The History and Future of Satellite Laser Ranging

Dr. John J. Degnan
Sigma Space Corporation
4801 Forbes Blvd.
Lanham, MD 20706 USA

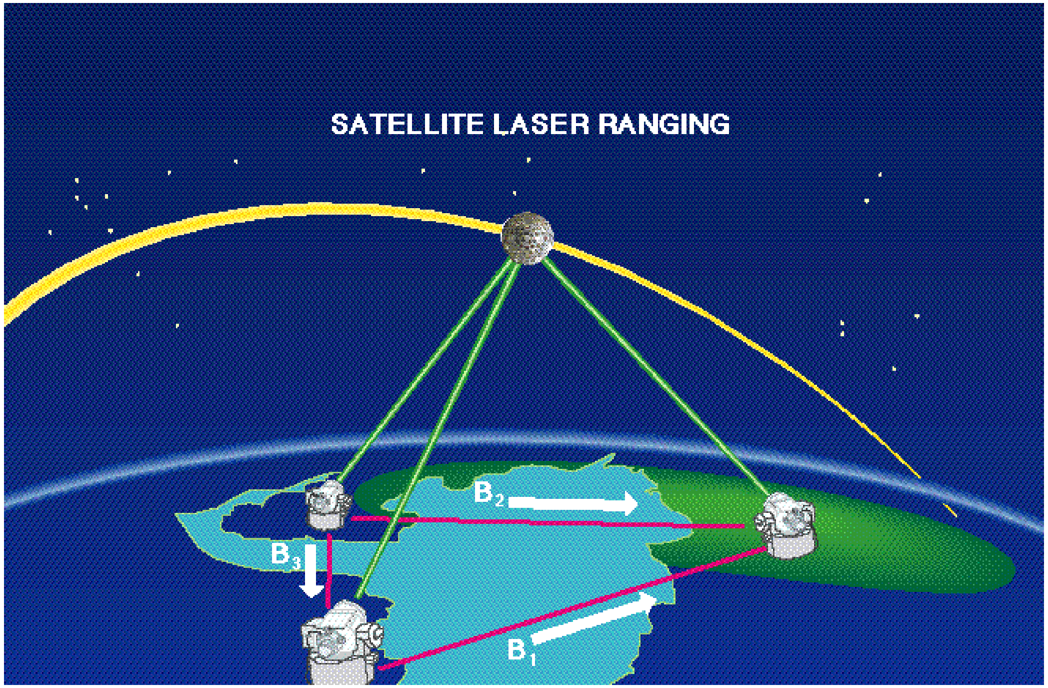
OVERVIEW

- Satellite Laser Ranging (SLR): Technique
- Brief History: Missions and Stations
- Lunar Laser Ranging (LLR)
- Science Applications of SLR and LLR
- International Laser Ranging Service (ILRS)
- SLR Technology Trends
- Interplanetary Laser Transponders and Applications

Satellite Laser Ranging Technique

Observable: The precise measurement of the roundtrip time-of-flight of an ultrashort (150 psec) laser pulse between an SLR ground station and a retroreflector- equipped satellite which is then corrected for atmospheric refraction using ground-based meteorological sensors.

- **Unambiguous time-of-flight measurement**
- **1 to 2 mm normal point precision**
- **Passive space segment (reflector)**
- **Simple refraction model**
- **Night / Day Operation**
- **Near real-time global data availability**
- **Satellite altitudes from 400 km to 20,000 km (GPS, GLONASS) and the Moon**
- **Centimeter accuracy satellite orbits**
  - **~ 1-2 cm (LAGEOS)**
  - **~ 2-3 cm (GPS)**



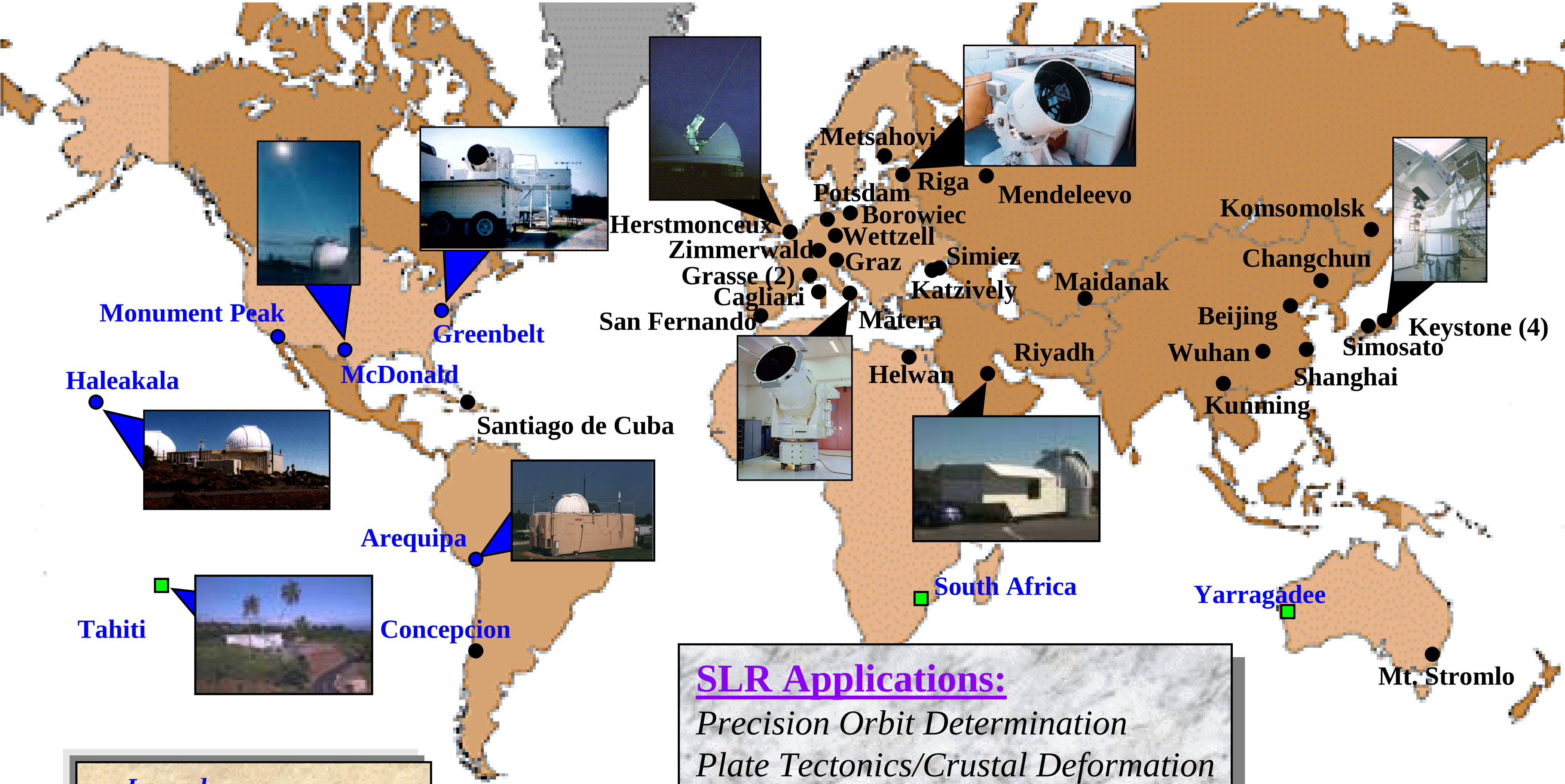
SLR generates unambiguous centimeter accuracy orbits!

