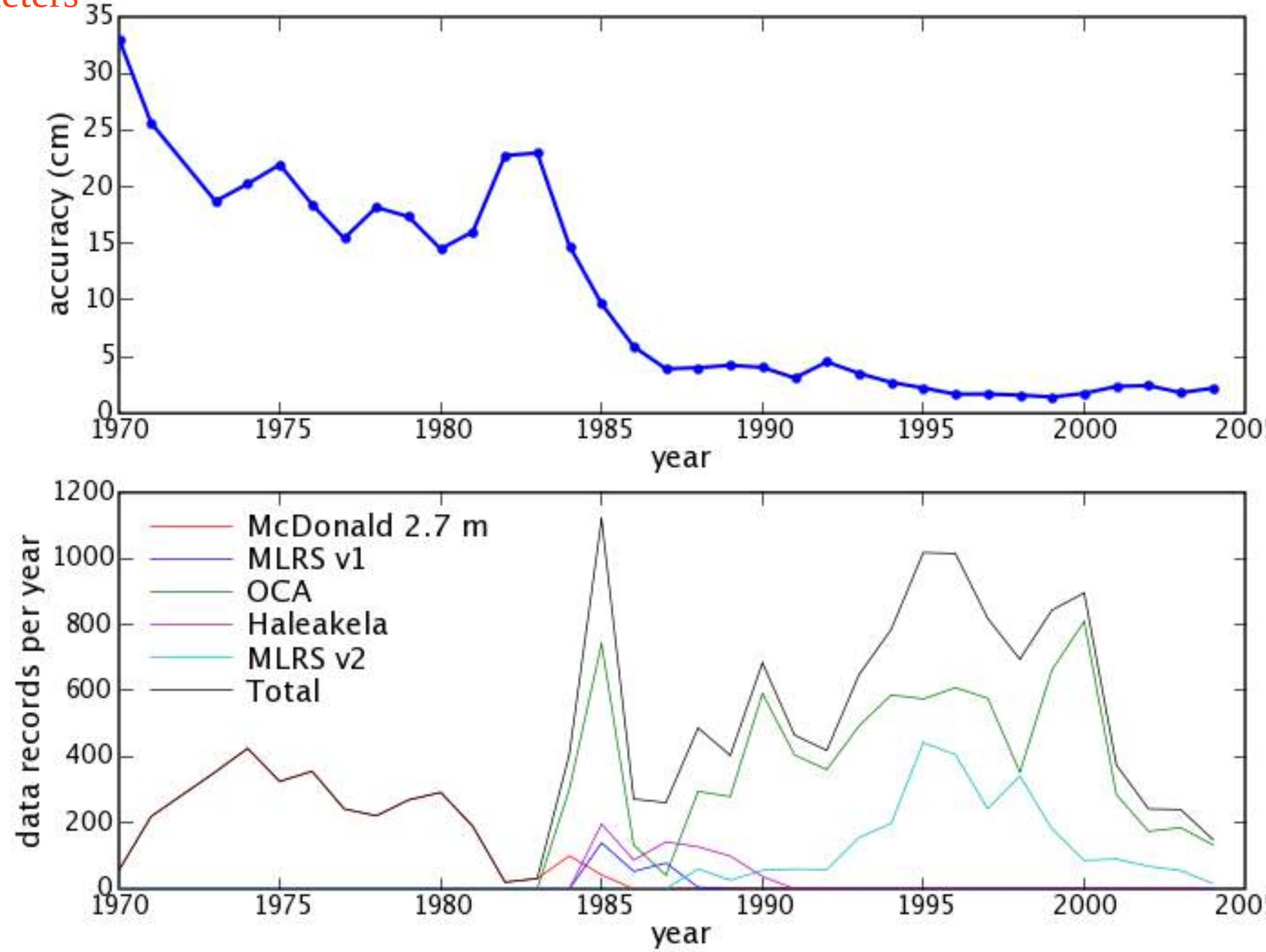


Lunokhod 3 at NPO-Lavochkin, Mosca

Lunokhod 3 at Space Museum, Moscow



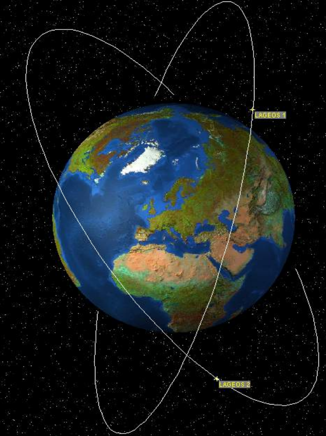
Before:
Hundreds of meters

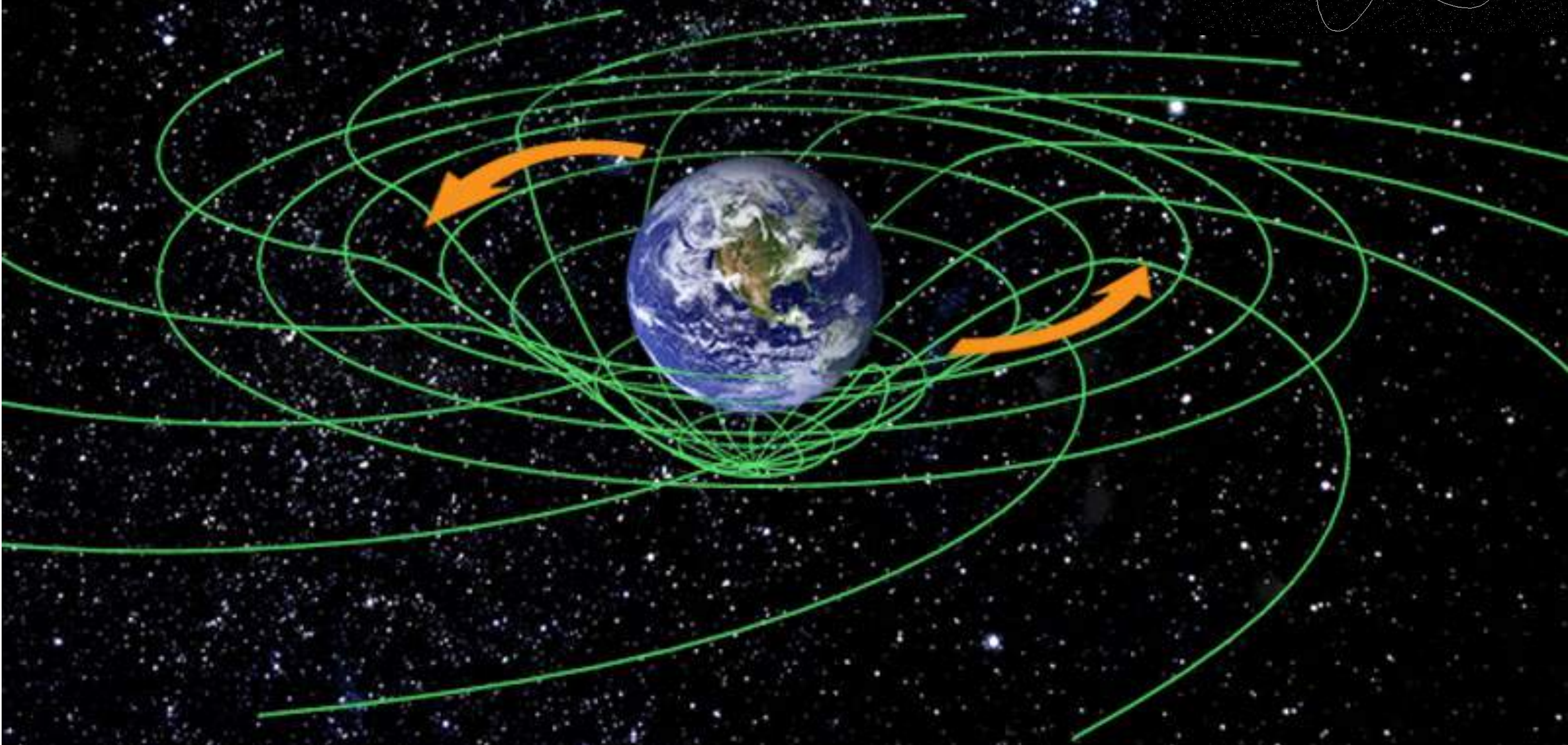


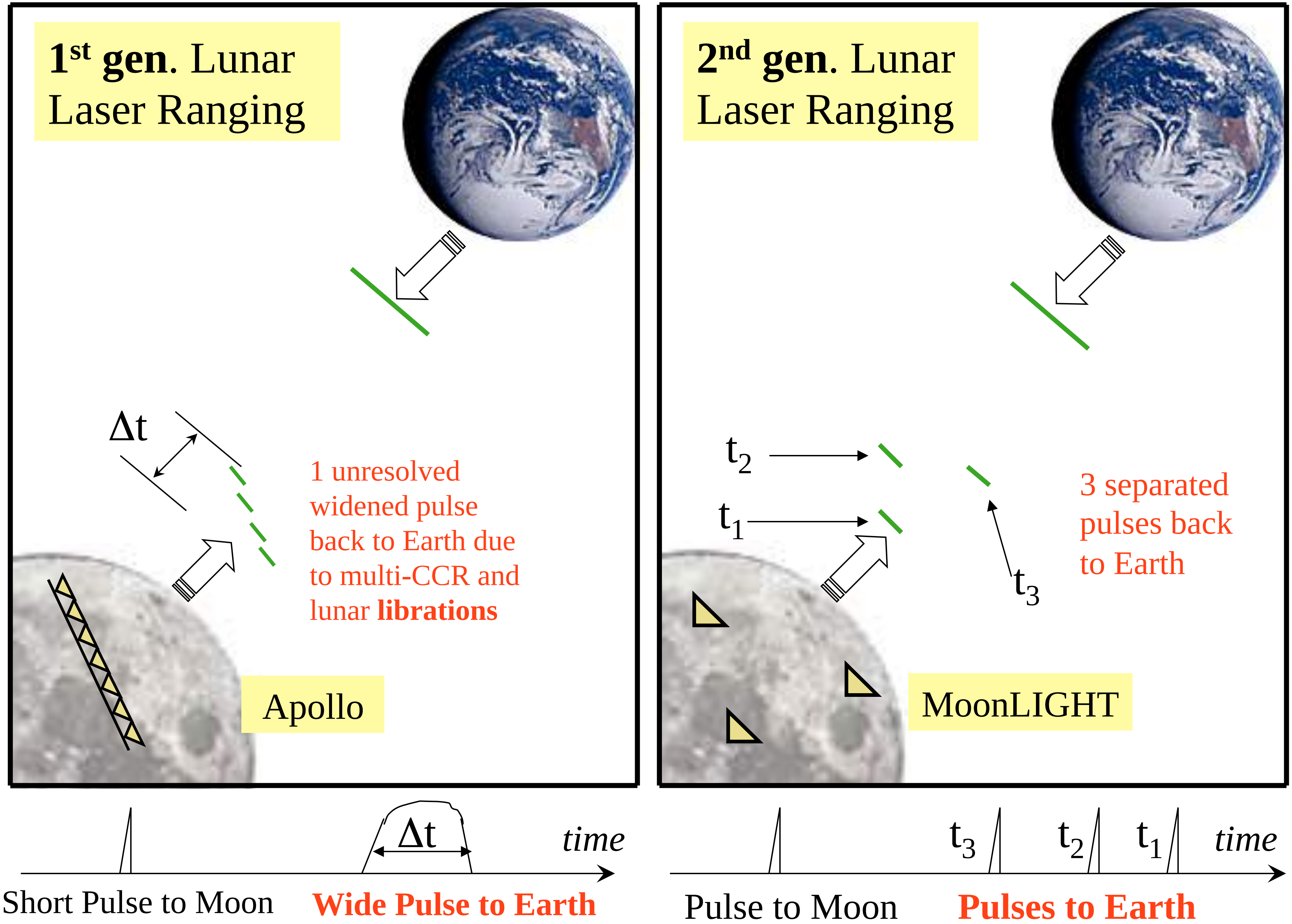
Fundamental Physics

- General relativity (and beyond)
- Technology: SLR/LLR to LAGEOS/Moon
- Exemples
  - Precision measurements, but also
  - Tests of violations of
