Satellite and Lunar Laser Ranging: Science and Technology Applications

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(www.infn.it/esperimenti/etrusco)

Winter College on Optics: **Light: a bridge between Earth and Space**

**IYL-2015**

ICTP, Trieste, Italy - February 19, 2015
Outline

• Laser Retroreflectors and Laser Ranging in Space
• Satellite Laser Ranging Science application: International Terrestrial Reference System
• SCF_Lab @INFN, Italy: Unique Test Facility for Laser Retroreflectors in Space
• Technology Application: Global Navigation Satellite System
• Lunar Laser Ranging Science Application: Test of General Relativity
• Applications to Exploration of Mars System
• Conclusions and vision foreword
Laser retroreflector working principle

Cube Corner Retroreflectors (CCRs) made of special fused silica glass (Suprasil). Total internal reflection (TIR) on each of the faces causes retroreflection in the same direction of incidence.

Triple (retro)reflection around the corner of the cube
Laser Retroreflectors

For ground positioning metrology: CCRs typically mounted inside half-spheres

Taylor-Hobson sphere
For angular measurements
Laser-retroreflector ground applications: theodolite (or laser “tracker”), retroreflector, time-of-flight

Used for positioning metrology of large physics installations, like Particle accelerators and particle physics experiments (at CERN in In Geneva, Fermilab in USA, Desy in Germany, DAΦNE in Italy ...)

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Laser Ranging in space: measurement of time-of-flight from ground laser station to satellite equipped with laser retroreflectors: pulsed laser, precision timing electronics, atomic clock and optical telescope and detector.
Led by G. Bianco, PI of “Laser Ranging to Galileo” for ASI
Telescope diameter = 1.5 m
SLR. LLR since 2010
Satellite/Lunar Laser Ranging (SLR/LRR)

Physical point-to-point link of laser pulses between ground and space

Unambiguous \textbf{position/distance} measurement (‘laser range’) to cube corner retroreflectors (CCRs) with short laser pulses and a time-of-flight technique. \textbf{Time-tagging} with H-maser clocks

\begin{itemize}
  \item \textbf{Precise} positioning (normal points at mm level, orbits at cm level)
  \item \textbf{Absolute} accuracy (used to define Earth center of mass, geocenter, and scale of length)
  \item \textbf{Passive, maintenance-free} Laser Retroreflector Arrays (LRAs)
\end{itemize}
Lunar Laser Ranging (LLR)
Satellite Laser Ranging (SLR)
Time of Flight measurement (ToF)

Cube corner retro-reflectors, CCRs

ToF, atmospheric corrections

Retroreflection

Normal reflection

LLR

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

LAGEOS “Sector”, engineering prototype by NASA-GSFC, now at INFN-LNF Frascati for testing
Laser Geodynamics Satellites (LAGEOS)
LAGEOS I (1976; NASA), LAGEOS II (1992; NASA/ASI)

Summers students
LAGEOS “Sector”, engineering prototype by NASA-GSFC, now at INFN-LNF Frascati for testing
LAGEOS laser-tracked by ILRS stations of Matera (IT), Herstmonceux (UK), Graz (AT), OCR (FR)
SLR/LLR examples

Moon (d ~ 380000 km): ToF ~ 2.5 sec

LAGEOS (altitude ~6000 km): ToF ~ 0.05 sec

Apollo LRA
Centro di Geodesia Spaziale Giuseppe Colombo
Matera, Italy
Site position known by SLR, VLBI, GNSS (“tri-located”)

MLRO,
Matera Laser Ranging Observatory
LLR since 2010
Satellite/Lunar Laser Ranging (SLR/LLR)

Time of Flight (ToF) measurements of short laser pulses

1st SLR to cube corner retroreflectors (CCRs): October 31, 1964 from NASA-GSFC, by H. Plotkin et al
Intern. Terrestrial Reference System (ITRS)

- **Geocenter** from SLR/LAGEOS
- **Scale** from SLR and VLBI
- **Orientation** from VLBI
- **Distribution** w/GNSS. Also DORIS

For Geodesy, GNSS, Gravity, Earth Observation

SLR CONSTELLATION
Low orbits to the Moon
SCF_Lab: retroreflector characterization