Background/Heritage
Satellite Laser Ranging (SLR)

NASA's Next Generation Photon-Counting SLR2000 System

- Since 1964, ***NASA/GSFC*** has ranged with lasers to spacecraft equipped with retroreflectors
  - Over 60 artificial satellites beginning with Beacon Explorer 22B in 1964
  - 5 lunar reflectors since the Apollo 11 landing in 1969
- ***Observable:*** Roundtrip time of flight of an ultrashort laser pulse to and from onboard reflectors on spacecraft/Moon
- ***Range precision*** is presently 1 to 2 mm (instrument limited)
- ***Absolute accuracy*** is sub-cm (atmosphere and target limited)
- ***Single-Ended SLR technique*** is not applicable much beyond lunar distances since the reflected signal strength falls off as R^{-4}.

International Satellite Laser Ranging Network



Legend:

- ● NASA
- 🟩 NASA Partner
- 🟨 NASA Partner (Proposed)
- ● International Cooperating

SLR Applications:

Precision Orbit Determination

Plate Tectonics/Crustal Deformation

Earth Orientation & Rotation

Static & Time-varying Gravity Field

Lunar Science & General Relativity

Active Space Missions : >20

Missions since 1964: ~60

TLRS

Arequipa, Peru
Hawaii, USA (future)

SLR2000
(Developmental)

MOBLAS

Maryland, USA
California, USA
Yarragadee,Australia
Tahiti, French Polynesia
South Africa

NASA SLR Stations

- Single Operator
- Distributed in Western and Southern Hemispheres
- Subcentimeter Ranging Accuracy
- Hourly Data Processing and Delivery

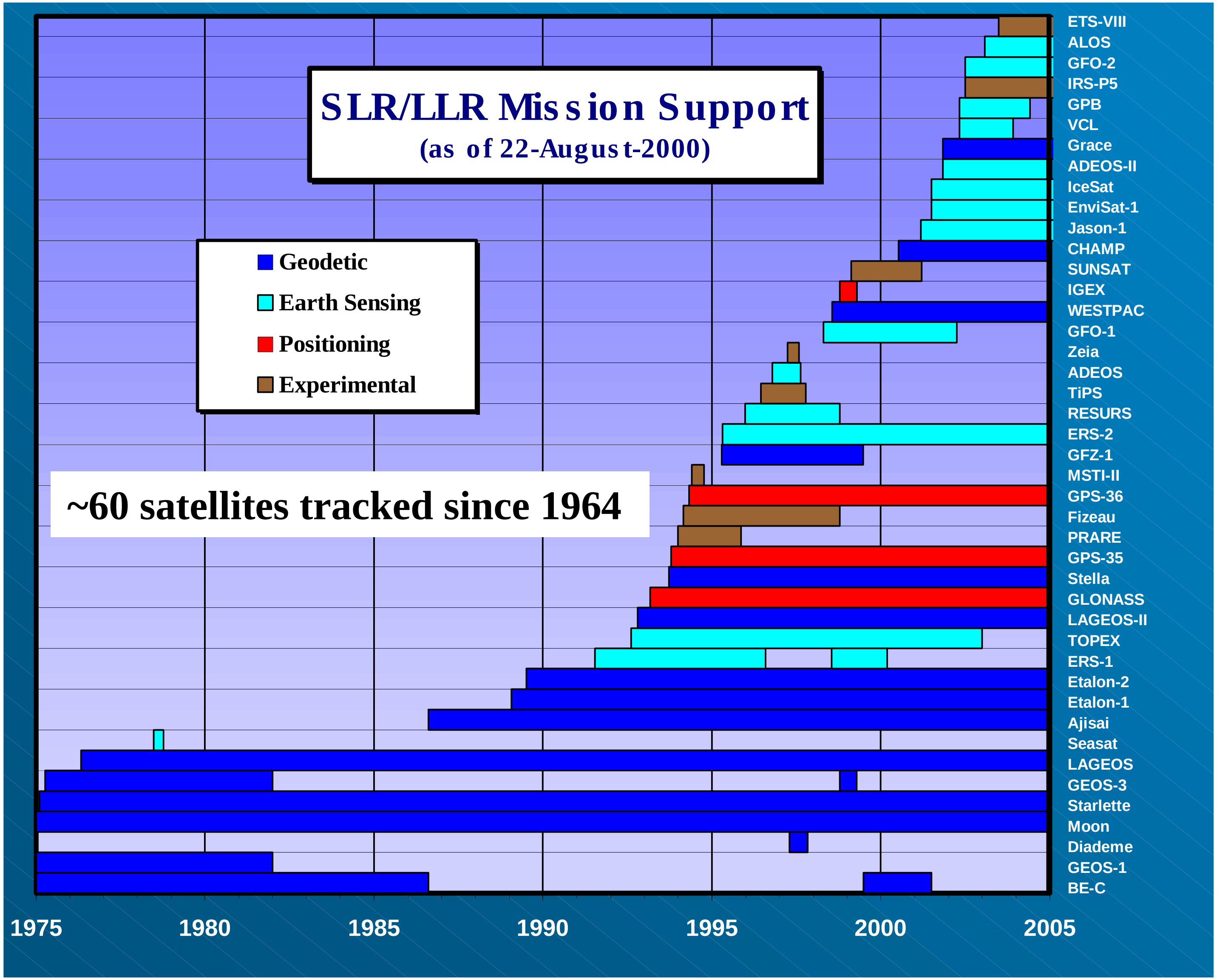
HOLLAS

Hawaii, USA
(SLR & LLR)
(decommissioned)

MLRS

Texas, USA
(SLR & LLR)

Space Missions Tracked by SLR


SLR/LLR Mission Support
(as of 22-August-2000)

~60 satellites tracked since 1964

Lunar Laser Ranging

MLRS ranging to the Moon

- **Currently five passive retroreflector arrays on the Moon**
  - **3 NASA (Apollo 11,14, and 15)**
  - **2 Soviet (Lunakhod 1 and 2)**
- **Long term LLR data set (1969-present) provided by three sites:**
  - **MLRS, McDonald Observatory, Texas, USA**
  - **CERGA LLR, Grasse, France**
  - **Mt. Haleakala, Hawaii, USA (decommissioned in 1992)**
- **New LLR systems coming on line:**
  - **MLRO, Matera, Italy**
  - **Apollo, Arizona, USA (multiphoton, 3.5 m telescope)**

