MoonLIGHT-INRRI

Istituto Nazionale di Fisica Nucleare

@SCF_LAB

Satellite/Lunar/GNSS laser ranging and altimetry Characterization Facility LABoratory

INFN LNF

Earth Rise photo, Dec. 24, 1968.

Taken originally in "portrait" orientation by the 1st translunar Apollo 8 mission; the 1st time humans left the Earth potential well …

Blue Marble photo, Dec. 7, 1972.

Original caption: "View of the Earth as seen by the Apollo 17 crew traveling toward the moon …. first time the Apollo trajectory made it possible to photograph the south polar ice cap …"

Simone Dell'Agnello (INFN-LNF) for the SCF_LAB Team

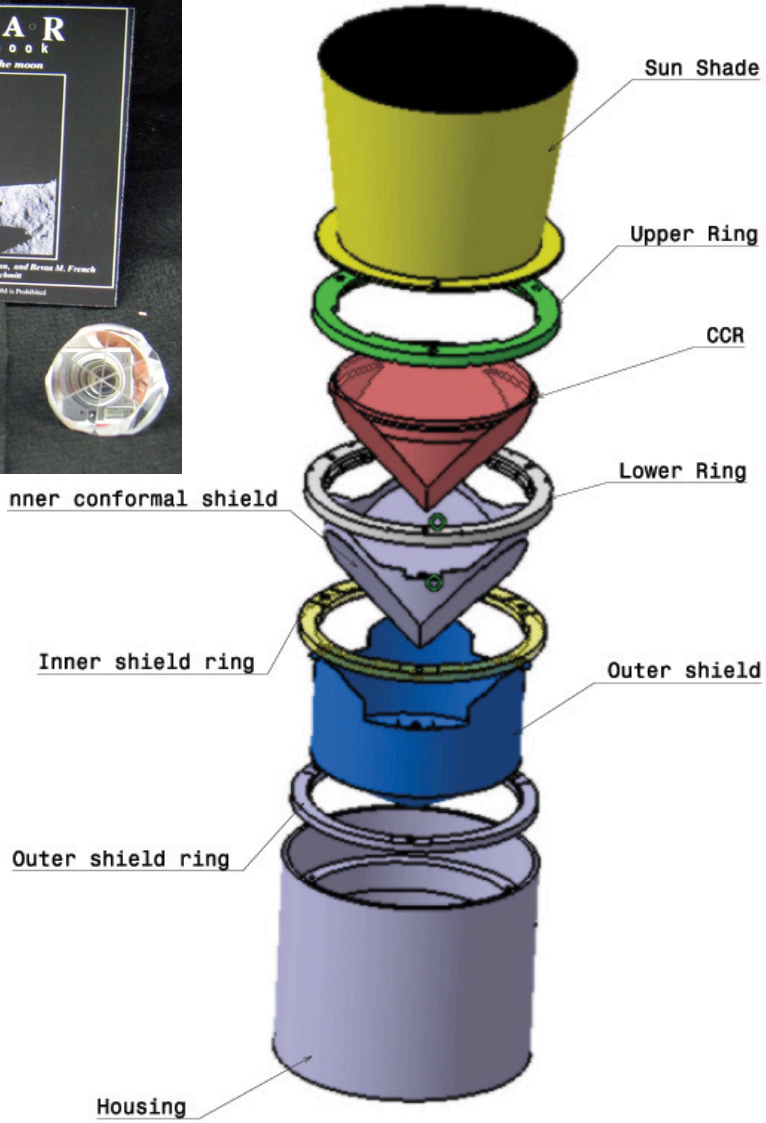
CdL Preventivi 2013, Frascati, July 3, 2012

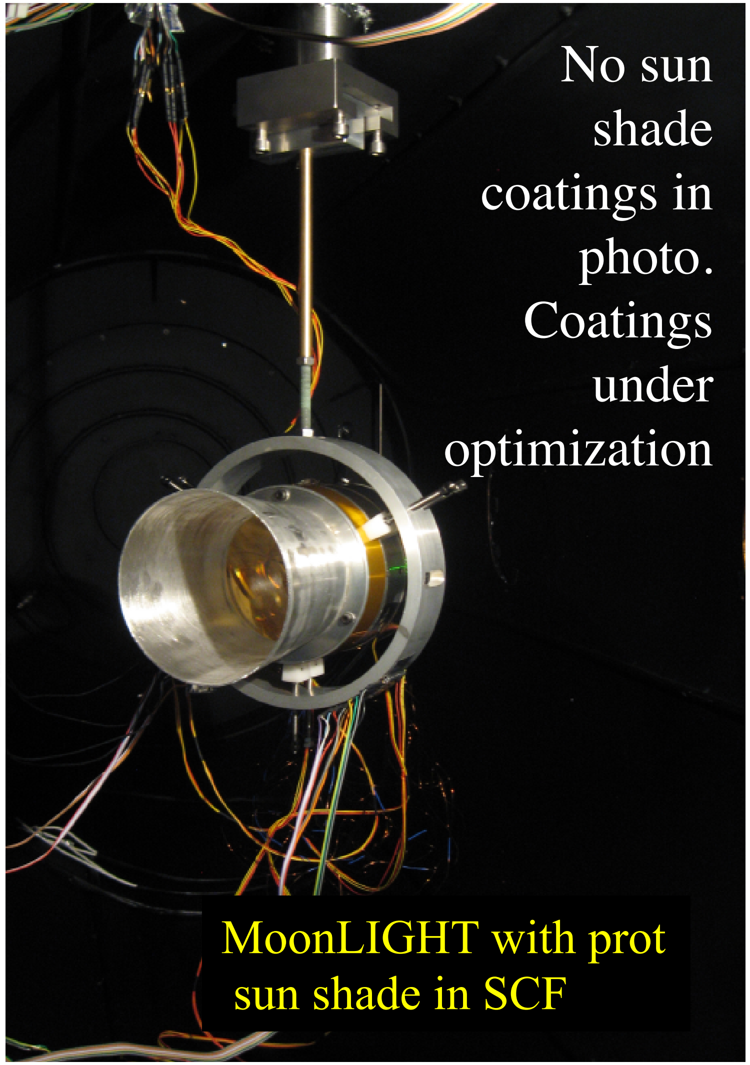
Outline

- Retroreflector payloads (PLs) developed in CSN5 for
  - Lunar Laser Ranging and Laser Altimetry
- New CSN2 activity on analysis of gravitational physics
  - Tests of General Relativity
  - Analysis of current LLR data
  - Effect of lunar dust on Apollo LLR
  - New physics predictions/constraints: spacetime Torsion, f (R) theories
- Mission opportunities and proposals
- Preparation of PLs for qualifications
- FTEs, CSNV/CIF Requests

MoonLIGHT: 10 cm reflector

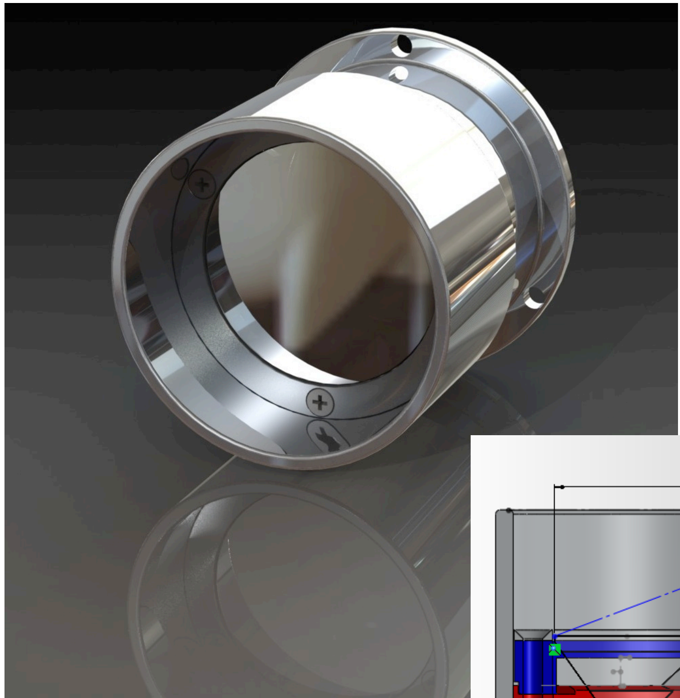
1 MoonLIGHT equivalent to ~50 Apollo CCRs