- Two Optical Ground Support Equipment (OGSE)
- SCF (top right) SCF-G (bottom right) dedicated to Galileo, other GNSS
- Two AM0 sun simulators, IR thermometry
- Detailed optical testing
SCF_Lab: retroreflector characterization

- Two Optical Ground Support Equipment (OGSE)
- (Better than) Class 10000 (ISO 7) Clean Room
SCF-Test: Retroreflector characterization

• Accurately laboratory-simulated space conditions
  • TV + Sun (AM0) simulato\ors
  • IR and contact thermometry
  • Payload roto-translations and thermal control

• Deliverables / Retroreflector Key Performance Indicators
  • Thermal relaxation time of retroreflector ($\tau_{CCR}$)
  • Optical response
    • Far Field Diffraction Pattern (FFDP)
    • Wavefront Fizeau Interferometer (WFI), vibe-insensitive

• Invariant lidar Optical Cross Section, OCS, in air/isothermal conditions
CCRs in space: thermal & optical issues

- **Compensation of station-satellite Velocity Aberration (or “point-ahead” effect):** requires accurate dihedral angle offsets w/0.5 arcsec accuracy to control shape (angle $\theta$) and intensity of laser return (FFDP. Far Field Diffraction Pattern) to ground

  - **Thermal perturbations:** temperature gradients across CCR can degrade laser performance
    - A CCR could work at STP, BUT not in space for thermal reasons
  - **Design** CCR array to control thermal and optical properties
  - **SCF-Test:** characterize performance at dedicated INFN-LNF facility

  ![Cube Corner Retro-reflector in space (CCR)](image)

  **Station emits laser from A then moves to B**

  **FFDP peaks back to ground**

  GNSS velocity aberration is
  $\theta \approx 2 \frac{v}{c} \cos \phi \approx 25 \mu\text{rad} \approx 500 \text{ m on the ground}$

  Achievable with choice of CCR diameter or variety of dihedral angle offsets from 90°

  Nominal distance between FFDP peaks is
  $2 \times \theta = 50 \mu\text{rad} \Rightarrow 1 \text{ Km}$
GLONASS, GPS and GIOVE-A/B CCRs

Benefits of LRAs on GNSS
- Only independent validation/calibration of GNSS orbits, with 2-4x better precision
- Absolute positioning, i.e., wrt ITRS
- Long term stability & geodetic memory
- Therefore: combining SLR+GNSS data will improve orbit reconstruction

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Russian GLONASS/GPS/GIOVE-A/B reflectors

Al-coated fused silica laser retroreflector technology, with thermal mounting not optimized as LAGEOS and Apollo Technology used since the 1980s until 2010s. Coating now abandoned due to SLR return inefficiencies experienced by ILRS and due to SCF-Test results.

Third and last GPS flight array ever made by USSR for GPS

- ~19 x 24 cm²
- ~1.3 Kg,
- 32 CCRs.

Property of University of Maryland (C. Alley, D. Currie), SCF-Tested at INFN-LNF
SCF-Test of GLO/GIOVE: de-qualification of Al coating

Sun on: laser return (FFDP) severely degraded (2 km distance)

Sun off: laser return (FFDP) peaks restored at 1 km distance

Factor ~7 reduction of FFDP at GNSS velocity aberration
SCF-Test of GLONASS, GIOVE

$T_{\text{outer ccr face}}(K)$ vs. time (sec)
SCF movies (of thermal behaviour)

SCF-Test of LAGEOS Sector:

IR movie of Sector moving from AM0 (sun simulator) window to laser window at 90°. IR camera is in between

For ESA’s test of Galileo reflectors, rotation accomplished in ~few seconds
LAGEOS IS THE ILRS REFLECTOR STANDARD

LAGEOS “Sector”, engineering model of NASA-GSFC. Inherits from Apollo. SCF-Tested @300K at INFN

LAGEOS: unperturbed laser return

LAGEOS: 20% degradation of laser return after 3 hr exposure to Sun simulator

GLO/GPS/GIOVE: ~ 87% degradation
SCF_Lab with Elachi (JPL) & Flamini (ASI)
GNSS, Global Navigation Satellite System