  - Principles (equivalence) and laws ($1/r^2$) of our mother Natura (*de rerum Natura*)
- One exemple: our LAGEOS brothers
- Three exemples: our sistem the Moon

LAGEOS orbits precess around Earth (also) due to the the space-time dragging effect related to the mass current given by the Earth spinning around its axis (gravitomagnetic effect, foreseen by general relativity)






1st gen. Lunar Laser Ranging
Δt
1 unresolved widened pulse back to Earth due to multi-CCR and lunar librations
Apollo
Δt
time
Short Pulse to Moon
Wide Pulse to Earth
2nd gen. Lunar Laser Ranging
t2
t1
t3
3 separated pulses back to Earth
MoonLIGHT
t3
t2
t1
time
Pulse to Moon
Pulses to Earth

39

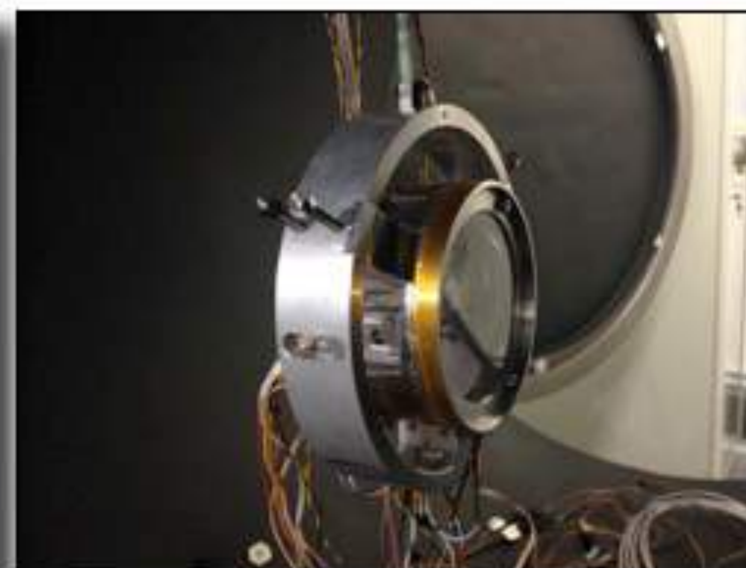
MoonLIGHT:

Italy-USA next-generation CCR

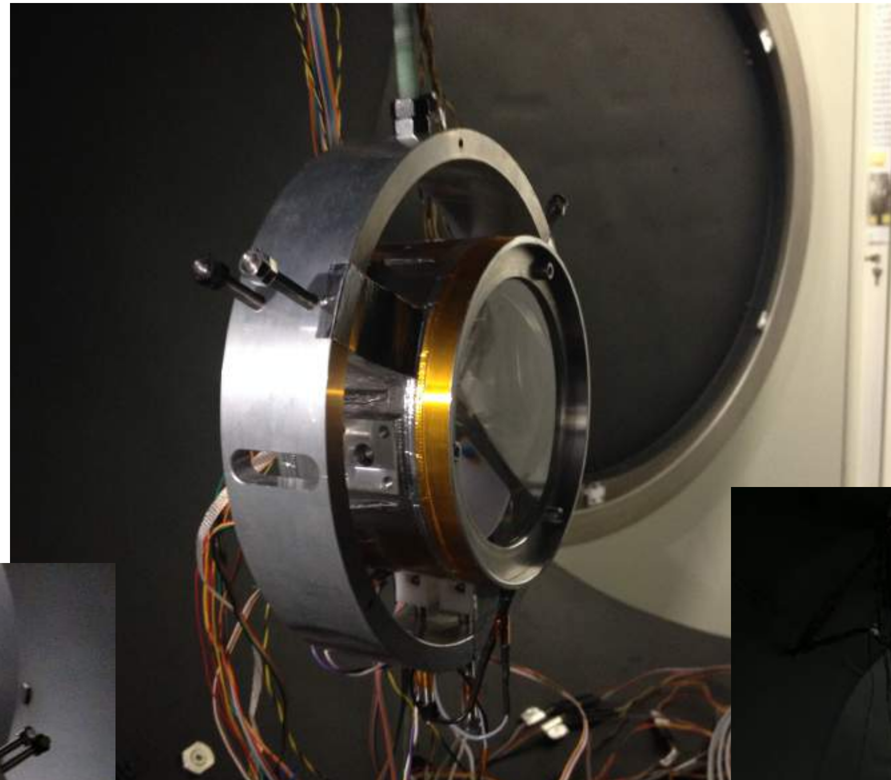
- Collaboration
  - INFN-Frascati, U. Maryland, INFN/Univ. Padova
  - Lunar stations: ASI-MLRO (Italy), APOLLO (US), OCR (Fr.)