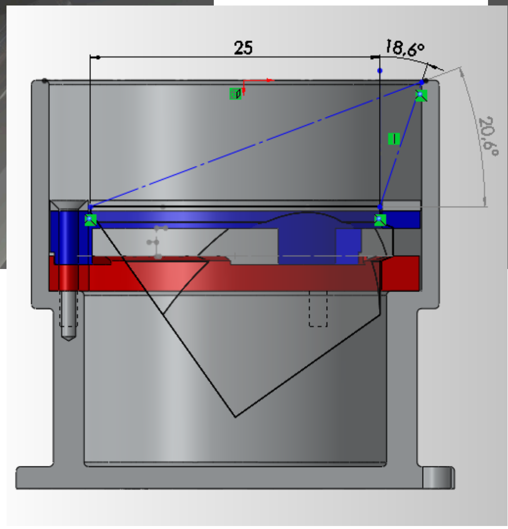




INRRI:

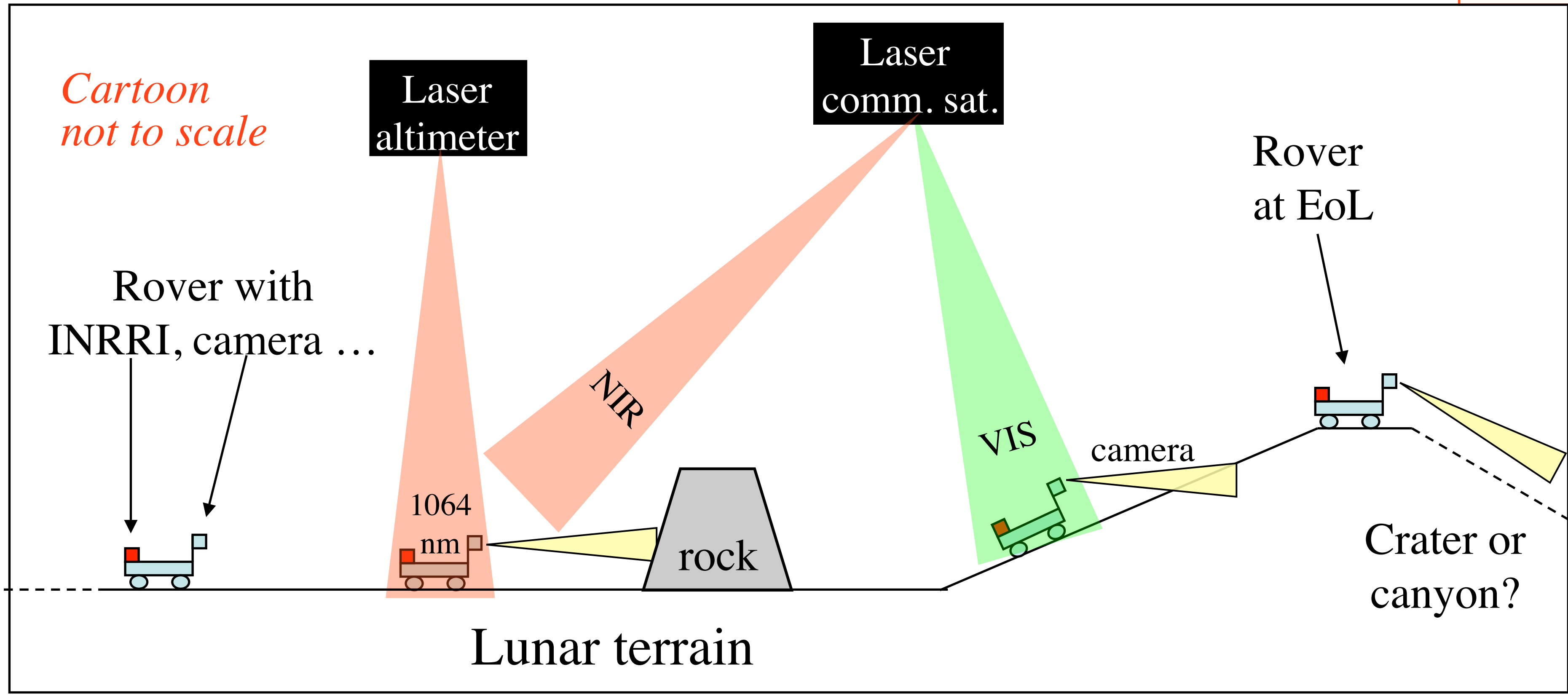
INstrument for landing-**R**oving laser altimetry
Retroreflector **I**nvestigations (~2.5 cm reflector)





Inheritance from Apollo/LAGEOS
and full sun shading

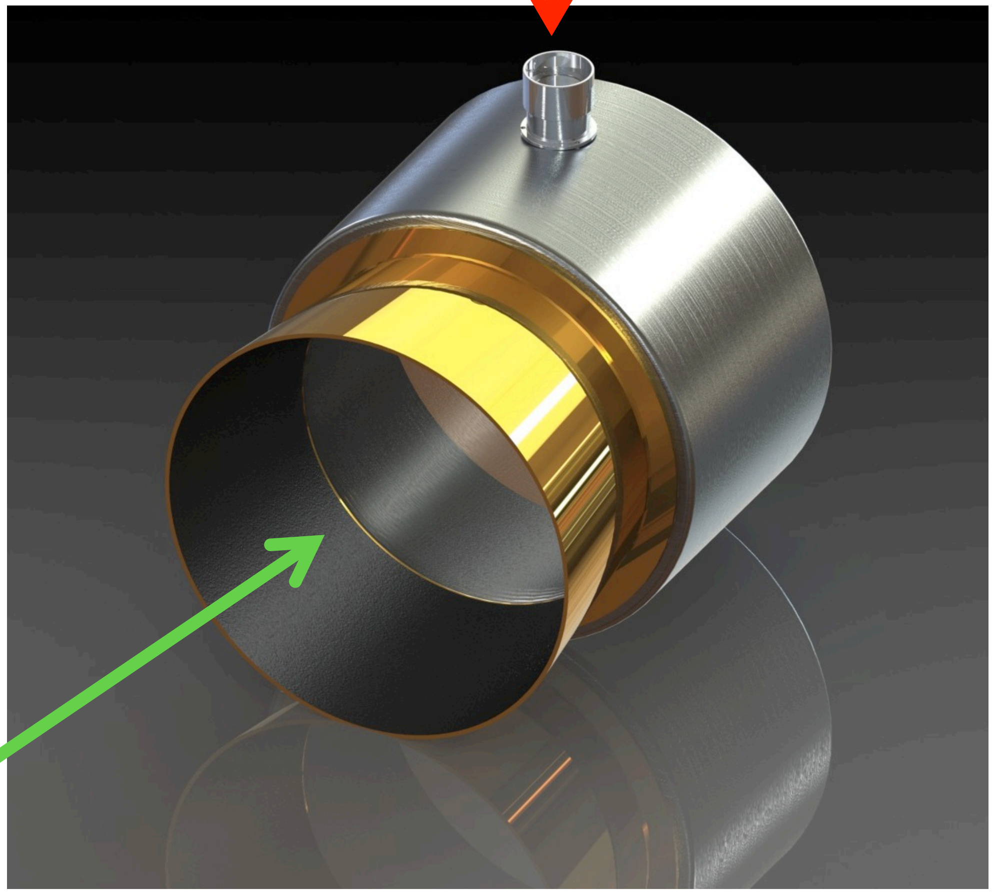
Near & far side lunar lander/rover seleno-location w/INRRI



- Seleno-locate rover during exploration, possibly linked to geologic context (camera)
  - Depending on orbiter dynamics and choice of landing/roving site, seleno-locate rover periodically (every orbit) over its lifetime
- At EoL, perform precise seleno-location of rover (and lander if equipped with INRRI). Locate positions also wrt to Earth.
- Potentially determine rover seleno-orientation (with INRRI-4 asymmetric *cross* configuration) in addition to seleno-location