~100 satellites, with laser retroreflectors

Indian IRNSS: 7 regional satellites

Japanese QZSS: 3 regional satellites

European Galileo: 26 satellites

US GPS: 24 global satellites

Chinese Compass/Beidou: 20 global, plus regional satellites

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How satellite navigation works

latitude + longitude + altitude + time check = position reading
Galileo implementation plan
Galileo In-Orbit Validation satellite (IOV)

MW (microwave) Antennas

H-maser clocks inside

LRA
(Laser Retroreflector Array)
Satellite Laser Ranging (SLR): position/distance measurement to cube corner retroreflectors (CCR) with short laser pulses and a time-of-flight technique time-tagging with H-maser clocks

- **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)
1: L-band antenna Transmits the navigation signals in the L-band.
2: Search & rescue antenna
3: C-band antenna
4: Two S-band antennas
5: Infrared Earth sensors
6: visible light Sun sensors
7: Laser retroreflector
8: Space radiators
9: Passive hydrogen maser clock

Mass: about 700 kg
Size with solar wings stowed: 3.02 x 1.58 x 1.59 m
Size with solar wings deployed: 2.74 x 14.5 x 1.59 m
Design life: more than 12 years
Available power: 1420 W (sunlight) / 1355 W (eclipse)
Towards a ‘Galileo’ Terrestrial Reference System

A Terrestrial Reference System (TRS) is a spatial reference system co-rotating with the Earth in its diurnal motion in space. In such a system, positions of points anchored on the Earth's solid surface have coordinates which undergo only small variations with time, due to geophysical effects (tectonic or tidal deformations). A Terrestrial Reference Frame (TRF) is a set of physical points with precisely determined coordinates in a specific coordinate system (Cartesian, geographic, mapping ...) attached to a TRS. Such a TRF is said to be a realization of the TRS. Next slide shows the current International TRS/TRF

In the future: when the Galileo constellation will be complete and fully operational, a GTRF realization and long-term maintenance might be possible, also thanks to its retroreflectors
GNSS Retroreflector Arrays (and LAGEOS))

• Left: Galileo IOV reflector array
• Center: LAGEOS Sector, reference payload for Earth Orbits
• Right: ASI-INFN product for standard GNSS Retro Array (GRA)
Test of Galileo IOV reflectors for ESA

Assembly setup ready for testing.
Galileo IOV Laser Retroreflectors

- 84 Corner Cube Retroreflectors (CCR)
  - doped fused silica (Suprasil 311) glass tetrahedron
  - no metallic coating on reflective surfaces
  - front surface coated with ITO
  - aperture face is included in a circle of 43 mm diameter
  - Minimum aperture 33 mm diameter
  - height of the tetrahedron is 23.3 mm
  - Iso-static mounting to plate
  - N = 1.46, critical angle 16.9°
    - which covers the entire LRR operating range (Earth radius of 12.44°)
    - no coating, total reflection is obtained without any loss
  - Velocity aberration compensation 24 μrad
  - CCR are randomly oriented
  - LRA Centre of Phase TBD after Qualification

- This information will be published in an update to “Specification of Galileo and GIOVE Space Segment Properties Relevant for Satellite Laser Ranging” (ESA-EUING-TN-10206) and in the “Mission Support Request Form”
Test of Galileo IOV reflector model
Retroreflector Front Face Infrared Temperature

Infrared Image of GALILEO IOV retroreflectors during SCF-Test at 0°C, heating phase

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SCF-Test of LAGEOS GLO/GPS/Giove

LAGEOS IS THE ILRS REFLECTOR STANDARD

LAGEOS “Sector”, engineering model of NASA-GSFC. Inherits from Apollo. SCF-Tested @300K at INFN

LAGEOS: unperturbed laser return

LAGEOS: 20% degradation of laser return after 3 hr exposure to Sun simulator

GLO/GPS/GIOVE: ~ 87% degradation
• Thermal-optical-vacuum test, “SCF-Test”, along the GNSS Critical Orbit, “GCO”

• Sunrise-Eclipse-Sunset probes critical features of the thermal and optical behavior of the CCR
GRA optical performance: no degradation wrt nominal (in-air) within ±15% errors
Co-location of SLR & GNSS positioning

Co-location at GNSS satellite (space-tie)

Laser positioning of GNSS referenced to *geocenter* thanks to laser ranging to LAGEOS, whose orbit defines *geocenter*