MoonLIGHT (100 mm) **GNSS (33 mm)**

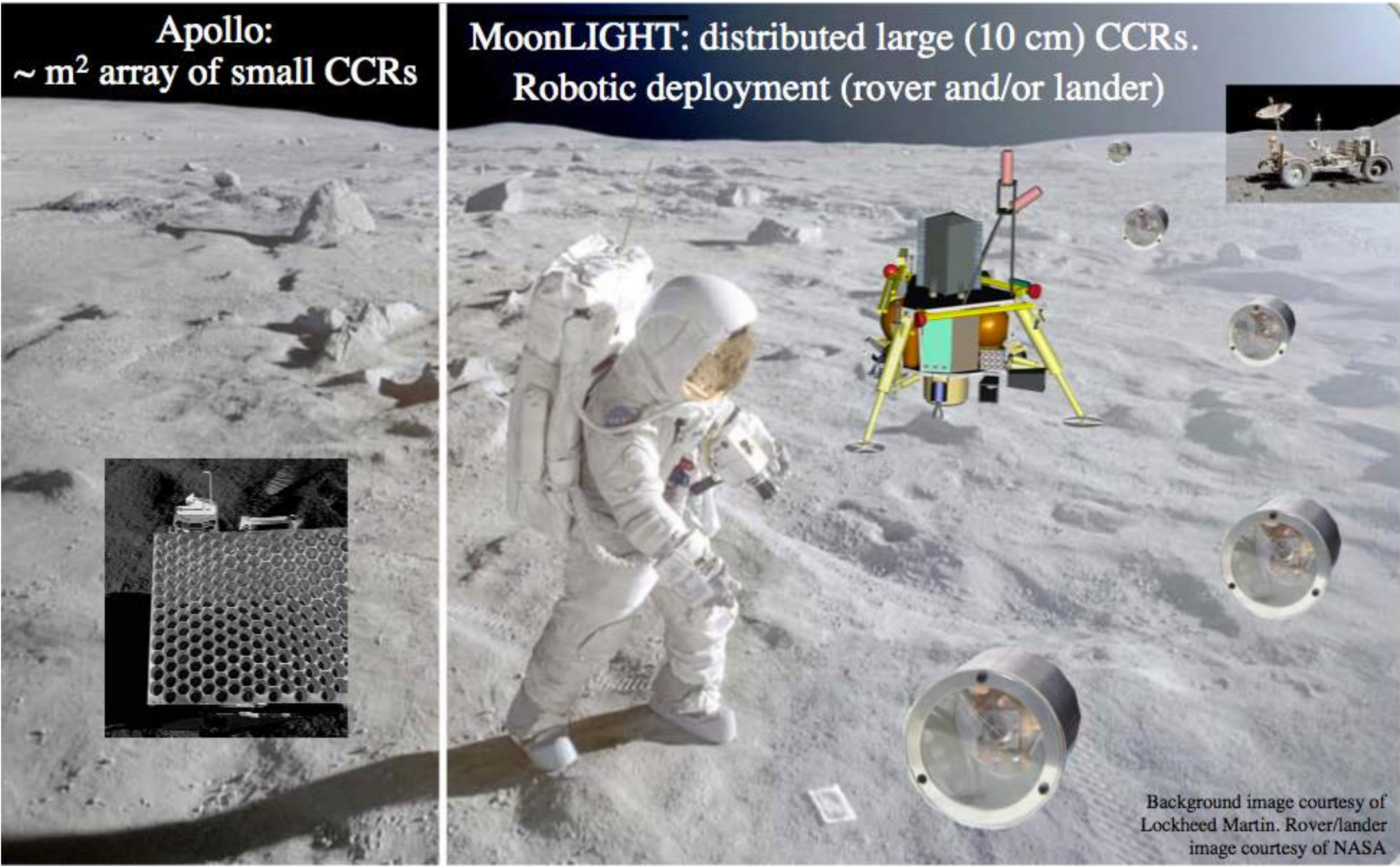
MoonLIGHT package



Caracterizatrion of MoonLIGHT @ LNF

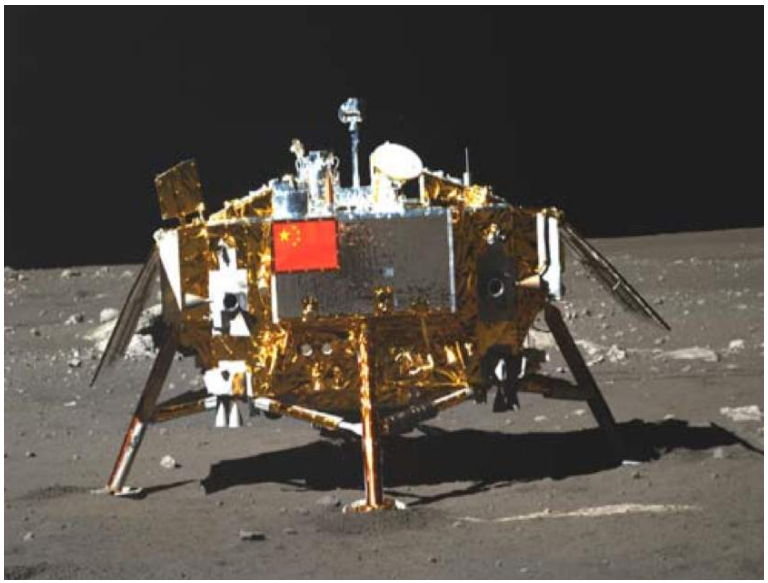


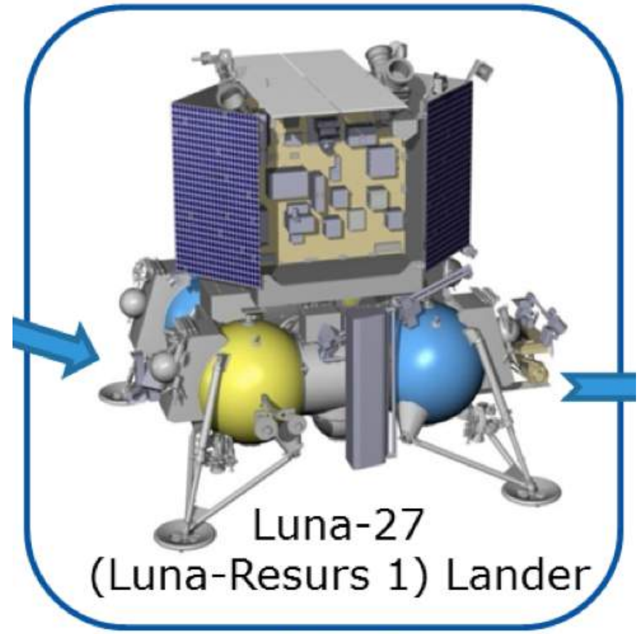
From arrays of small CCRs to the Giant