Combining MoonLIGHT with INRRI at lunar poles

INRRI for Laser altimetry with 1064 nm laser from lunar orbiters



MoonLIGHT for Lunar Laser Ranging with 532 nm from Earth

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	$\|\beta-1\|<1.1\times10^{-4}$	10^{-5}	10^{-6}
Weak Equivalence Principle (WEP)	Few years	$\|\Delta a/a\|<1.4\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	Few years	$\|\eta\|<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of the Gravitational Constant	~5 years	$\|\dot{G}/G\|<9\times10^{-13}yr^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	~10 years	$\|\alpha\|<3\times10^{-11}$	10^{-12}	10^{-13}
Geodetic Precession	Few years	$\|K_{gp}\|<6.4\times10^{-3}$	6.4×10^{-4}	6.4×10^{-5}

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

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

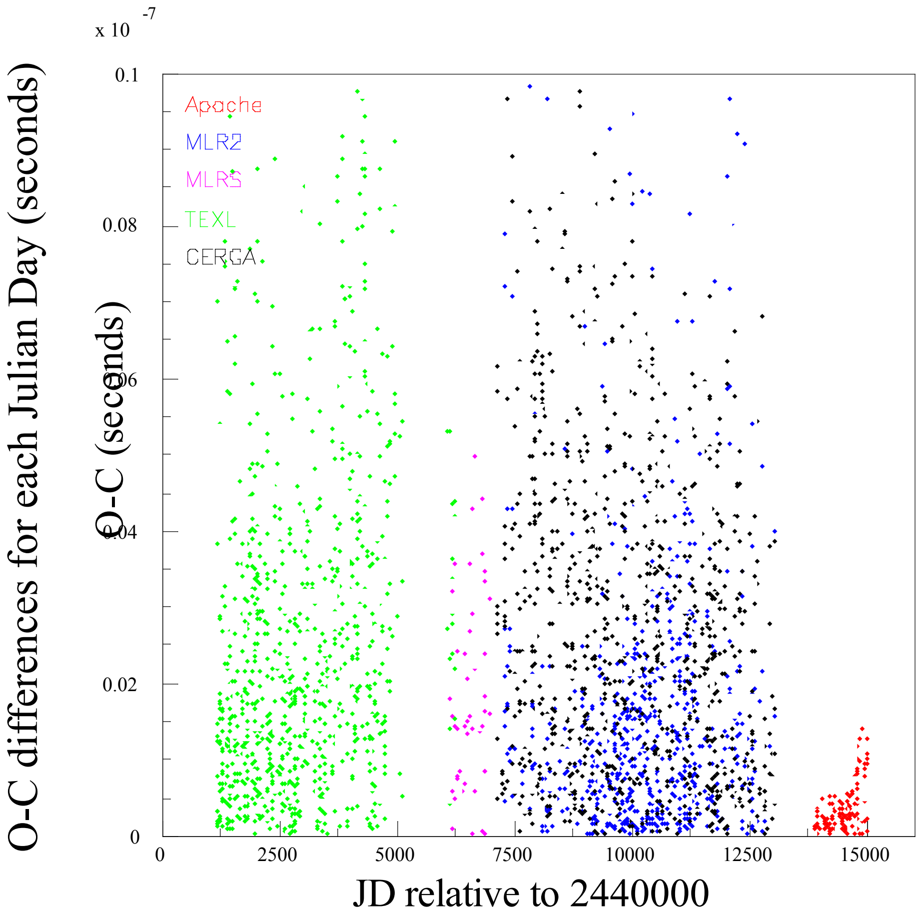
Number of laser returns to make a “standard” ~2-cm LLR range:

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

LLR ToF residuals with PEP, the Planetary Ephemeris Program by CfA run at LNF since 2009

Data by station from 1969 to 2009

The model parameter estimates are refined by minimizing the residual differences, weighted least-squares sense, between observations (O) & model predictions by PEP (C= Computation)



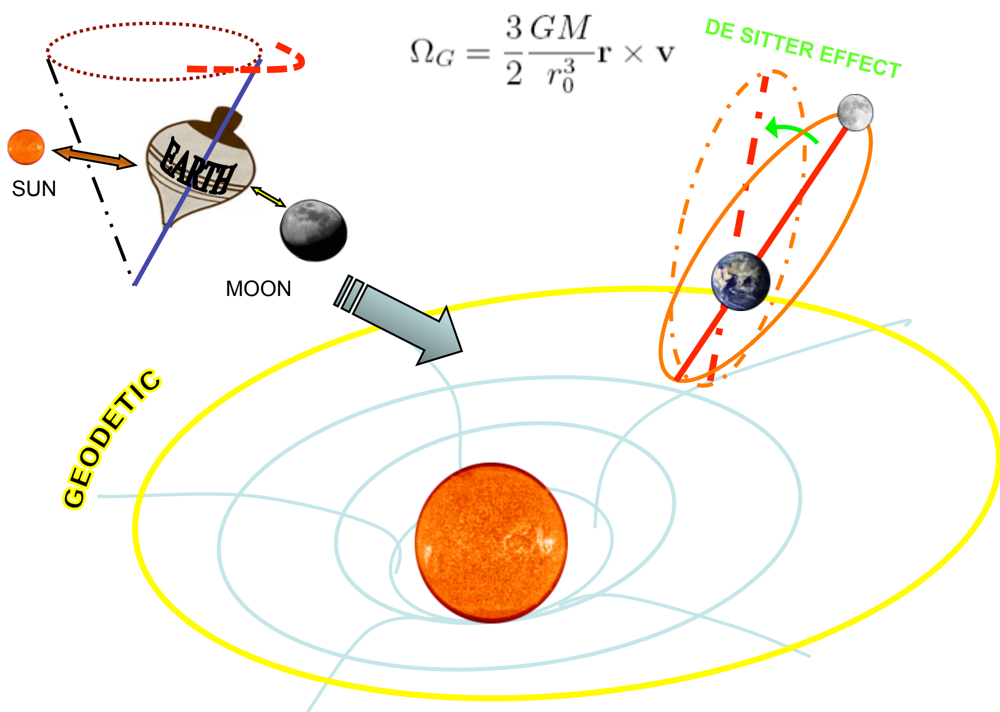
Within a single day, differences between (O-C)'s should have a very small variation. We study the quantity |max(O-C)-min(O-C)| for days where multiple measurements were recorded for Apollo 11, 14 and 15

LLR measurement of geodetic precession

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

precession of a moving gyroscope (the Moon orbiting the Earth) in the field of the Sun

The precession due simply to the presence of a central mass is **~ (3.00± 0.02)m/M$_{orbit}$ ~ 2"/cy**



$$\Omega_G = \frac{3}{2}\frac{GM}{r_0^3}\mathbf{r}\times\mathbf{v}$$

Relative deviation of geodetic precession from GR value:

JPL: J. G. Williams et al 2004 PRL. 93, 261101

K_{GP} = (-1.9 ± 6.4) x10^{-3}

Our measurement with CfA's software (Planetary Ephemeris Program): ~ 1% accuracy

LLR data give unique science products both in relativistic gravity AND in lunar geophysics.

Ω_G geodetic precession

r_0 circular orbit radius

v gyroscope velocity

r position vector

G gravitational constant

M central body mass

LLR measurement of geodetic precession

the data available to us from the Apollo 11, 14 and 15 LRAs. Results are reported for data taken by the old ILRS[8] stations until 2003 (the McDonald station in Texas, USA, in the old location, TEXL, and in its new site equipped with the new laser, MLR2; the CERGA station in France) and data acquired by the new ILRS station, APOLLO[9], from 2007 to 2009:

APOLLO: -9.6×10^{-3}
CERGA: -1.6×10^{-2}
MAUI: 6.0×10^{-3}
MLR2: 9.5×10^{-3}
TEXL: -4.4×10^{-2}

In this analysis $\beta=\gamma=1$, $dG/dt=0$. Nominal errors returned by the fit are significantly smaller than the above estimated values of K_{GP}.

This preliminary measurements are to be compared with the best result published by JPL ($K_{GP}=(-1.9\pm6.4)\times10^{-3}$ [1]), obtained using a completely different software package, developed over the last 40 years. On the contrary, after the original 2% K_{GP} measurement by CfA in 1988, the use of PEP for LLR has been resumed only since a few years, and it is still undergoing the necessary modernization and optimization.