Co-location at geodesy station (ground tie)

Galileo IOV or GPS

LAGEOS

MLR (ASI) or GGAO (NASA)
Laser Ranging validation of GNSS orbits

Mean and Sigma of SLR O-C Residuals (mm)

IGS  IGR  COD  EMR  ESA  GFZ  JPL  MIT  NGS  SIO  ESA Repro
“Residual” between GPS orbit and Satellite Laser Ranging (SLR) measurement

R-716 for 2007 - 2014

RMS of SLR residuals for satellite 716
Conclusions: benefits of SLR for GNSS

- SLR by ILRS provides independent validation of GNSS orbits
- Combining GNSS and SLR measurements is NOT easy, but provide the most accurate and stable GNSS orbits, with absolute reference to the geocenter and scale of the ITRS
- To achieve this improvement we need
  - Best possible LRAs on GNSS satellites: GLONASS, Galileo, GPS, Beidou, IRNSS, QZSS, and their future generations ...
  - ILRS Stations keep optimizing laser ranging procedures & instrumentation
Lunar Laser Ranging

- Laser invented ~1960
- MIT and URSS shoot lasers to lunar surface in the ‘60s
- Laser Retroreflectors deployed by 3 Apollo missions and 2 Luna/Lunokhod missions

- Apollo: arrays of fused silica Suprail 1 with circular aperture of 3.8 cm
- Apollo 11 e 14: used 100 CCR
- Apollo 15: 300 CCR
LLR: only Apollo experiment still providing data since 1969 (2009 NASA patch)
Riflettori lunari di 1ª generazione

Apollo 11

Apollo 14

Lunokhod 2

Lunokhod 1

Apollo 15
Precision: $\sim 2 \text{ cm} \sim 5 \times 10^{-11}$ of Earth-Moon distance

Distance and size approximately to scale
(animated GIF from Wikipedia)
Round-trip time of flight $\sim 2.5$ sec
Distance $\sim 384,000$ km
L’uomo è atterrato davvero sulla Luna?

Lo testimoniano da 40 anni i retroriflettori delle missioni Apollo. Non basta?
Immagini di Apollo 11 da LROC, la camera digitale del Lunar Reconnaissance Orbiter (NASA)
Apollo 11 & 14 seen by LROC on LRO
Apollo 14 seen by LROC on LRO

Scientific Instruments
Astronaut Footpath
LM Shadow
Lunar Module (Antares)

100 meters
Lunokhod 1, re-discovered by LRO

French retroreflector on Russian rover
Lunokhod 3 at NPO-Lavochkin, Moscow
Lunokhod 3 at Space Museum, Moscow
Lander Luna 17/Rover Lunakhod 1, ritrovati da LRO

Enlargement of Luna 17 lander, note the rover Lunokhod 1 tracks starting at the ramp and circling the lander [NASA/GSFC/Arizona State University].
Lunokhod 1 re-discovered by Laser Ranging

Nuova stazione ‘APOLLO’ (dal 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
LLR distance precision from 1970 to 2000s

Prima:
centinaia di metri
Lunar retroreflectors: Apollo & Lunokhod
ANALYSIS OF GCO Orbit

• Initial condition: payload to cold shield (-90°) and plate at steady state at -45°C.
• Sunrise (3h): 1FFDP+1IR every 20m.
• Earth Shadow (1h): 1IR every 30s, 1FFDP/min for first 15m, 1FFDP/2m for next 15m, 1FFDP/30m for last 30m.
• Sunset (3h): 1FFDP+1IR every 20m.

- Thermal data analysis: IR pictures analyzed them with a dedicated software and temperature variation of the 7 temperature probes positioned on the rear of each CCR mounting of the array.