Lunar Laser Retroreflector Arrays

Retroreflector Array Sites

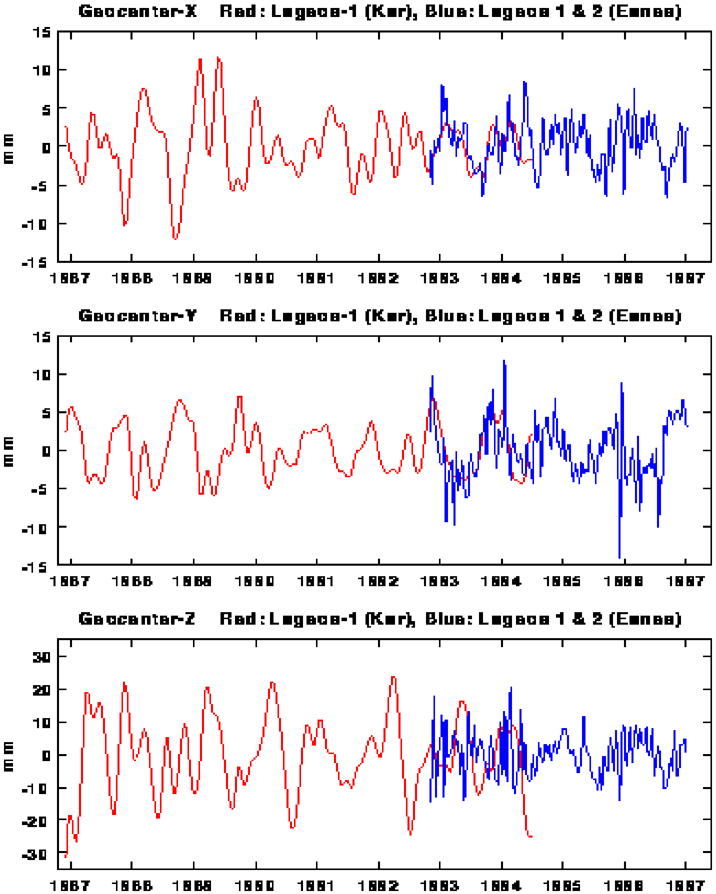
Apollo 11, 1969

Science Applications of Satellite and Lunar Laser Ranging

- Terrestrial Reference Frame (SLR)
  - Geocenter motion
  - Scale (GM)
  - 3-D station positions and velocities (>50)
- Solar System Reference Frame (LLR)
  - Dynamic equinox
  - Obliquity of the Ecliptic
  - Precession constant
- Earth Orientation Parameters (EOP)
  - Polar motion
  - Length of Day (LOD)
  - High frequency UT1
- Centimeter Accuracy Orbits
  - Test/calibrate microwave navigation techniques (e.g., GPS, GLONASS, DORIS, PRARE)
  - Support microwave and laser altimetry missions (e.g., TOPEX/Poseidon, ERS 1&2, GFO-1, JASON, GLAS, VCL)
  - Support gravity missions (e.g. CHAMP, GRACE, Gravity Probe B)
- Geodynamics
  - Tectonic plate motion
  - Regional crustal deformation
- Earth Gravity Field
  - Static medium to long wavelength components
  - Time variation in long wavelength components
  - Mass motions within the solid Earth, oceans, and atmosphere
- Lunar Physics (LLR)
  - Centimeter accuracy lunar ephemerides
  - Lunar librations (variations from uniform rotation)
  - Lunar tidal displacements
  - Lunar mass distribution
  - Secular deceleration due to tidal dissipation in Earth's oceans
  - Measurement of $G(M_E + M_M)$
- General Relativity
  - Test/evaluate competing theories
  - Support atomic clock experiments in aircraft and spacecraft
  - Verify Equivalence Principle
  - Constrain β parameter in the Robertson-Walker Metric
  - Constrain time rate of change in G
- Future Applications
  - Global time transfer to 50 psec to support science, high data rate link synchronization, etc (French L2T2 Experiment)
  - Two-way interplanetary ranging and time transfer for Solar System Science and improved General Relativity Experiments (Asynchronous Laser Transponders)

Unique Capabilities of SLR

- IERS Terrestrial Reference Frame (TRF)
  - Defines geocenter (TRF origin) at mm level
  - Defines scale (GM)
- Range observable is unambiguous and highly accurate
  - Sub-centimeter instrument accuracy confirmed by system collocations
  - 70 times less sensitive to water vapor and the ionosphere than VLBI or GPS
  - Sub-centimeter absolute range accuracy using simple atmospheric models
  - Dual wavelength systems capable of ~2 mm absolute accuracy
- SLR can accurately measure distance to objects at or beyond GPS orbits, e.g.
  - GPS, GLONASS
  - Geosynchronous
  - Moon (LLR) -lunar physics, relativity
  - Major and Minor Planets (future - transponders)



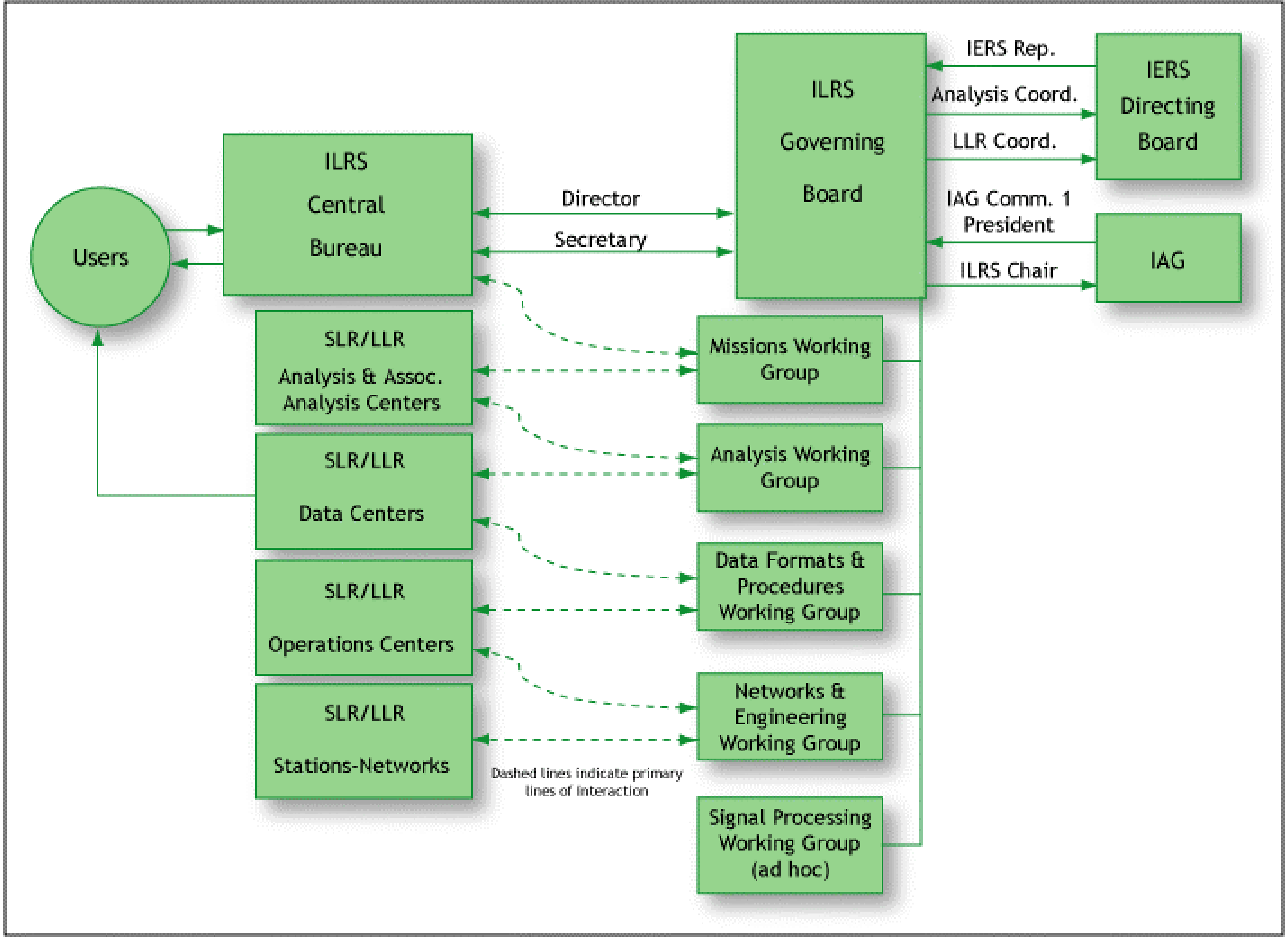
Geocenter Location from LAGEOS 1 and 2 (UTCSR)

International Laser Ranging Service (ILRS)

- **ILRS was created in 1998 as a successor organization to the CSTG Satellite and Lunar Laser Ranging Subcommission. Later designated an official service of the International Association for Geodesy (IAG)**
- **Coordinates the activities of approximately 30 countries in mission planning, tracking, data formatting and analysis, technology development, etc.**
- **Central Bureau at NASA Goddard Space Flight Center (GSFC) in Greenbelt, MD**
- **16 Member Governing Board sets policy**
  - **Board members are either appointed or elected by their peers and chairperson is elected by Board members**

ILRS Web Site: http://ilrs.gsfc.nasa.gov/

ILRS Organization Chart



Users

ILRS Central Bureau

Director

Secretary

ILRS Governing Board

IERS Rep.

Analysis Coord.

LLR Coord.