New: Modified gravity theories – “f (R)” theories

Theoretical Aspects of Modified Gravity Theories and Phenomenological/ Experimental constraints

Collaboration between LNF associates (R. March, G. Bellettini, R. Tauraso), LNF physicists with Orfeu Bertolami and Jorge Paramos of the Instituto Superior Tecnico (IST), Universidade Tecnica di Lisboa

The previous LNF research on theories of gravity was focused on gravity with torsion. We studied how constraining space-time torsion by means of Laser Ranging data from the Moon and LAGEOS satellites, and Radar Ranging data from Mercury.

In the present research activity we plan to study constraints on non-minimally coupled gravity by means of Solar System experiments. In non-minimally coupled gravity the action functional of General Relativity is replaced by a more general functional involving two arbitrary functions of the scalar space-time curvature (so called “f (R) theories). We aim to find suitable constraints on such functions of curvature by requiring that predictions of non-minimally coupled gravity be compatible with Solar System tests of gravity

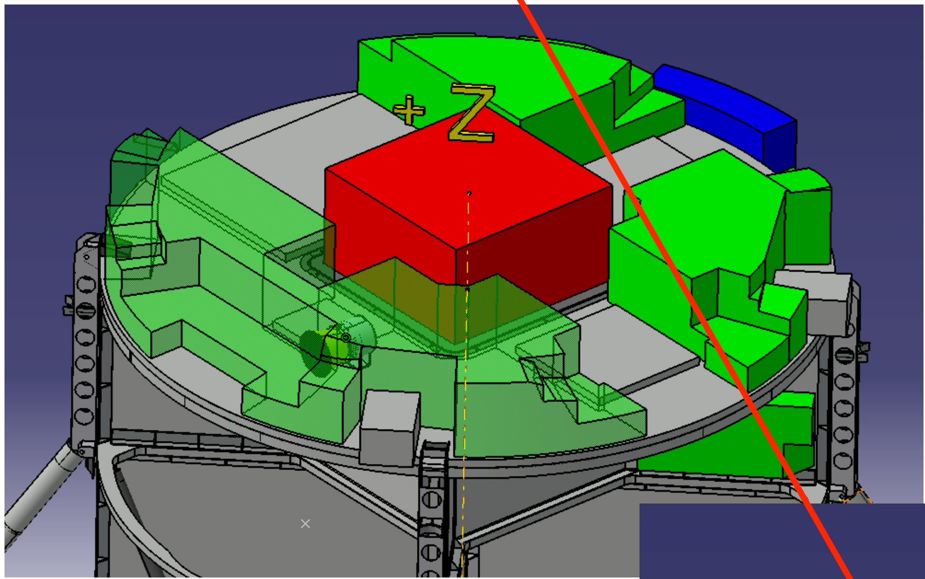
(including Lunar and Mars Laser Ranging and Laser Altimetry)

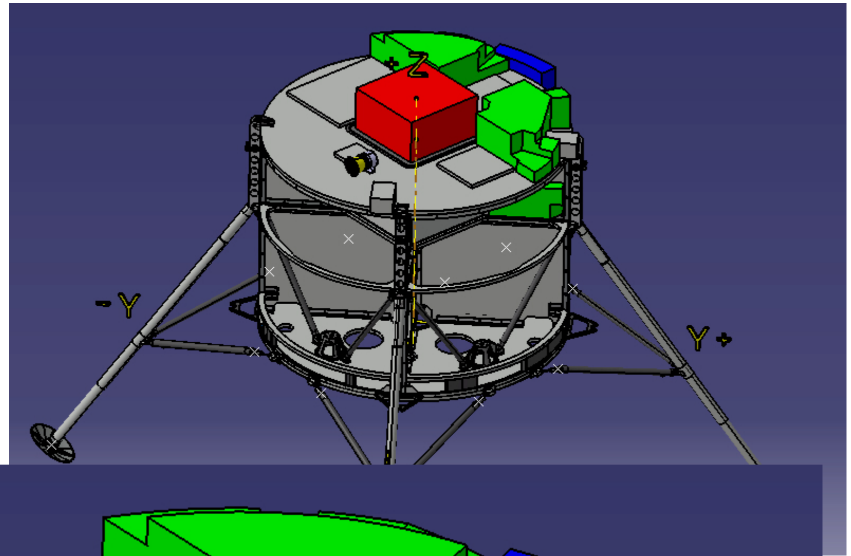
Courtesy of R. Fisackerly (ESA)

We (LNF+US colleagues) have proposals and/or negotiations for:

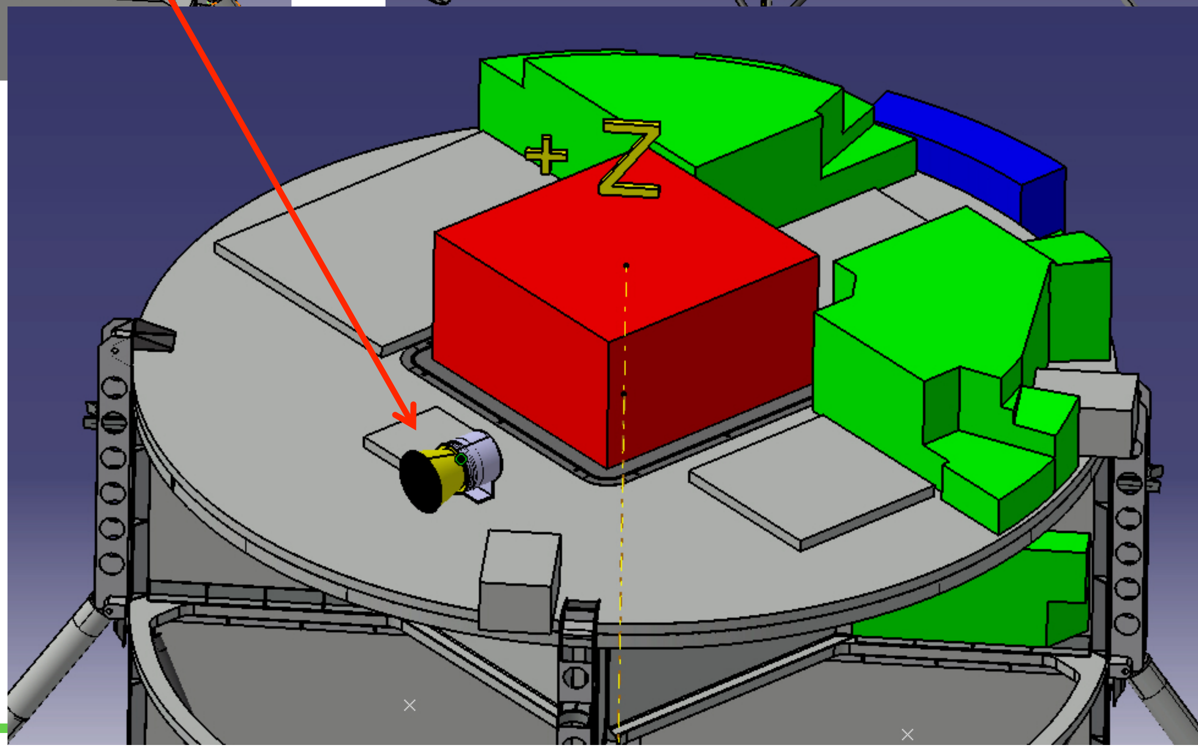
- **European Lunar Lander (led by ESA)**
- **SELENE-2 (JAXA)**
- **CHANDRAYAAN-2 (ISRO +ROSCOSMOS)**
- **GOOGLE-X missions**

MoonLIGHT on the European lunar lander





Need to develop a system for pointing MoonLIGHT to the Earth with 1-2 degree accuracy



SCF_LAB Team (approx. Full Time Equivalents)