- Optical data analysis: MATLAB program to process the raw optical data of the two polarization components. For each tested CCR, the program computes:
  • FFDP
  • OCS intensity distribution vs va.
  • OCS intensity distribution in annulus at 24 μrad va.
  • Average OCS intensity at 24 μrad velocity aberration at total CCR FFDP.
GRA and Galileo IOV reflector performance

- GRA (GNSS Retroreflector Array) by INFN-ASI: 3.5 kg, 400 mm diameter; lighter/smaller than Galileo IOV
- No degradations within ±15% errors (note scale of plot)
Advanced laser reflectors for the Moon

• The Moon: a laser-ranged test body for General Relativity
• Precision of old reflector array limited by librations and
• New **single, large reflector** “MoonLIGHT”
  • D. Currie, Univ. of Maryland
    • Apollo Veteran
  • Italian Teams: INFN (PI), ASI-Matera, University of Padua
Δ$t$

**Pulse to Moon**

**Wide Pulse to Earth**

*Apollo, Lunokhod, ANY array*

1 unresolved widened pulse back to Earth due to multi-CCR and lunar **librations**

Many small CCRs

**Pulse to Moon**

**Short Pulses to Earth**

*MoonLIGHT/ LLRRA21 Single CCR*

3 separated pulses back to Earth

Large, single, CCRs
MoonLIGHT: single, large sparse reflectors

Apollo: ~ m² array of small CCRs

MoonLIGHT: distributed large (10cm) CCRs. Robotic deployment (rover and/or lander)

Background image courtesy of Lockheed Martin. Rover/lander image courtesy of NASA
Lunar mission opportunities

- **Moon Express**, lander for Google Lunar X Prize, 2015

- Proposal to IKI-RAS/Roscosmos for the Lander **Luna-27**
MoonLIGHT laser retroreflector

(Moon Laser Instrumentation for General relativity High accuracy Tests)

MoonLIGHT single reflector vs. Apollo reflector arrays:
- Suprasil 311 vs. Suprasil 1
- Optical specs wave/10 RMS vs. wave/4
- Single reflector 100 mm vs. array of 100-300 reflectors of 38 mm
- Laser return better than Apollo 15 (brightest reflector array) due to A15 degradation, likely due to dust deposit
Science with Lunar Laser Ranging

- **General Relativity**: precisions tests, improvement potentially up to $\times 100$, in the long term
- **Selenodesy**: measurement of deep interior; first evidence of molten lunar core; complementary to GRAIL
- **Exploration**: precise positioning of landing site, hopping and roving. GLXP

| Science measurement / Precision test of violation of General Relativity | Apollo/Lunokhod few cm accuracy* | MoonLIGHTs 1 mm | MoonLIGHTs 0.1 mm |
|---|---|---|
| Parameterized Post-Newtonian (PPN) $\beta$ | $|\beta - 1| < 1.1 \times 10^{-4}$ | $10^{-5}$ | $10^{-6}$ |
| Weak Equivalence Principle (WEP) | $|\Delta a/a| < 1.4 \times 10^{-13}$ | $10^{-14}$ | $10^{-15}$ |
| Strong Equivalence Principle (SEP) | $|\eta| < 4.4 \times 10^{-4}$ | $3 \times 10^{-5}$ | $3 \times 10^{-6}$ |
| Time Variation of the Gravitational Constant | $|G/G_0| < 9 \times 10^{-13} \, \text{yr}^{-1}$ | $5 \times 10^{-14}$ | $5 \times 10^{-15}$ |
| Inverse Square Law (ISL) | $|\alpha| < 3 \times 10^{-11}$ | $10^{-12}$ | $10^{-13}$ |
| Geodetic Precession | $|K_{gp}| < 6.4 \times 10^{-3}$ | $6.4 \times 10^{-4}$ | $6.4 \times 10^{-5}$ |

Geodetic precession in GR

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

\[ \sim 3.00 \text{ m/orbit (28 Earth days) } \sim 2''/\text{century} \]

Relative deviation of geodetic precession from GR value:

\[ K_{GP} = \left( \Omega_G - \Omega_G \right) / \Omega_G \]

\( \Omega_G \) = geodetic precession
\( r_0 \) = circular orbit radius
\( v \) = gyroscope velocity
\( r \) = position vector
\( G \) = gravitational constant
\( M \) = central body mass
‘Small LAGEOS’ to test $1/r^2$ in deep space

- Active spacecraft and passive test-mass
- **Objective**: accurate tracking of the test-mass
- 2-step tracking: common-mode noise rejection
  - Radio: Earth → spacecraft
  - Laser: spacecraft → test-mass
- Flexible formation: distance may vary
- The test mass is at an environmentally quiet distance from the craft, > 250 m
- Occasional maneuvers to maintain formation
INRRI: INstrument for landing-Roving laser Retroreflector Investigations