IERS Directing Board

IAG Comm. 1 President

ILRS Chair

IAG

SLR/LLR Analysis & Assoc. Analysis Centers

SLR/LLR Data Centers

SLR/LLR Operations Centers

SLR/LLR Stations-Networks

Missions Working Group

Analysis Working Group

Data Formats & Procedures Working Group

Networks & Engineering Working Group

Signal Processing Working Group (ad hoc)

Dashed lines indicate primary lines of interaction

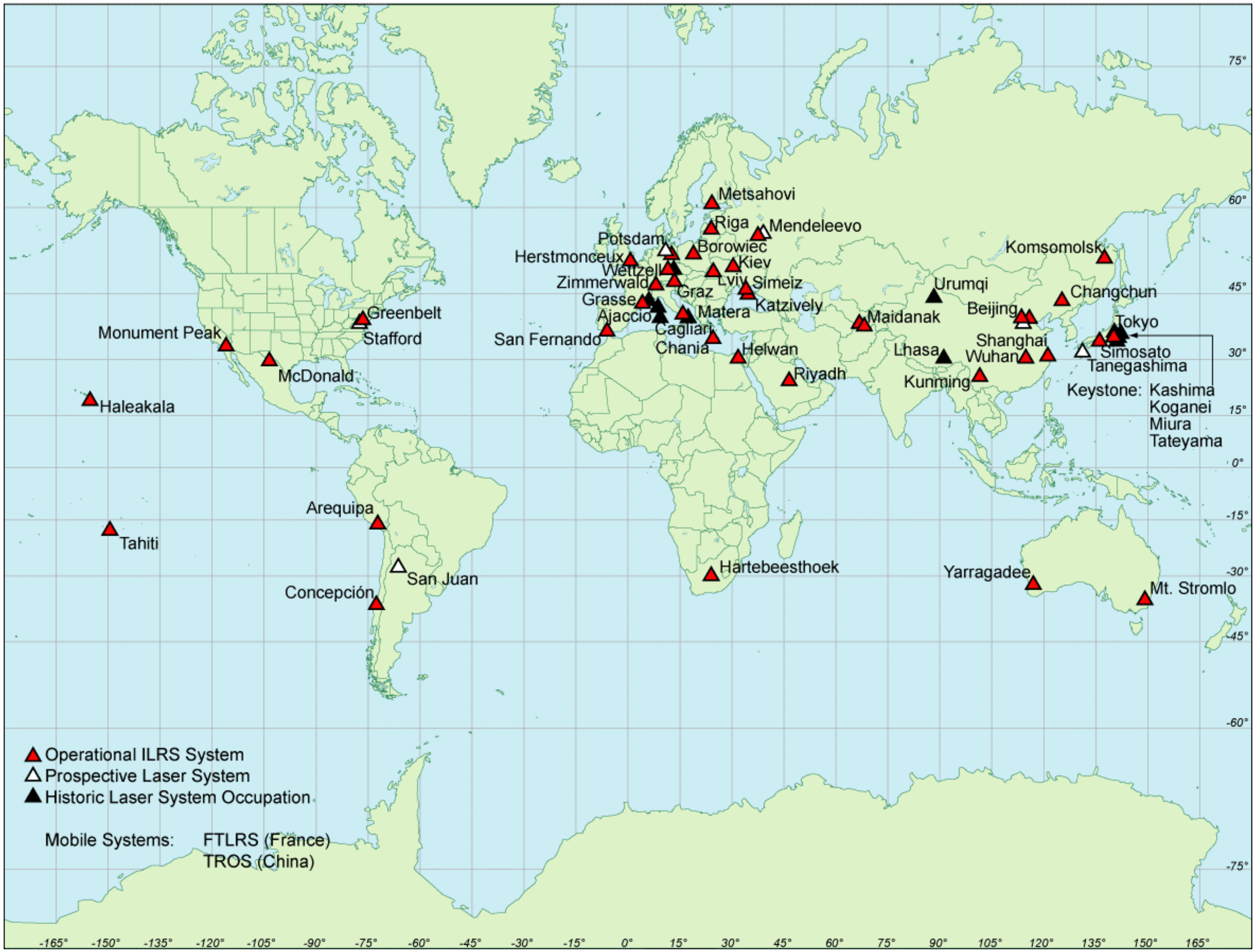
Current ILRS Governing Board

Ex-Officio Members:
Michael Pearlman -USA (Director, Central Bureau)
Carey Noll -USA (Secretary, Central Bureau)
Hermann Drewes -Germany (CSTG President)

Appointed Members:
Bob Schutz -USA (IERS representative to ILRS)
Werner Gurtner –Switzerland, Chair, ILRS Governing Board (Eurolas Network Rep.)
Guiseppe Bianco –Italy (Eurolas Network Rep.)
Hiroo Kunimori – Japan (WPLTN Network Rep.)
Ben Greene -Australia (WPLTN Network Rep.)
David Carter –USA (NASA Network Rep.)
Jan McGarry –USA (NASA Network Rep.)

Elected Members:
Ron Noomen -Netherlands (Analysis Center Rep.)
Graham Appleby –UK (Analysis Center Rep.)
Wolfgang Seemueller- Germany (Data Center Rep.)
Peter Shelus- USA (LLR Rep.)
Ulrich Schreiber –Germany (At Large Rep.)
Georg Kirchner - Austria (At Large Rep.)

International Laser Ranging Service (ILRS) Network



SLR Technology Trends

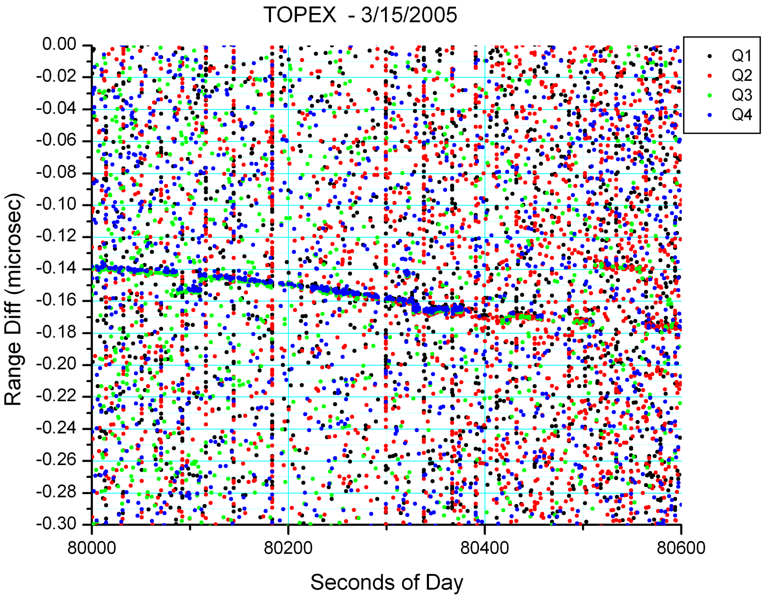
- **High Level of Automation**
  - Fully automated (NASA SLR2000 goal – not yet achieved)
  - Semi-automated: Single Operator or Remote Operation (many modern stations have achieved this)
- **Kilohertz Systems**
  - Implemented in USA (NASA SLR2000) and Austria (Graz)
  - Others in planning stage (UK, Germany, others?)
- **Eyesafe Operation**
  - Eyesafe wavelengths beyond 1300 nm (Australia, Czech Republic)
  - Low energy KHz systems at non-eyesafe wavelengths (NASA SLR2000)
- **Millimeter Accuracy**
  - Two color systems for directly measuring the atmospheric refraction correction (USA, Germany, France,Austria,Czech Republic)
  - Better corrections for target signature effects (ILRS Ad-hoc WG)

SLR2000: An Eyesafe Photon-Counting Satellite Laser Ranging System

System Characteristics:

- **Day/Night Eyesafe Operation**
- **Wavelength : 532 nm**
- **Transmitted Energy: 60 μJ**
- **Laser Fire Rate: 2 kHz**
- **Transmitted Power: 120 mW**
- **Pulsewidth: 300 psec**
- **Telescope Diameter: 40 cm**
- **Mean Signal Strength: <<1 pe per pulse**