	MoonLIGHT-INRRI (GR2)	ETRUSCO-GMES (GR5)
S. Dell'Agnello, Resp.	0.5	0.5
G. Delle Monache, Vice	0.4	0.3
R. Vittori,		0.2
C. Cantone,	0.3	0.7
A. Boni	0.3	0.7
C. Lops,	0.4	0.6
M. Maiello	0.4	0.6
S. Berardi,	0.4	0.6
G. Patrizi,		1
Manuele Martini	0.5	0.5
G. Bellettini	0.5	
R. Tauraso	0.5	
R. March,	0.4	
N. Intaglietta	0.4	0.3
M. Tibuzzi,	0.4	0.6
E. Ciocci,	0.5	0.5
L. Salvatori,		1
M. Lobello,		1
A. Stecchi		0.2
TOTALE	**6.0 FTE**	**9.2 FTE**

Students: L. Palandra,
S. Contessa, S. Rinaldi,
R. Heller (US DoE)

Requests

CSN5:

- Retroreflector payloads for qualifications, robotic positioning system: consumables
- MI/ME
- Apparata/durables (cryoc./computing)

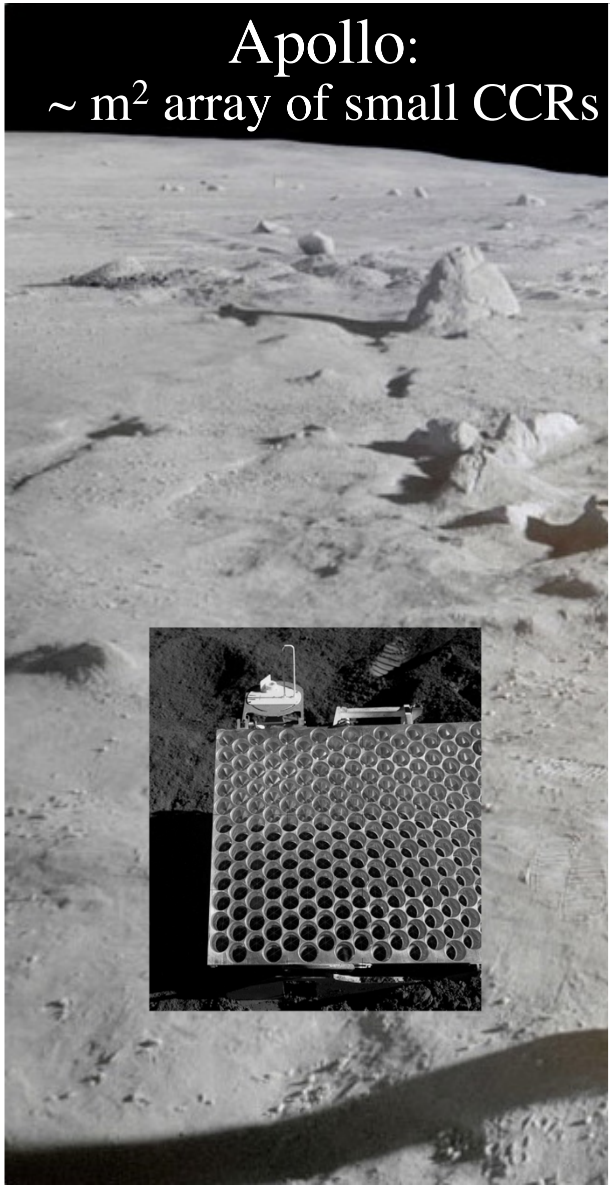
CIF (mu):

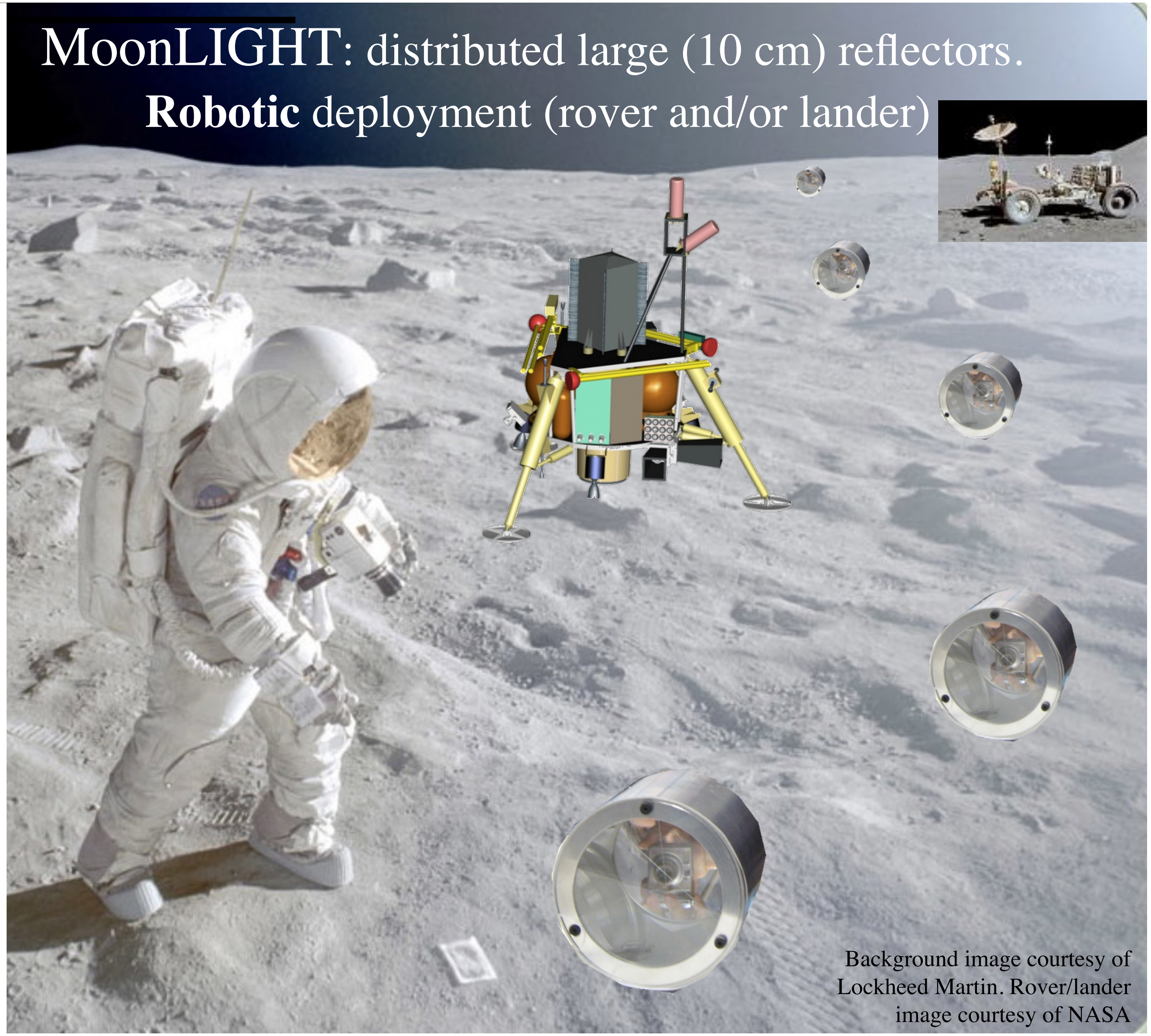
- SPCM officina 0.5 (2012), 1.0 (2013)
- SEA: autom. 4.5 mu (2012), 5.5 (2013); elett. 1 (2012), 1 (2013)
- Cryo: 1 mu (2012), 1 mu (2013).