• Laser-located by orbiters like NASA mission LADEE
  – LLCD demonstrated laser time-of-flight with ~100 picosec accuracy
  – Accurate positioning of landing site and roving exploration activity
  – Multiple INRRIs: establish MGN (Mars Geophysical Network)

• Motivated by effort on lasercomm by NASA, ESA, etc.:
  – Mars Lasercomm terminals by JPL (Mars 2020), GRC (iROC)
  – ESA: OGS @Tenerife, Alphasat-Sentinel 1A; OPALS @ISS by JPL

• Passive, maintenance-free, lifetime of decades
  – Several geometries/n. CCRs: 5, 7, 8, …
  – Lightweight: ~25 gr
  – Compact (~5 cm x 2 cm)
  – No pointing required
INRRIs on Moon, Mars, Jupiter/Saturn moons

- Selenolocate Rover/Lander with laser retroreflector:
  - Laser Ranging/Comm to reflectors anywhere (LLCD/iROC/OPALS-like)
- Deploy INRRI networks. Also on far side of Earth’s Moon
Some NASA slides by D. Cornwell

- Shown at workshop IPM-2014, Instrumentation for Planetary Mission
  - November 2014 at NASA-GSFC
- Approved for public release
- Shown to justify how deployment for laser retroreflectors for Solar System exploration can exploit lasercomm payloads capable or time-of-flight (laser ranging) measurements
NASA’s Optical Communications Program

Don Cornwell, Director
Optical Communications Division
Space Communications and Navigation (SCaN) Program
NASA Headquarters, Washington, DC

Keeping the universe connected.

www.nasa.gov
Where is SCaN within NASA?

NASA Administrator
General Charles Bolden

Associate Administrator
for Human Exploration and Operations
Mr. William Gerstenmaier

Chief Technologist
Chief Engineer
Safety and Mission Assurance
Chief Health and Medical Officer
Chief Scientist

Optical Communications Division
Dr. Donald Cornwell

Launch Services Office
CF

Space Communications & Navigation Program
Mr. Badri Younes
CG

Resources Management Office
DH

Strategic Analysis & Integration Division
CL

Mission Support Services Office
CL

Exploration Systems Development Division
SLS
MPCV
21st Century Ground Systems

Human Spaceflight Capabilities Division
- Core Capabilities
  - RPT
  - SFCO
  - MAF
  - MOD
  - EVA
  - CHS

International Space Station Division
- System O&M
  - Crew & Cargo Transportation Services

Commercial Spaceflight Development Division
- Commercial Crew
- COTS

Advanced Exploration Systems Division
- AES
- Robotic Precursor Measurements

Space Life & Physical Sciences Research & Applications Division
- HRP
- Fund. Space Bio
- Physical Sciences

HEOMD ORG
4.9.12
The Lunar Laser Communication Demonstration (LLCD), Flown to the Moon in September 2013

NASA GSFC, MIT Lincoln Laboratory, NASA JPL, ESA
LLCD: NASA’s First High-Data-Rate, Two-Way Space Lasercomm Demonstration

• LLCD was flown to the Moon on the Lunar Atmosphere and Dust Environment Explorer (LADEE)
• Launched on September 6, 2013
• IMMEDIATE LASER CONTACT on October 17, 2013
• Set records for download and upload speeds to the Moon
• Planned operations ended November 22nd

LLCD returned data by laser to Earth at a record 622 Megabits per second (Mbps) = streaming 30+ HDTV channels simultaneously!
LLCD Accomplishments – Streaming HD Video and Delivering Useful Scientific Data from LADEE to Earth

Real LADEE Science Data and Telemetry Transmitted via LLCD

NASA Administrator Charles Bolden filmed a short message to become the first video relayed to and from the moon.