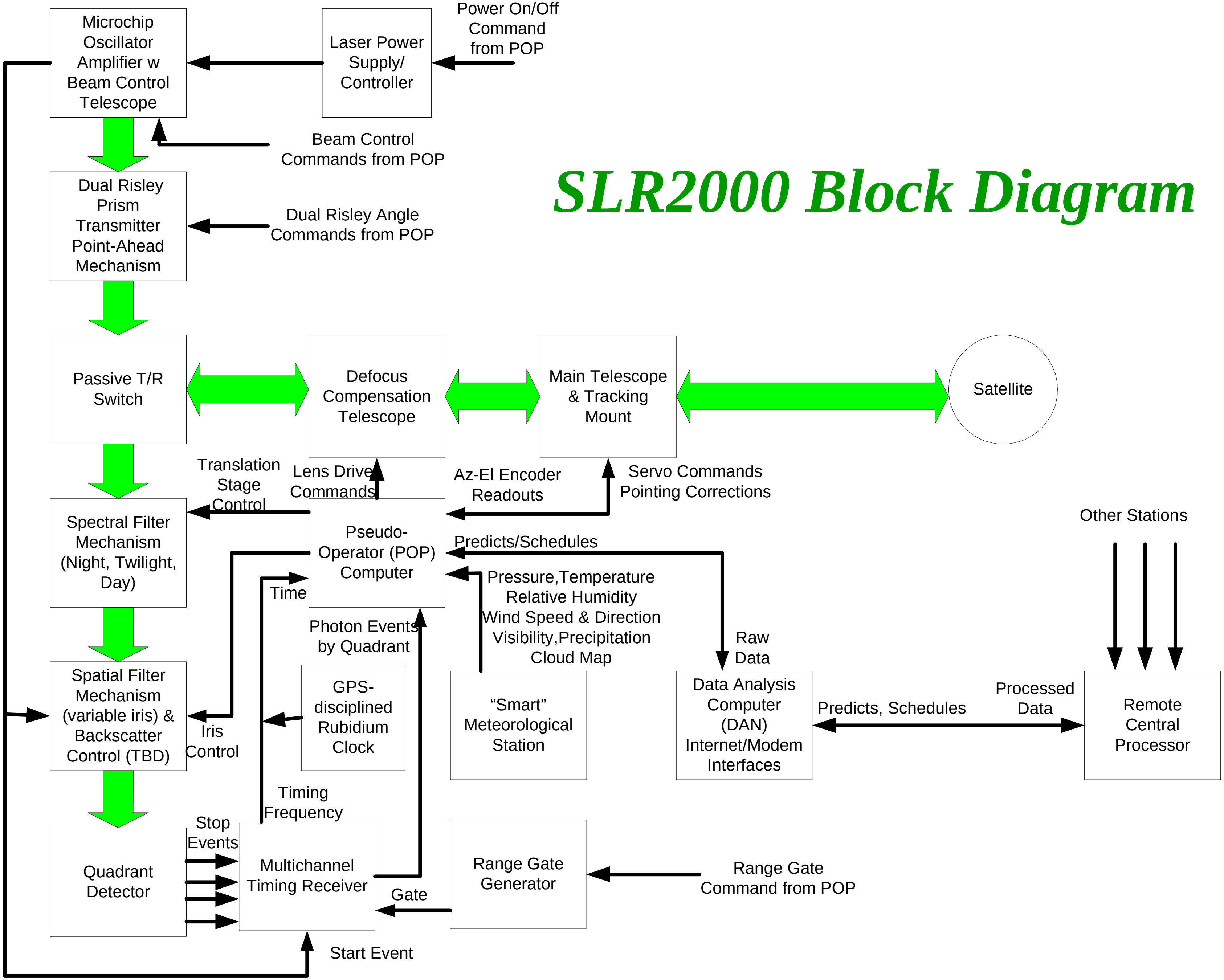
TOPEX/Poseidon Satellite
Altitude: 1350 km
Daylight Pass: 3/15/05



SLR2000 Technical Goals

- **Unmanned, eyesafe operation**
- **24 hour laser tracking to satellites up to 22,000 Km slant range (GPS, GLONASS, ETALON)**
- **One cm (1σ RMS) single shot ranging or better**
- **1 mm precision normal points to LAGEOS**
- **Mean Time Between Failures: >4 months**
- **Automated two-way communications with central processor via Internet with modem backup**
- **Free of optical, electrical, and chemical hazards**
- **Reduce system replication cost to ~$1.5M per system**
- **Reduce network operations costs through standardization and COTS technology utilization.**

SLR2000 Block Diagram



Microchip Oscillator Amplifier w Beam Control Telescope

Laser Power Supply/ Controller

Power On/Off Command from POP

Beam Control Commands from POP

Dual Risley Prism Transmitter Point-Ahead Mechanism

Dual Risley Angle Commands from POP

Passive T/R Switch

Defocus Compensation Telescope

Main Telescope & Tracking Mount

Satellite

Translation Stage Control

Lens Drive Commands

Az-El Encoder Readouts

Servo Commands Pointing Corrections

Spectral Filter Mechanism (Night, Twilight, Day)

Pseudo-Operator (POP) Computer

Predicts/Schedules

Other Stations

Time

Pressure, Temperature Relative Humidity Wind Speed & Direction Visibility, Precipitation Cloud Map

Photon Events by Quadrant

Raw Data

Spatial Filter Mechanism (variable iris) & Backscatter Control (TBD)