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, October 2011, Volume 32, Issue 1, pp 19-35 ASI Phase A study.
- [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-6] International Lunar Network (http://iln.arc.nasa.gov/), Core Instrument and Communications Working Group Final Reports.
- [RD-7] Yi Mao, Max Tegmark, Alan H. Guth, and Serkan Cabi, Constraining torsion with Gravity Probe B, Physical Review D **76,** 104029 (2007).
- [RD-8] March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., **Constraining spacetime torsion with the Moon and Mercury**, Physical Review D **83**, 104008 (2011).
- [RD-9] March, R., Bellettini, G., Tauraso, R., Dell'Agnello, S., **Constraining spacetime torsion with LAGEOS**, Gen Relativ Gravit (2011) 43:3099–3126.
- [RD-10] **ETRUSCO-2: An ASI-INFN project of technological development and "SCF-Test" of GNSS LASER Retroreflector Arrays**, S, Dell'Agnello, 3rd International Colloquium on on Scientific and Fundamental Aspects of the Galileo Programme, Copenhagen, Denmark, August 2011

MoonLIGHT: large, single, distributed reflectors





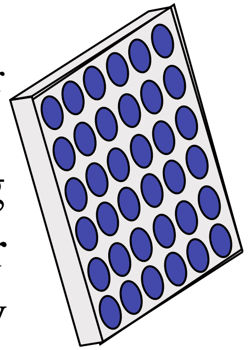
Background image courtesy of Lockheed Martin. Rover/lander image courtesy of NASA

Current dominant error on LLR

Libration rotations up to ~8°
(effect of *e* and *i* of Moon orbit).
Current accuracy of ~ 2 cm

far corner

Libration
Multi-reflector
array



near corner

Laser Pulse

Past
(Apollo)

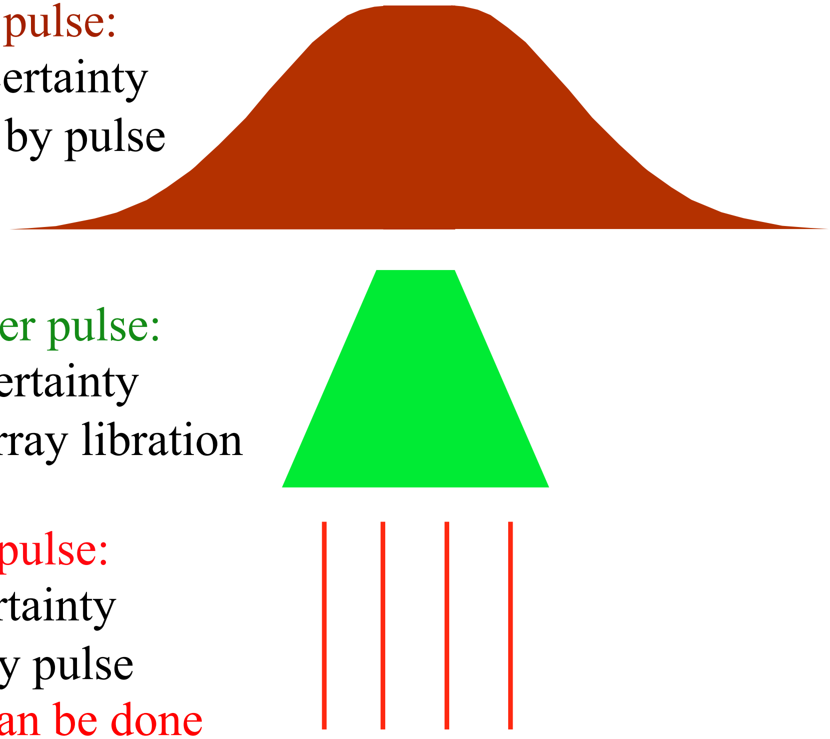
fat laser pulse:
return uncertainty
dominated by pulse

Present
(Apollo)

medium laser pulse:
return uncertainty
dominated by array libration

Future
(MoonLIGHT)

short laser pulse:
return uncertainty
dominated by pulse
Shorter pulses can be done



LLR test of the Strong Equivalence Principle

Williams et al, arXiv: gr-qc/0507083v2, 2 Jan 2009

- LLR test of EP sensitive to *both* composition-dependent (CD) and self-energy violations

UW: Baessler et al, PRL **83**, 3585 (1999);
Adelberger et al Cl. Q. Gravity **12**, 2397 (2001)

- University of Washington (UW) laboratory EP experiment with "miniature" Earth and Moon, measures *only* CD contribution:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,UW} = (1.0 \pm 1.4) \times 10^{-13}$$

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{WEP,LLR} = (-1.0 \pm 1.4) \times 10^{-13}$$

- Subtracting UW from LLR results one gets the SEP test:

$$[(M_G/M_I)_{earth} - [(M_G/M_I)_{moon}]_{SEP} = (-2.0 \pm 2.0) \times 10^{-13}$$

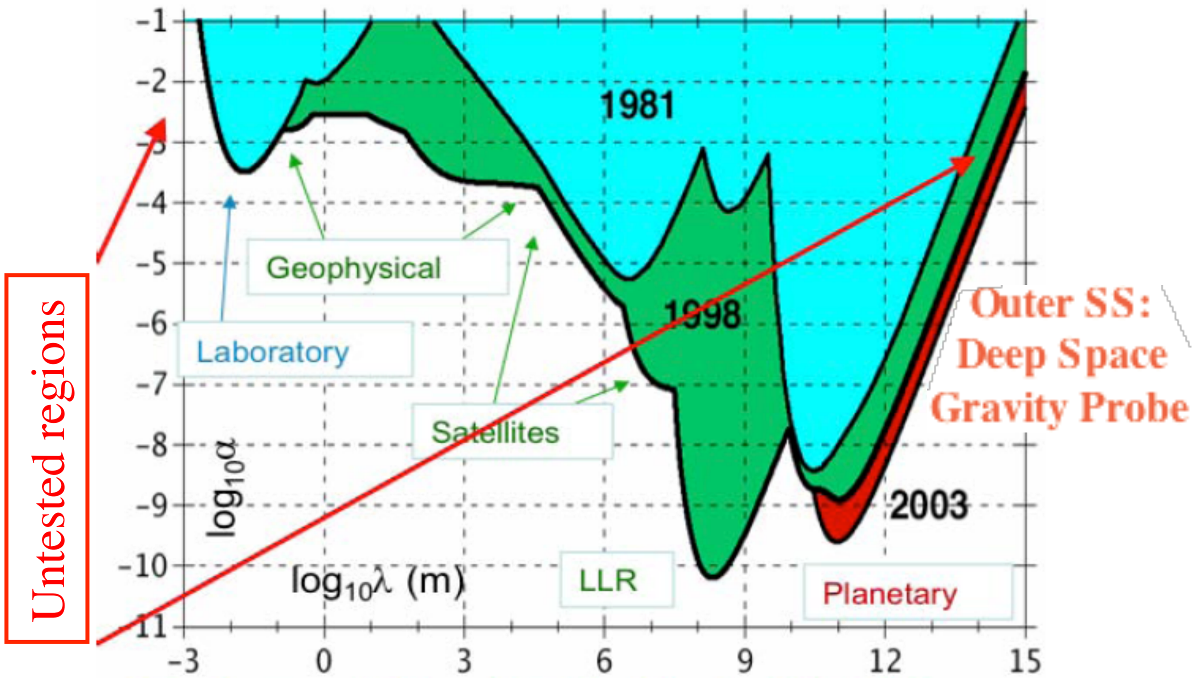
SEP can only be tested LLR

Limits on $1/r^2$ deviations in the Solar System

Current limits on additional Yukawa potential: **$\alpha \times$ (Newtonian-gravity) $\times e^{-r/\lambda}$**

MoonLIGHT designed to provide accuracy of 100 μm on the space segment (the CCR).

If the other error sources on LLR will improve with time at the same level then a MoonLIGHT CCR array will improve limits from ~10^{-10} to 10^{-12} at scales of 10^6 meters



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

Work done on extension of General Relativity with addition of spacetime torsion

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.