Here is his message...
Geographic site diversity is required to reduce the likelihood that clouds will interrupt the link; it also allowed the opportunity to demonstrate international interoperability while sharing the costs of the system of LLCD.
Optical Payload for Lasercomm Science (OPALS)

ESA’s Optical Ground Station

2400 m above sea level on the volcanic island of Tenerife, the OGS has performed world-class demonstrations of optical Space-to-Ground communications. Several laser communications experiments are performed between the OGS and Telescopes in La Palma island 143 km away, using visible green laser beams for aligning the transmitting and receiving telescopes. This picture also features Tenerife’s Teide volcano and the Milky Way in the background.
LaserComm for the Mars 2020 Rover

- Optical Terminal will support dual links:
  - “Proximity” link, to optical terminal on orbiter (20 Mb/s max)
  - Direct-To-Earth link (200 kb/s max, from 0.5 AU)
- Optical Aperture Diameter: 5 cm
- Average Laser Power: 1 W
- DC Power Consumption: 50 W
- Mass: 5.7 kg
- Volume: 4.6 liters
INRRI for Mars Rovers (and Landers)

- Geodesy/Geophysics: Mars Geophysical Network, Definition of Meridian 0
- Georeference exploration (Also light/laser flash + optical camera)
- Precision Lidar-based landing (return to astrobiologically relevant site)
- Lidar atmosphere trace species detection
- Lasercomm test & diagnostics
INRRI for Mars Rovers (and Landers)

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INRRI-2020:
INstrument for landing-Roving laser Retroreflector Investigations on Mars 2020
Europa/Encelado, “the” icy/rocky moons

• Europa/Enceladus Cube Corners retroreflectors for Exploration/Exolife
  • Recent NASA AO on Europa did not include landing/roving
  • But JPL has study for Europa Lander
  • Ultimate destination: Enceladus, and its “springlets”

• Terrestrial and Celestial Reference Frames
  • Link Earth-Moon, Mars/Phobos/Deimos and Europa/Encelado laser retroreflector networks

• Depending on mission/body
  • Different geometries
  • Varying sizes & n. of reflectors
  • Depending especially on s/c orbit (velocity aberration)
The Martian system

• Goals for the Mars surface
  • Georeferencing of lander or rover exploration activity
  • Define Mars Prime Meridian
    • Now: Airy-0 crater, accurate at 50 m level
  • Multiple INRRIs on landers/rovers can establish MGN
  • Lasercomm test/diagnostics (wavelength independent)
  • Atmospheric trace species detection by space-borne lidar
    • Full column sampling, at varying angles
  • Lidar-based/aided landing

• Phobos /Deimos
  • PANDORA: Phobos AND DeimOs laser Retroreflector Array
Conclusions

• Satellite and Lunar Laser Ranging started in 1964 about 50 years ago (~same time of ICTP)
  • Laser: T. Maiman, C. Townes, ~1960
  • Now: ILRS network of 40+ ground laser stations world-wide
    • SCF_Lab @INFN, Italy to design, build, validate, characterize, diagnose Laser Retroreflectors in Space

• Applications:
  • International Terrestrial Reference System (geocenter, scale)
  • Global Navigation Satellite System (Galileo etc)
  • Lunar Laser Ranging (Test of General Relativity)
  • Exploration of Mars System and rest of solar system, exploiting lasercomm
## Acronyms and definitions

1. AM0: Air Mass Zero
2. ASI: Agenzia Spaziale Italiana
3. CCR: Cube Corner Retroreflector
4. EO = Earth Observation
5. ESA: European Space Agency
6. ETRUSCO: Extra Terrestrial Ranging to Unified Satellite Constellation
7. DEM = Digital Elevation Model
8. FFDP: Far Field Diffraction Pattern
9. FOC: Full Orbit Capability
10. GCO: GNSS Critical half Orbit
11. GMES = Global Monitoring for Environment and Security
12. GNSS: Global Navigation Satellite System
13. GPS: Global Positioning System
14. GRA: GNSS Retroreflector Arrays
15. IOV: In Orbit Validation
16. IPR: Intellectual Property Rights
17. ITRF: International Terrestrial Reference Frame
18. ITRS: International Terrestrial Reference System
19. KPI: Key Performance Indicator
20. OCS: Optical Cross Section
21. LAGEOS: LAr Geodynamics Satellite
22. SCF: Satellite/lunar/GNSS laser ranging and altimetry Characterization Facility
23. SCF-G: Satellite laser ranging Characterization Facility optimized for GNSS
24. SLR: Satellite Laser Ranging
25. WI: Wavefront Interferogram

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19/Feb/2015, ICTP-Trieste
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