Iris Control

GPS-disciplined Rubidium Clock

“Smart” Meteorological Station

Data Analysis Computer (DAN) Internet/Modem Interfaces

Predicts, Schedules

Processed Data

Remote Central Processor

Timing Frequency

Stop Events

Quadrant Detector

Multichannel Timing Receiver

Gate

Range Gate Generator

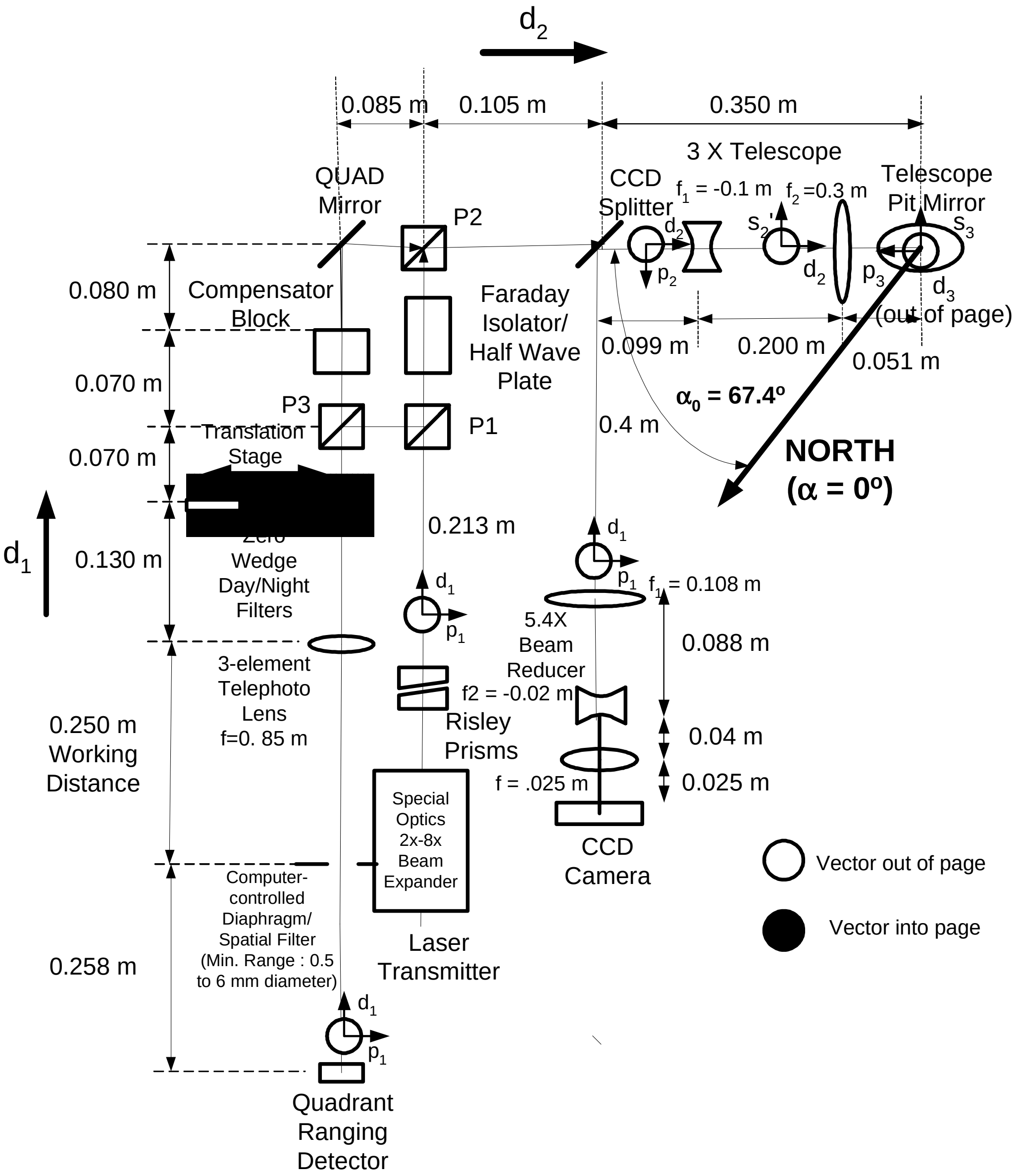
Range Gate Command from POP

Start Event

SLR2000 Transceiver

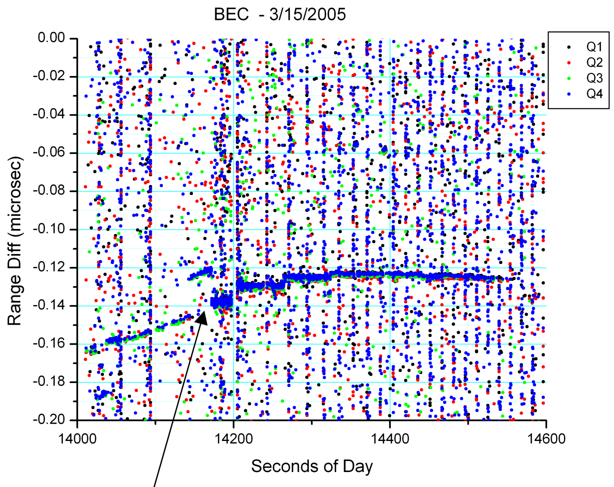
Automated Devices

- Star CCD camera periodically updates mount model
- 3x telescope compensates for thermal drift in main telescope focus
- Beam magnifier controls laser spot size and divergence at telescope exit aperture
- Risley prism pair controls transmitter point-ahead
- Variable iris controls receiver field of view (FOV)
- Photon-counting quadrant ranging detector provides fine pointing corrections
- Liquid crystal optical gate protects sensitive detector from laser backscatter (not shown)

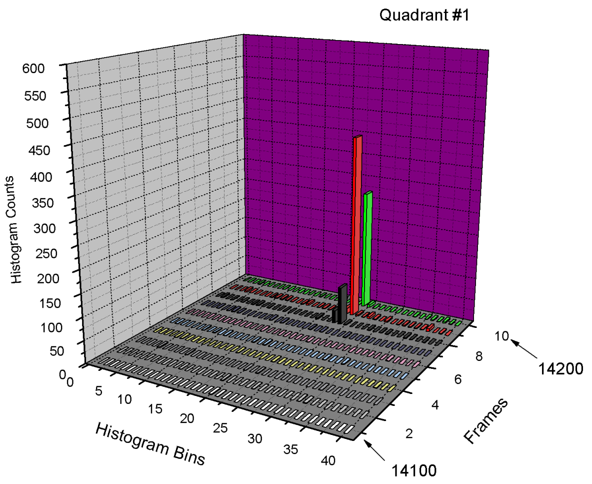


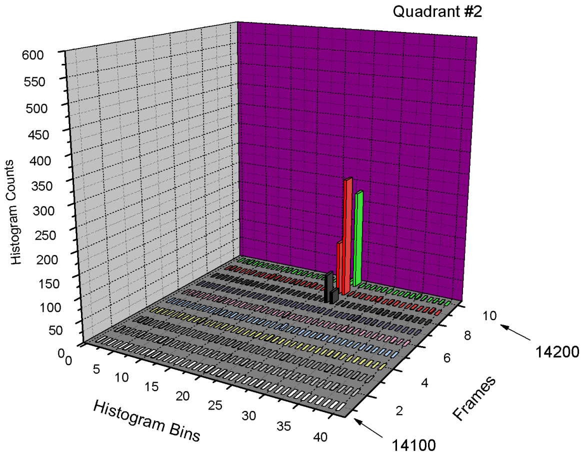
Closed Loop Tracking of BEC Satellite

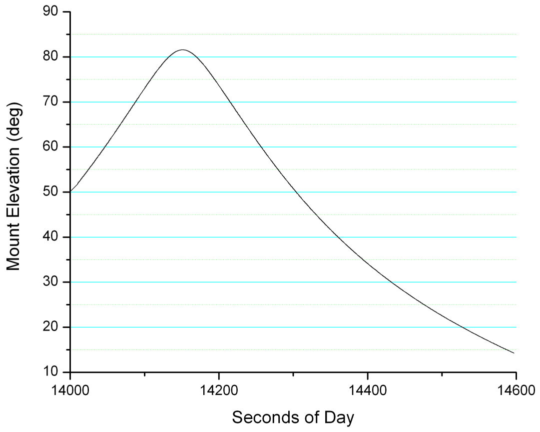
Photon-Counting Quadrant Detector and Transmitter Point-Ahead