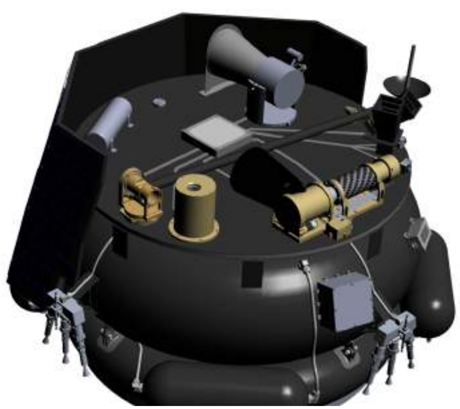


Next landings:

China, Russia, commercial GLXP, USA ...





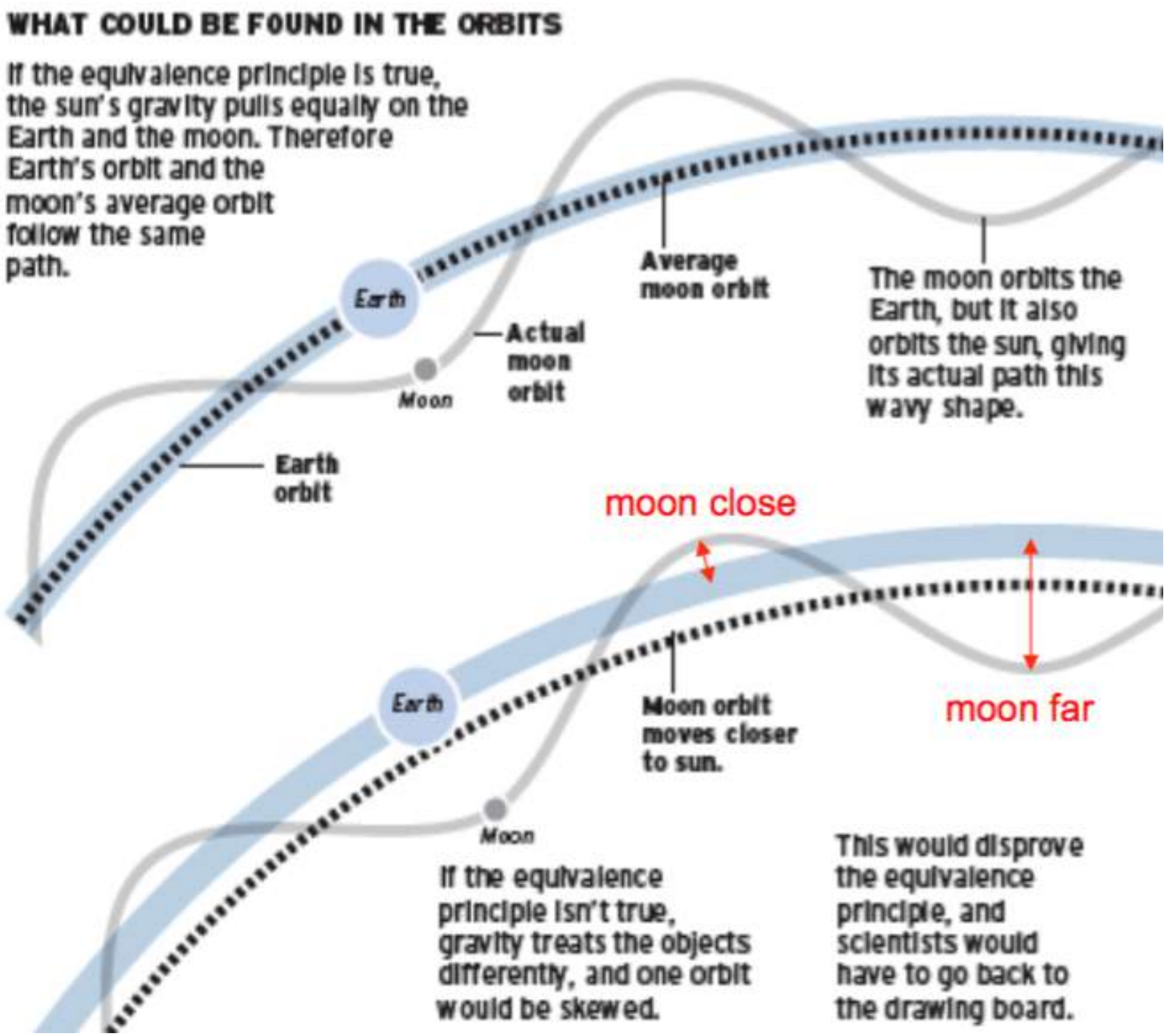


Sun-Earth-Moon System

Unique, diversified, very accurate test of Einstein’s theory:

- Earth & Moon: two bodies orbiting the Sun
- Equivalence principles: weak and strong
  - Related, respectively to different compositions and quantities of masses of the gravitating bodies
  - Conceptual experiments of Galileo and/or of the Astronaut
- ‘Geodetica’ precession of the lunar orbit
- Test of force-law $1/r^2$

Tests of Equivalence Principles of Galileo-Einstein



Tests of the two Equivalence Principles

Weak version (Galileo): hammer and feather have a very different type/ quality of mass compositions, but they fall with the same acceleration in the field of the Moon

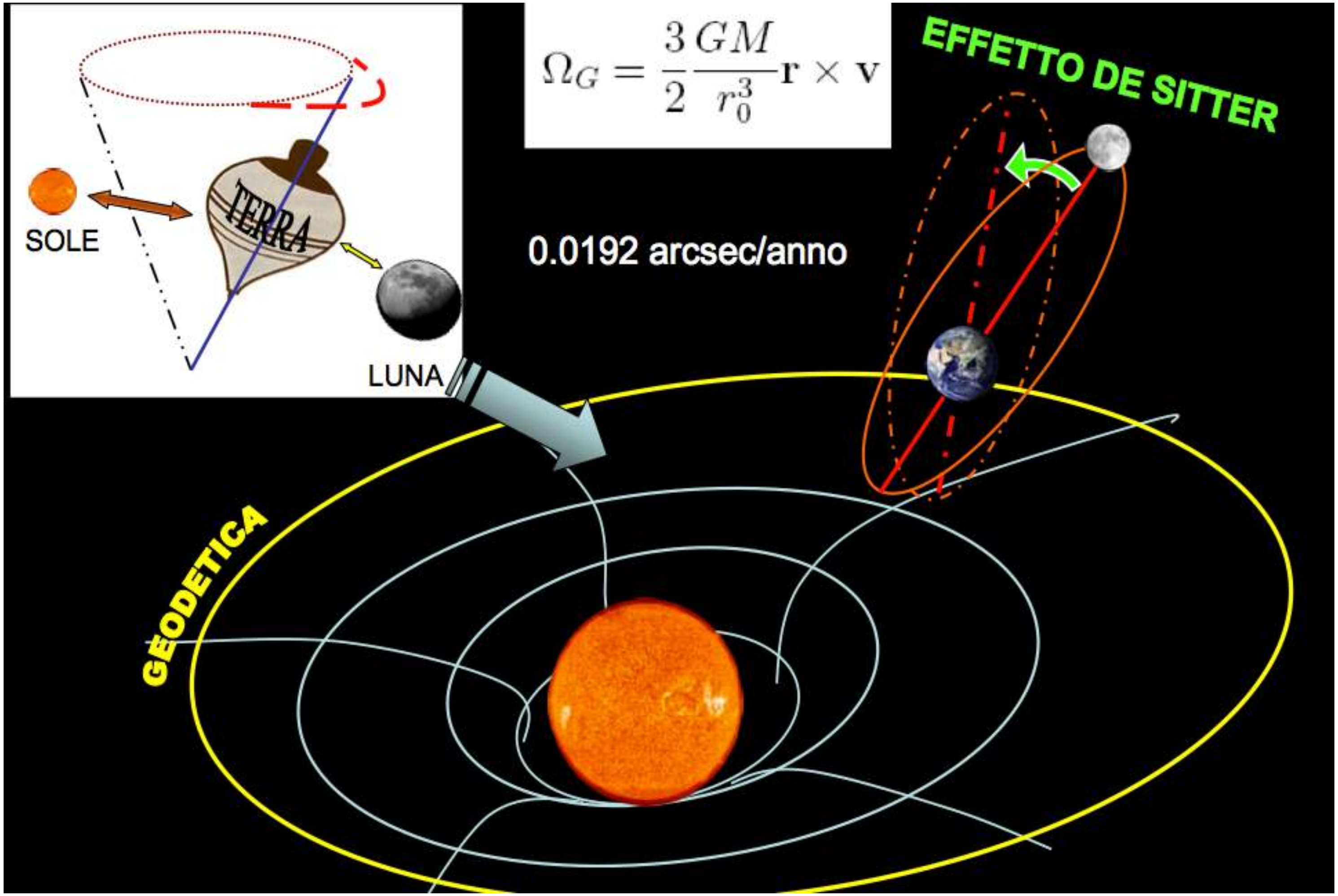
Strong version (Einstein):
the heavy hammer (Earth) and lighter hammer (Moon) have a relatively similar composition (rocky) but in very different quantities. But again they fall with the same acceleration in the field of the Sun − Measured with LLR