Extension of work by Y. Mao, M. Tegmark, A. H. Guth and S. Cabi, PRD 76, 1550 (2007)

Constraining GR with spacetime torsion with the Moon and Mercury [RD-7,8,9]

Lunar Laser Ranging (LLR)
measurement of the lunar geodetic precession:
<u>no deviation from general relativity within</u>

0.64% accuracy

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

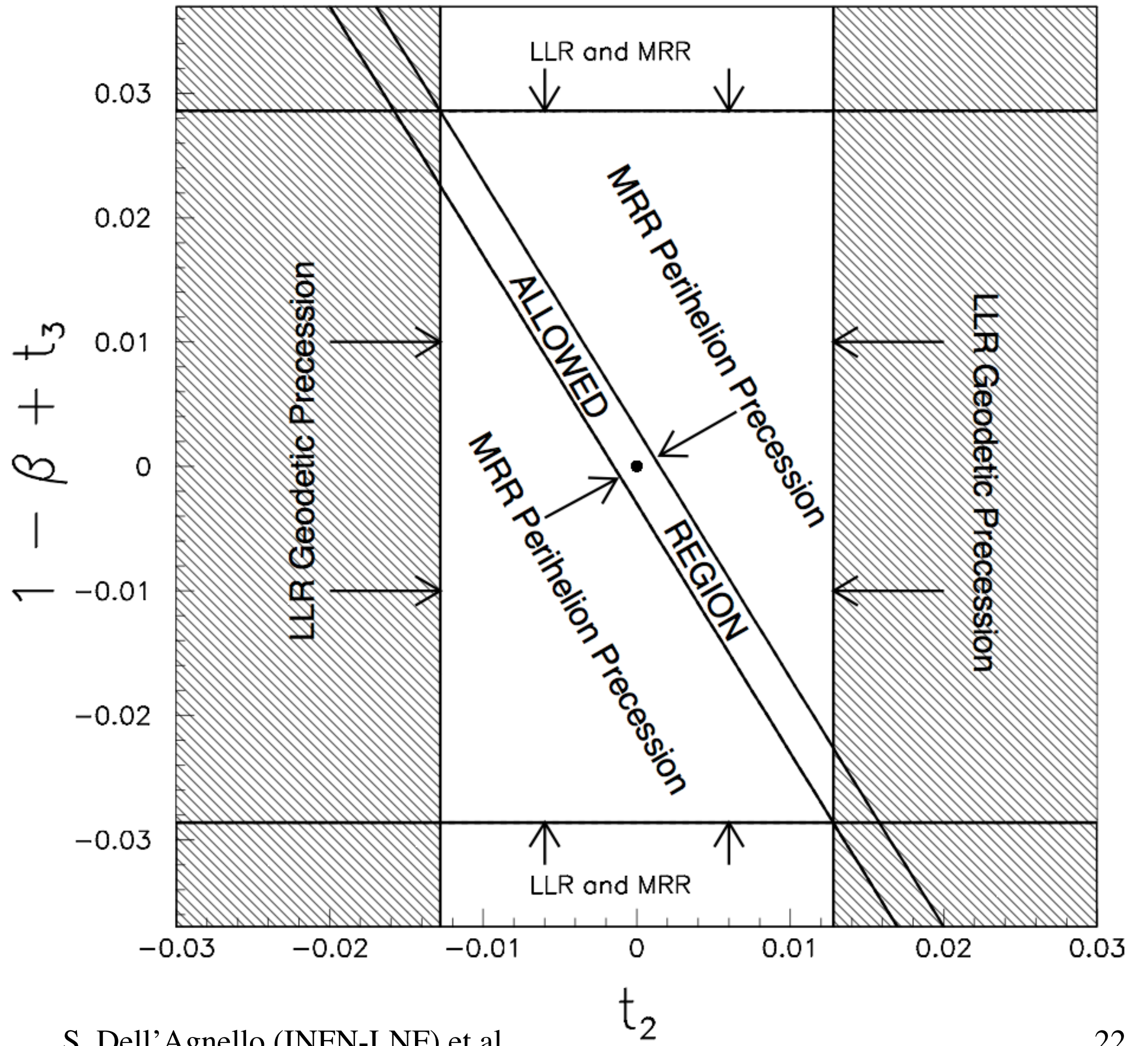
Mercury Radar Ranging (MRR) measurement of Mercury perihelion precession:
<u>no deviation from general relativity within</u>

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.

$$|1 - \beta + 2t_2 + t_3| < 0.003.$$

$$|t_2| < 0.0128.$$



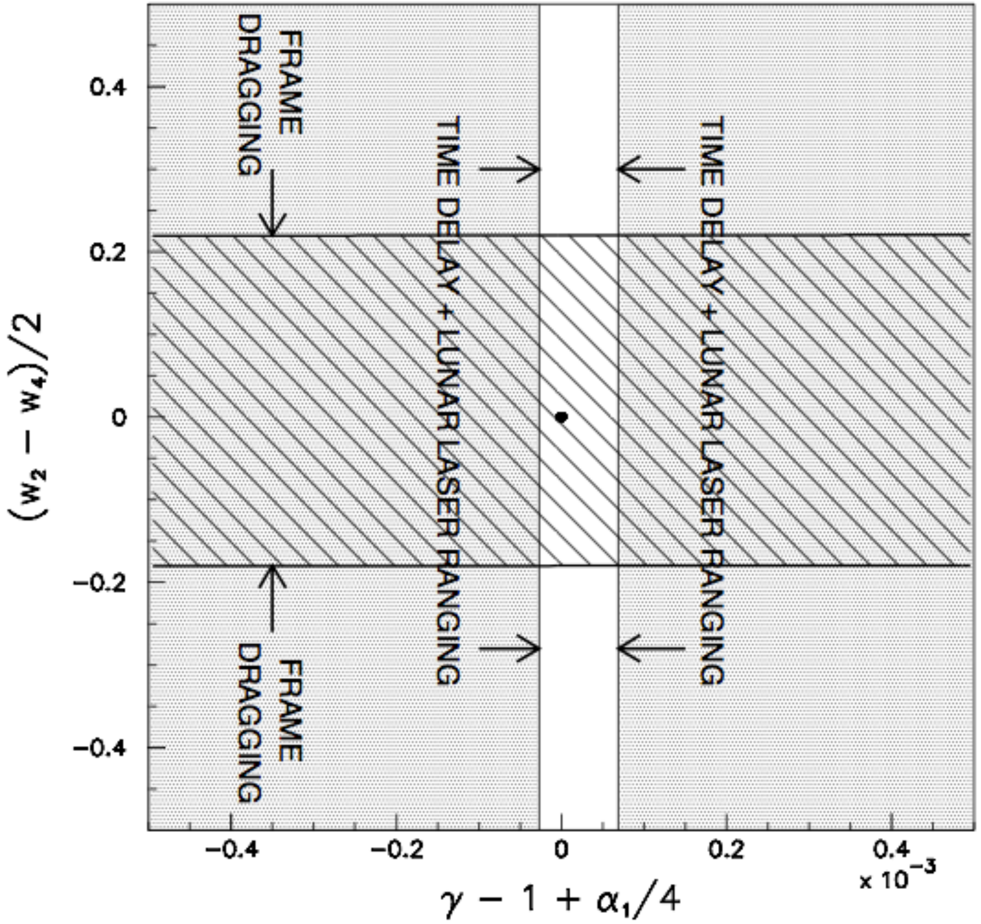
Constraining spacetime torsion with LLR, GP-B and LAGEOS

Geodetic Precession by LLR needs to be subtracted to measure both Lense-Thirring (LT) effect and to set torsion limits with LAGEOS. Gravity Probe B (GPB), instead, has measured separately GP & LT

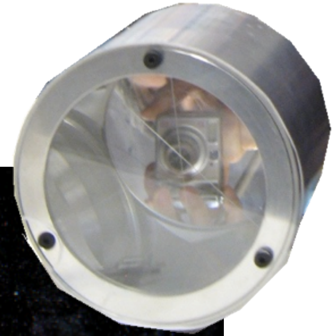
GPB and LAGEOS are complementary LT and torsion experiments. They constrain different linear combinations of 5 additional parameter of the theory, which describe additional FRAME DRAGGING due to SPACETIME TORSION:

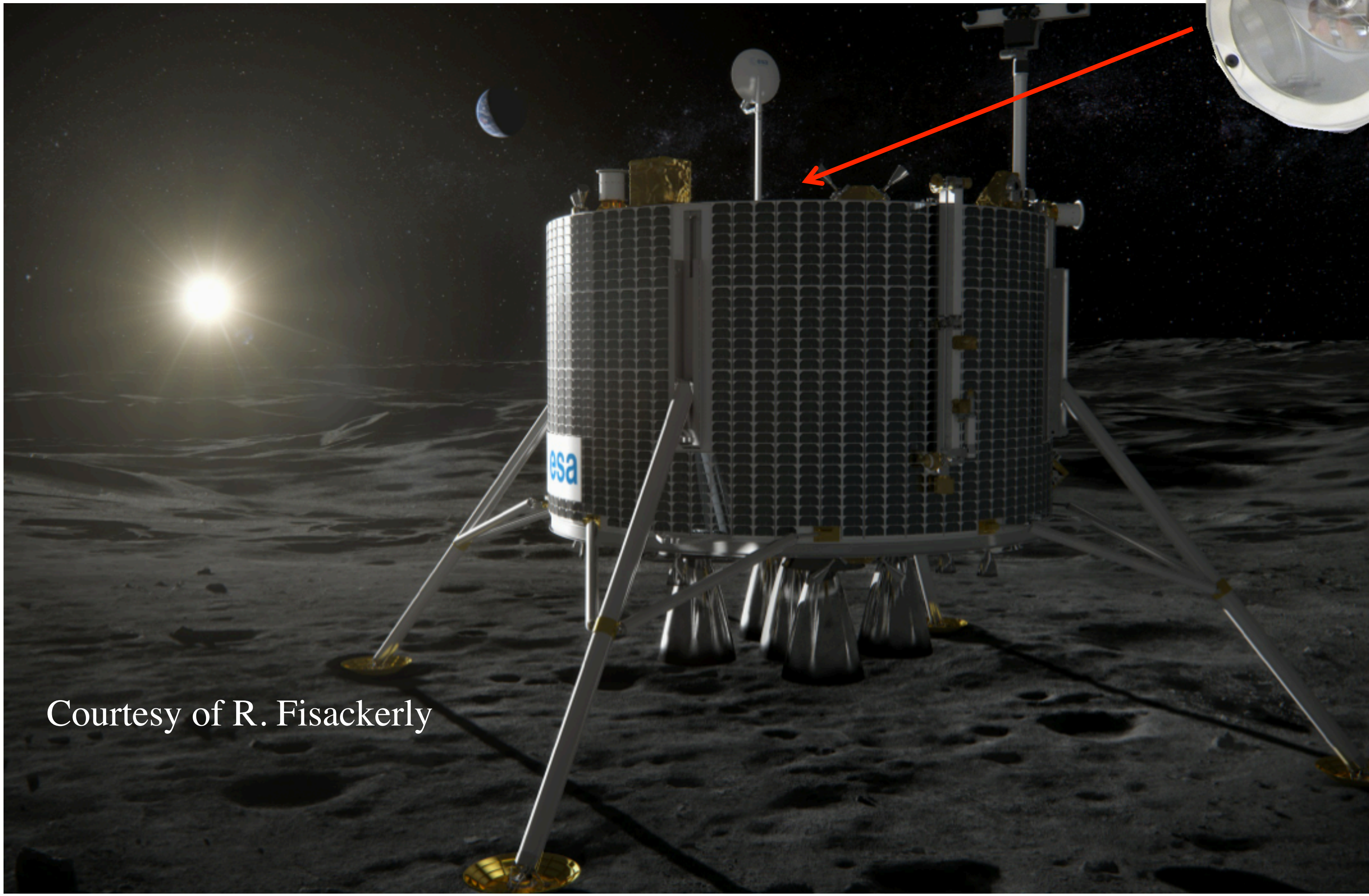
$w_1+w_2+w_3-2w_4+w_5$ (GPB)
$(w_2-w_4)/2$ (LAGEOS, node)

See [RD-7,8,9]



ESA lander at lunar south pole: MoonLIGHT to go on top of lander, pointing to the Earth



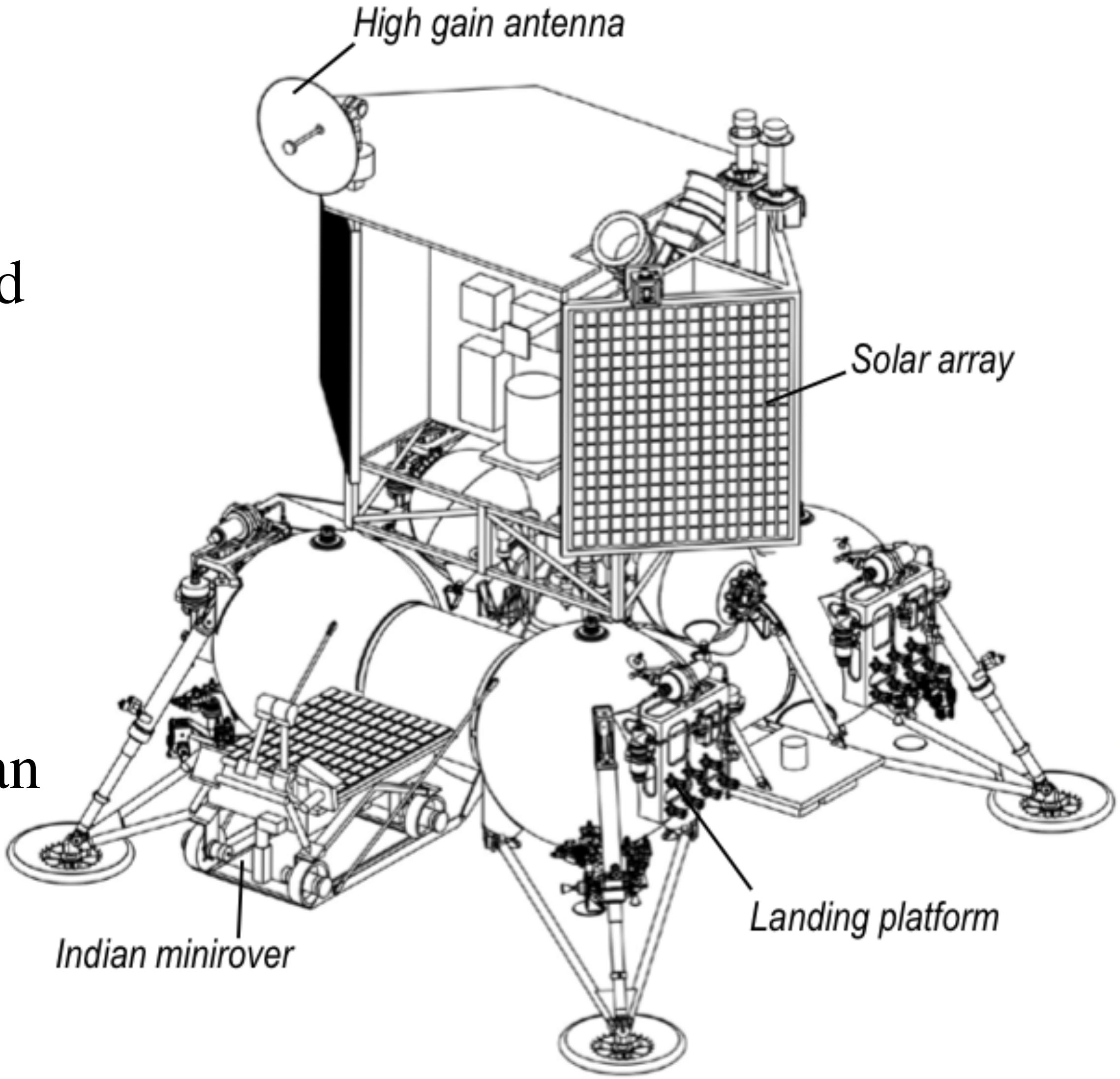


ISRO-ROSCOSMOS Chandrayaan-2 mission to the Moon

- Chandrayaan-1 orbiter discovered recently that water is forming on the Moon surface thanks to solar wind and polar cold traps (and more ….)

- Indian rocket launcher
- Indian orbiter.

- Russian lander and Indian MiniRover in picture



Japan-Italy-US agreement on SELENE-2 LLR

Scientific Cooperation Agreement
of
RISE (Research In SElenodesy) Project, National Astronomical Observatory of Japan
and
University of Maryland
and
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati

January 30, 2012.

Dr. Hirotomo Noda
Principal Investigator of SELENE-2 LLR
RISE project, National Astronomical Observatory of Japan
Hirotomo Noda Date 30. January 2012

Professor Sho Sasaki
Project Manager of RISE Project, National Astronomical Observatory of Japan
Sasaki Date 30 January, 2012

Professor Douglas Currie
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Date 4 October 2011

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Responsible for of SCF Facility
Leader of MoonLIGHT-ILN Experiment of INFN-CSNV
Leader of ETRUSCO-2 Project of Technological Development of ASI and INFN
INFN-LNF
Frascati, Italy
Dell'Agnello Simone Date 26/October/2011