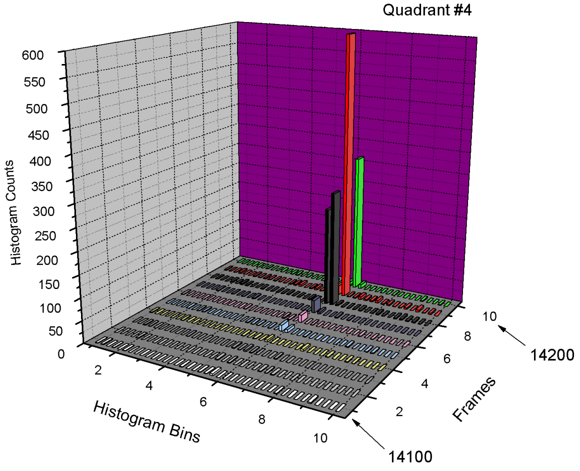


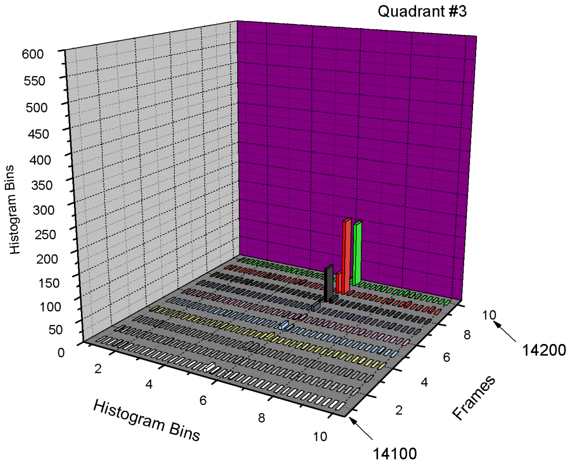
First closed-loop correction here







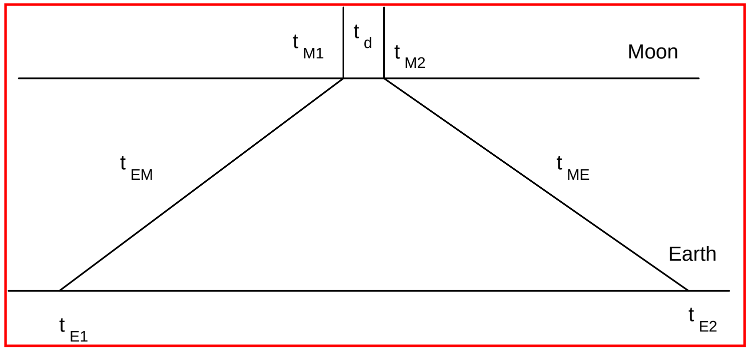




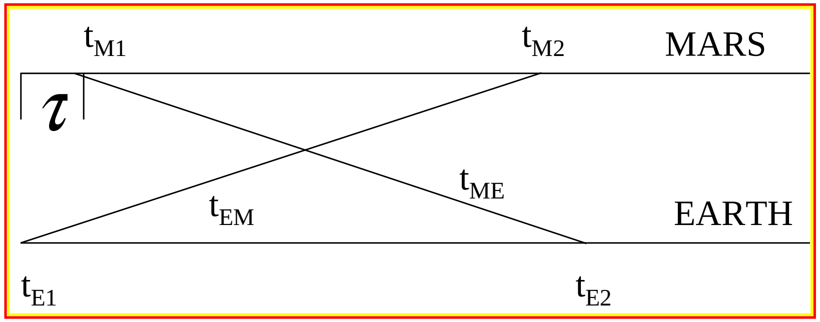
Laser Transponders:
Laser Ranging Beyond the Moon

- Given the current difficulty of laser ranging to passive reflectors on the Moon, conventional single-ended ranging to passive reflectors at the planets is unrealistic due to the R^{-4} signal loss.
- Since double-ended laser transponders have active transmitters on both ends of the link, signal strength falls off only as R^{-2} and interplanetary ranging is possible.

Types of Transponders

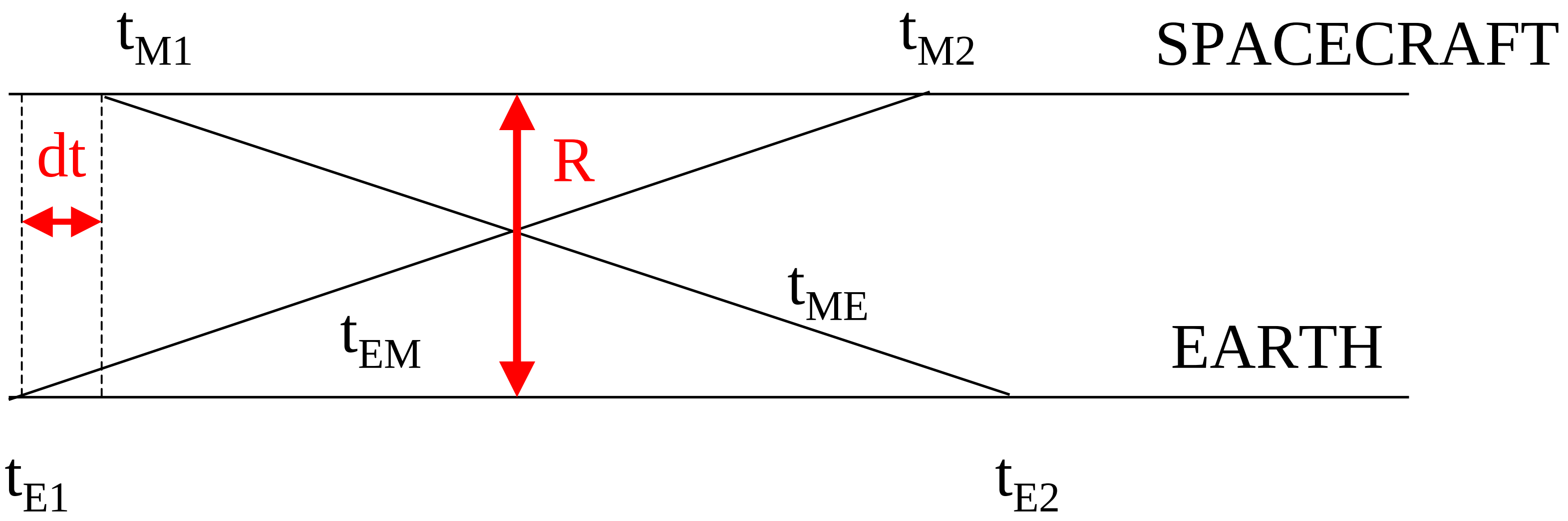


- ***Echo Transponders (R <<1 AU)***
  - Spacecraft transponder detects pulses from Earth and fires a reply pulse back to the Earth station.
  - To determine range, the delay t_d must be known a priori (or measured onboard and communicated back to Earth) and subtracted from the measured round-trip time-of-flight at the Earth station.
  - Works well on “short” links (e.g. to the Moon) where the round trip transit time is short and the single shot detection probability at both terminals is high.



- ***Asynchronous Transponders (R >1 AU)***
  - Transmitters at opposite terminals fire asynchronously (independently).
  - Signal from the opposite terminal must be acquired autonomously via a search in both space and time (easier when terminals are on the surface or in orbit about the planet)
  - The spacecraft transponder measures both the local transmitter time of fire and any receive “events” (signal plus noise) on its own time scale and transmits the information back to the Earth terminal via the spacecraft communications link. Range and clock offsets are then computed.
  - This approach works well on “long” links (e.g., interplanetary) even when the single shot probability of detection is relatively small

Timing Diagram and Equations for Asynchronous Ranging and Time Transfer



Range $R = c(t_{ME} + t_{EM})/2 = c\,[(t_{E2}-t_{E1})+(t_{M2}-t_{M1})]/2$

Clock Offset $dt = [(t_{E2}-t_{E1})-(t_{M2}-t_{M1})]/[2(1+\dot{R}/c)]$

Some Transponder Applications

- **Solar System Science**
  - Solar Physics: gravity field, internal mass distribution and rotation
  - Few mm accuracy lunar ephemerides and librations
    - Improves ranging accuracy and temporal sampling over current lunar laser ranging (LLR) operations to Apollo retroreflectors on the Moon with small, low energy, ground stations
  - Decimeter or better accuracy planetary ephemerides
  - Mass distribution within the asteroid belt
- **General Relativity**
  - Provides more accurate (2 to 3 orders of magnitude) tests of relativity and constraints on its metrics than LLR or microwave radar ranging to the planets, e.g.
    - Precession of Mercury’s perihelion
    - Constraints on the magnitude of G-dot ($1x10^{-12}$ from LLR)
    - Gravitational and velocity effects on spacecraft clocks
    - Shapiro Time Delay
- **Lunar and Planetary Mission Operations**
  - Decimeter or better accuracy spacecraft ranging
  - Calibration/validation/backup for Deep Space Network (DSN) microwave tracking
  - Subnanosecond transfer of GPS time to interplanetary spacecraft for improved synchronization of Earth/spacecraft operations
  - Transponder is a pathfinder technology for interplanetary optical communications and can serve as an independent self-locking beacon for collocated laser communications systems

Laser vs Microwave Transponders

- **Laser Advantages**
  - Ranging/timing instrumentation is more accurate (~1 mm) due to availability of picosecond transmitters, detectors, and timers in the optical regime
  - Divergence of transmitted optical beam is 4-5 orders of magnitude smaller than microwaves for a given transmit aperture (~λ/D)
    - More energy focused at the opposite receiver
    - Smaller antennas (telescopes) and transmitters, more lightweight, less prime power
  - Charged particles cannot follow optical frequencies so
    - no propagation delays due to Earth's ionosphere or the interplanetary solar plasma
    - no need for solar plasma models or correction via dual wavelength methods
  - Optical atmospheric propagation delay uncertainties are typically at the sub-cm level with ground measurements of pressure, temperature, and relative humidity.
- **Laser Disadvantages**
  - Requires more precise pointing knowledge and control (but well within SOA)
  - Link availability affected by weather and clouds but can be > 99% via several globally distributed ground sites or three orbiting terminals
  - As with any new technology, lasers have not yet demonstrated space heritage, lifetime and reliability comparable to more mature microwave transponders but several laser altimeters have operated in Earth, Lunar, and Mars orbit with another on its way to Mercury.