Digression: *visual archives* of Alan Bean

Digressions: *visual archives* of Alan Bean

3-body effect, Sun-Earth-Moon (de Sitter effect) predicted by GR

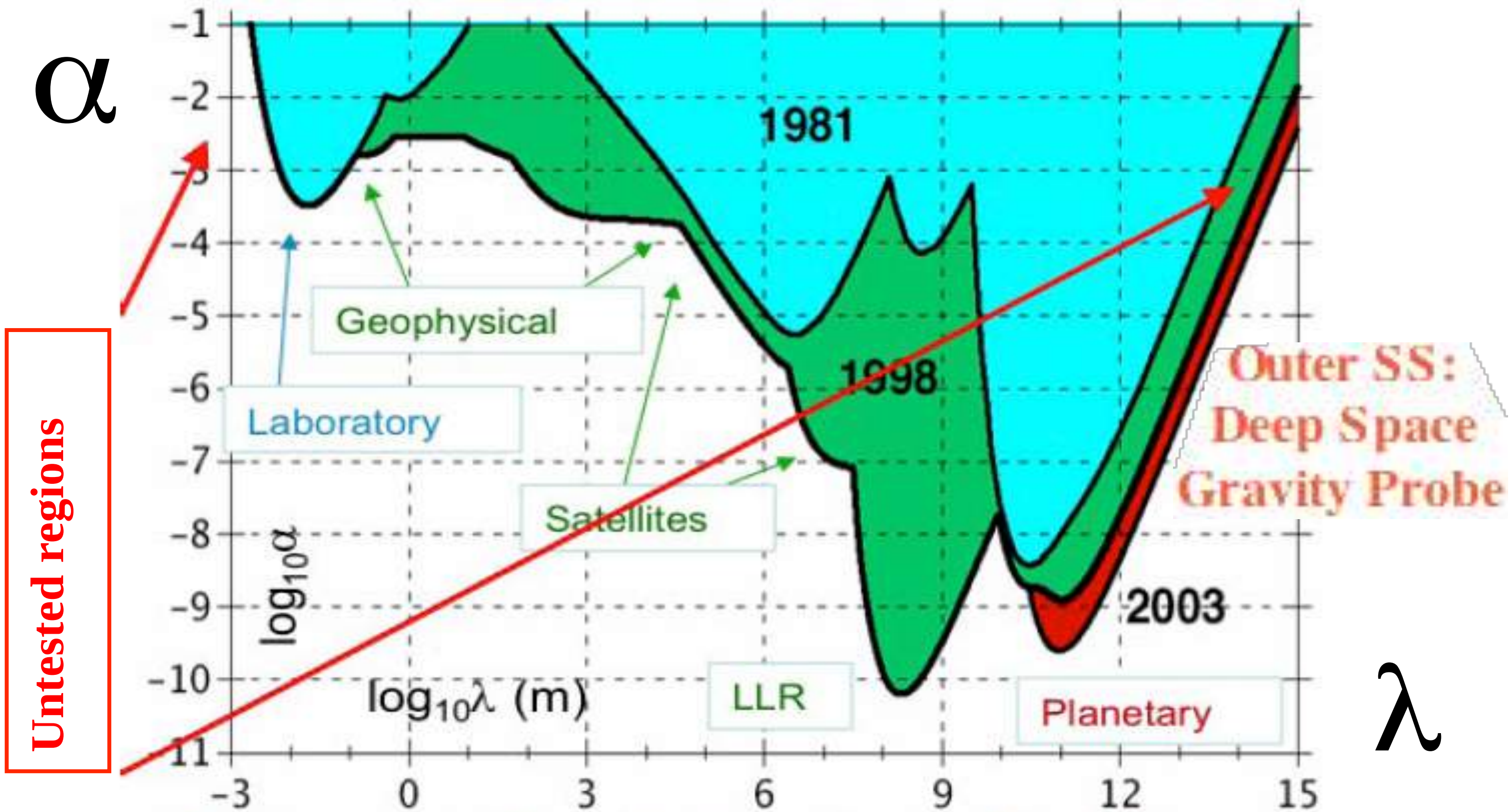
~ 3 meters / lunar orbit (~ 2“/cy)



Yukawa potential?

$\alpha \times$ (Newton potential) $\times e^{-r/\lambda}$

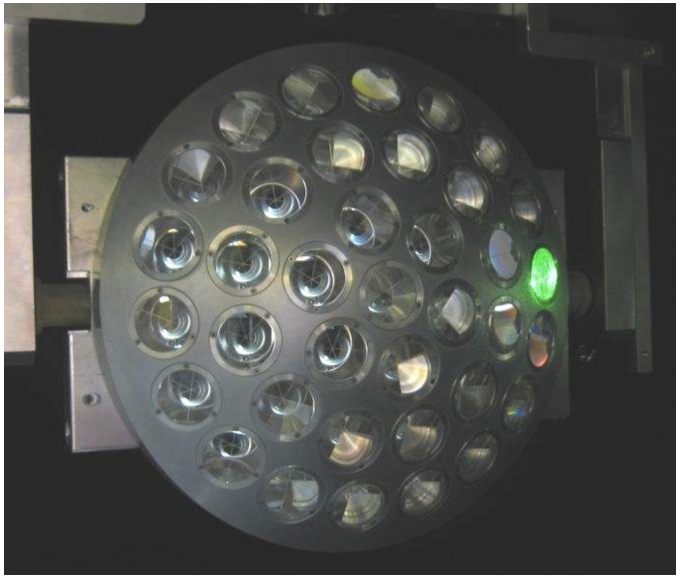
With our new lunar CCRs we will improve this test x 100



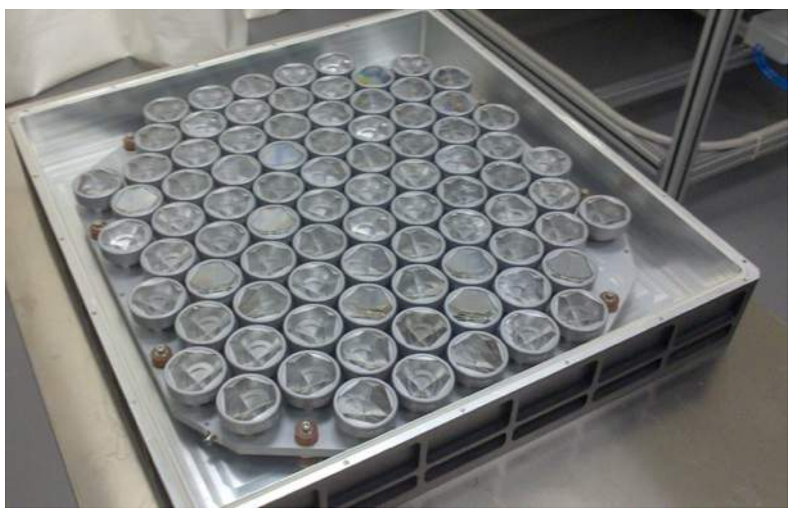
Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