Two-Way Transponder Experiment to the Messenger Spacecraft (May/June 2005)

GSFC 1.2 Meter Telescope

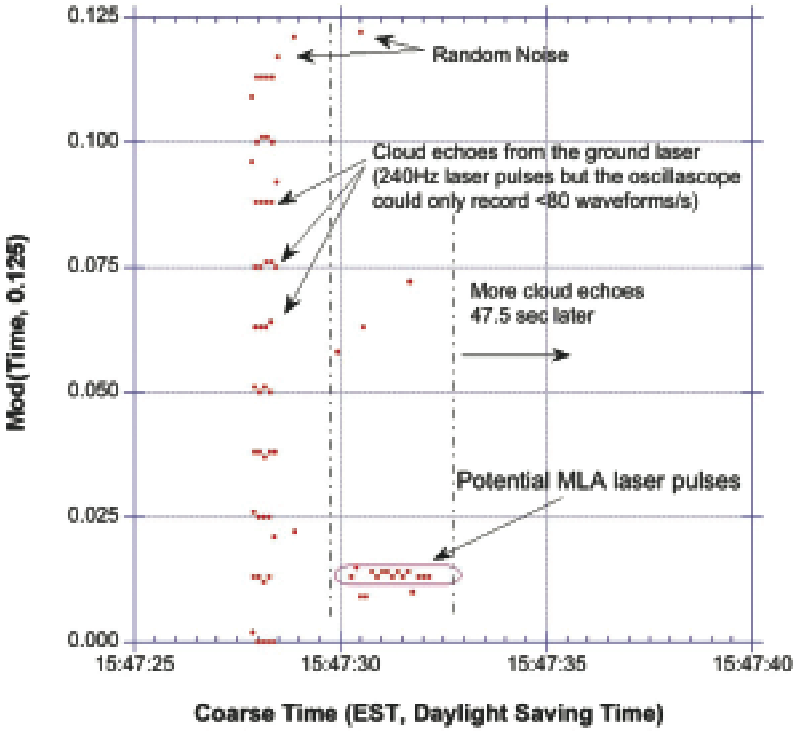
24.3 Million Km

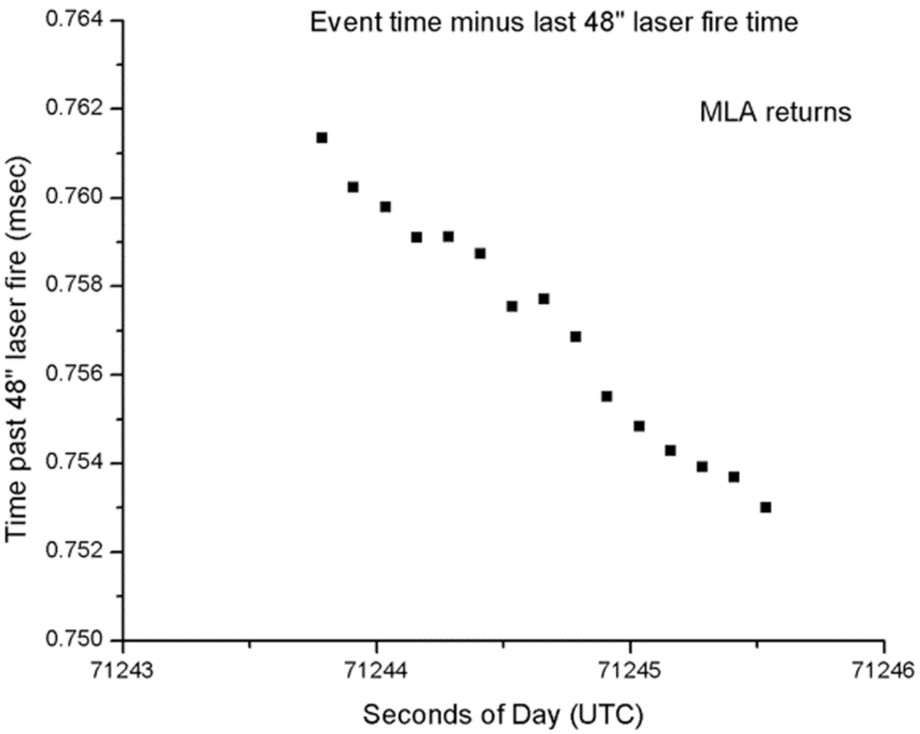
Messenger Laser Altimeter (MLA) enroute to Mercury

Ground Station
Xiaoli Sun Jan McGarry
Tom Zagwodzki John Degnan
D. Barry Coyle

Science/Analysis/Spacecraft
David Smith Maria Zuber
Greg Neumann John Cavenaugh

Two Way Laser Link between Earth and Messenger Spacecraft





Downlink – Space to Earth

Uplink – Earth to Space

One-Way Earth-to-Mars Transponder Experiment (September 2005)

GSFC 1.2 Meter Telescope

80 Million Km!

100’s of pulses observed at Mars!

Mars Orbiter Laser Altimeter (MOLA)

<u>Ground Station</u>

Xiaoli Sun Jan McGarry
Tom Zagwodzki John Degnan

<u>Science/Analysis/Spacecraft</u>

David Smith Maria Zuber
Greg Neumann Jim Abshire

Transponder Link Parameters

Experiment	**MLA (cruise)**		**MOLA (Mars)**
Range (10^6 km)	**24.3**		**~80.0**
Wavelength, nm	**1064**		**1064**
	Uplink	**Downlink**	**Uplink**
Pulsewidth, nsec	10	6	5
Pulse Energy, mJ	16	20	150
Repetition Rate, Hz	240	8	56
Laser Power, W	3.84	0.16	8.4
Full Divergence, μrad	60	100	50
Receive Area, m^2	.042	1.003	0.196
EA-Product, J-m^2	0.00067	0.020	.0294
PA-Product, W-m^2	0.161	0.160	1.64

Table 1: Summary of key instrument parameters for recent deep space transponder experiments at 1064 nm.

Proposed Transponder Missions

- Lunar Reconnaissance Orbiter (NASA/GSFC)
  - Science Mission: Measure lunar topography and gravity field
  - Onboard detector in lunar orbit detects laser pulses from Earth at 532 nm (one way)
- Selene 2 (Japan)
  - Two way laser transponder to lunar lander
- LATOR (NASA/JPL)
  - Two-way Earth to Mercury orbit link to measure relativistic effects (Shapiro effect)

Summary

- SLR has a 42 year history with major contributions to:
  - Earth and lunar science
  - General Relativity and Fundamental Physics
- SLR is expanding beyond the Moon to the planets and will contribute to:
  - Precise ranging, time transfer, and optical communications between the planets
  - Higher precision relativity and fundamental physics experiments
  - Solar system physics and precise planetary ephemerides
- The ILRS coordinates the SLR activities of approximately 30 member nations and looks forward to welcoming its newest member – **South Korea!**

Review articles on the history, theory, and engineering of SLR and transponder systems can be found on the ILRS Web Site at http://ilrs.gsfc.nasa.gov/reports/degnan/