- **Gravitational redshift**
- Atomic clocks of Galileo (Maser e Rubidio) run faster than clock on Earth
- Effect ~25m (80nsec×*c*) after 2 min ~18Km (60μsec×*c*) after 1 day (two GPS orbite)

Tested CCRs



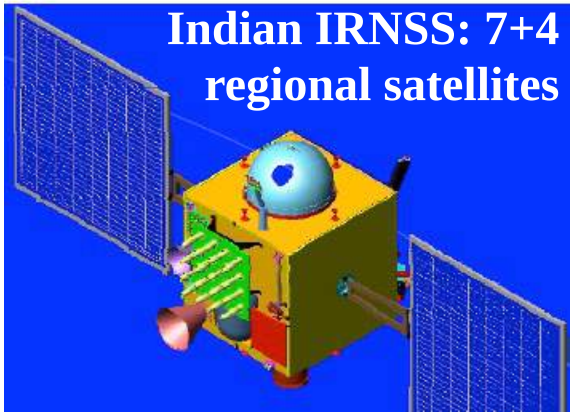
LAGEOS, GPS, Galileo (clockwise)



Galileo In-Orbit Validation satellite (IOV)

Global Navigation Satellite System (GNSS)

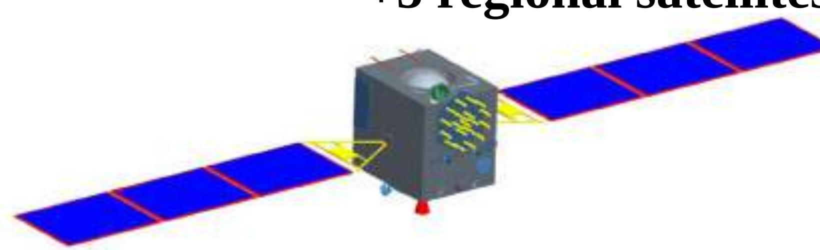
~100 satelliti con retroriflettori laser!



SCF-Tested

Galileo europeo:
30 satelliti
Caratterizzati ai LNF

Chinese Compass/ Beidou: 20 global, +5 regional satellites



Russian GLONASS: 24 global satellites: SCF-Tested

What Next?

- Fundamental physics
  - Improve tests from factor 5 to 100
  - Improve by factor 10 the metrology of the Geocenter
    - 1 mm per epoch (10 yers) and stability of 0.1 mm/yr
- New destinations:
  - Mars, far side (not the dark side!!!) of the Moon
  - Asteroids adn Comets
  - Icy/rocky moons of Juputer and Saturn (*all these worlds can be ours, including Europa* ...)

Abstract

L’inseguimento laser dei satelliti e della Luna (in inglese “Satellite and Lunar Laser Ranging” o SLR/LLR) sono riconosciute come le tecniche più precise e, al tempo stesso, meno costose per realizzare il posizionamento assoluto nel sistema Terra-Luna. I retroriflettori laser portati 40 anni fa sulla superficie lunare dalle missioni Apollo hanno permesso nel tempo di conoscere l’orbita della Luna con la precisione di pochi centimetri, di effettuare molteplici accurati test della Teoria della Relatività Generale di Einstein e importanti misure della struttura interna della Luna. Questo è l’esperimento spaziale costruito dall’uomo più longevo di tutti. Nel 1976 la NASA lanciò il satellite LAGEOS (LAser GEOdynamics Satellite), una sfera metallica massiccia coperta di retroriflettori laser. Nel 1992 NASA e ASI lanciarono LAGEOS II. Le loro orbite sono usate come “metro” spaziale e per definire (in un certo senso “materializzare”) il centro di massa della Terra (altrimenti inaccessibile direttamente). Le missioni Apollo e i due satelliti LAGEOS sono due pietre miliari della fisica fondamentale del sistema Terra-Luna e della geodesia spaziale. Sono anche tra le prime e le più feconde applicazioni scientifiche e tecnologiche del laser, inventato agli inizi degli anni 60. L’acquisizione e l’analisi dei loro dati, che sono gratuiti, continua a ritmo incessante da parte della rete di stazioni di Terra dello ILRS (“International Laser Ranging Service”).

Le due frontiere di questo campo della ricerca spaziale sono l’installazione di retroriflettori laser di seconda generazione sulla superficie della Luna con missioni robotiche e a bordo delle moderne costellazioni navigazione satellitare, come Galileo, il GNSS (Global Navigation Satellite System) dell’Europa. In questi due ambiti è attivo e all’avanguardia il laboratorio di test spaziale SCF_Lab dei LNF, il cui contributo originale alla disciplina dell’inseguimento laser è stata la realizzazione di due apparati sperimentali unici al mondo (SCF e SCF-G) e di una nuova procedura di test spaziale dei retroriflettori laser (SCF-Test). I LNF stanno anche sviluppando nuovi retroriflettori lunari in collaborazione con l’Università del Maryland a College Park (USA), l’istituzione che fu responsabile dei retroriflettori delle missioni Apollo. I nuovi riflettori targati Maryland/Frascati avranno prestazioni migliori fino a un fattore 100 rispetto a quelli Apollo e a quelli installati sui rover Russi Lunokhod.