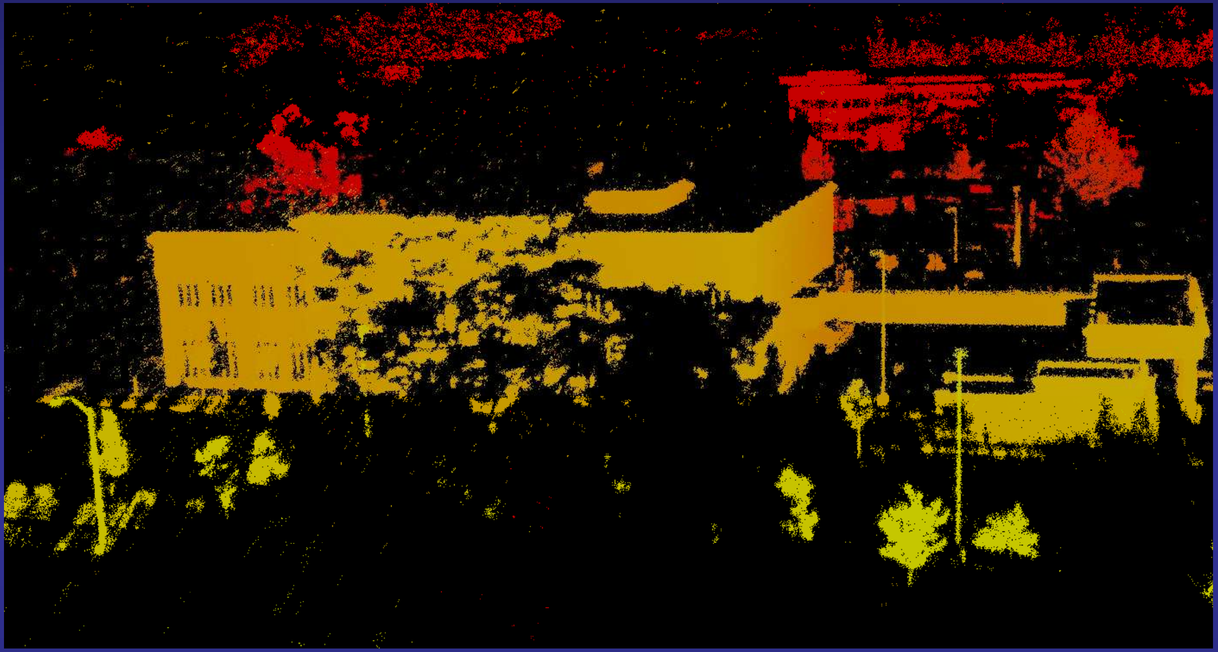
EMERGING TECHNOLOGIES



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ILRS Workshop, Grasse, France
September 25-28, 2007

OVERVIEW

- **Kilohertz Photon-Counting Systems**
- **Components**
  - Detectors
  - Precision Timing
  - Picosecond Kilohertz Lasers
- **Multi-Wavelength Ranging**
- **Remote or Autonomous Operation**
- **Applications**
  - Laser Time Transfer
  - Interplanetary Laser Transponders
  - Laser Altimetry and 3D Imaging

Kilohertz Photon-Counting Systems

- **Photon-counting 2 KHz rate SLR2000 system was first suggested in 1994* and later presented at 1996 SLR Workshop in Shanghai.**
- **As of the 2006 Canberra Workshop, there were three kHz systems tracking artificial satellites :**
  - NASA’s SLR2000 (LAGEOS and below, eyesafe)
  - Graz, Austria (up to GPS, not eyesafe)
  - Herstmonceaux, UK (LAGEOS and below, not eyesafe)
- **Other groups have indicated they also plan to develop kHz systems.**
- **In Canberra, Russia announced plans to develop a large network (~15) of intermediate 300 Hz, 2.5 mJ systems with 25 cm telescope apertures.**

*“Satellite Laser Ranging in the 1990’s: Report of the 1994 Belmont Workshop”, **J. J. Degnan** (Ed.), Elkridge, MD, February 1-2, 1994.

KHz Station Comparison

System	SLR2000	Graz 2 kHz System
Laser Energy	60 µJ	400 µJ
Laser Fire Rate	2 kHz	2 kHz
Laser Pulsewidth	300 psec	25 psec
Laser Wavelength	532 nm	532 nm
Telescope Receive Area	0.126 m^2 (40 cm diameter)	0.196 m^2 (50 cm diameter)
Detector Quantum Efficiency	0.13 (Bi-Alkali MCP/PMT) 0.40 (GaAsP MCP/PMT)	0.2 (C-SPAD)
QE-Energy-Aperture Product (Figure of Merit)	0.98 µJ-m^2 (SLR2000 Prototype) 3.00 µJ-m^2 (GaAsP) 7.3 µJ-m^2 (GaAsP + 50 cm tel.)	15.7 µJ-m^2
Signal Strength Advantage (Normalized to SLR2000 prototype)	1 (SLR2000 prototype) 3.07 (GaAsP upgrade) 7.5 (GaAsP + 50 cm telescope)	16 (rel to SLR2000 prototype) 5.2 (rel toGaAsP upgrade) 2.1(rel to GaAsP+50 cm upgrade)
Transmitter Fills Telescope?	Yes, Monostatic	No, Bistatic
Meets ANSI Eye Safety Standards?	Yes	No
Telescope/Tracking Mount	Developmental	Established System
Operator-assisted	Yes – during test phase No - operationally	Yes
Maximum Satellite Altitude Targeted	20.000 km (GPS)	20,000 (GPS/GLONASS)
Maximum Satellite Altitude Demonstrated to Date	5900 km (LAGEOS)	20,000 km (GPS/GLONASS)

SLR2000 transmitted energy and pulsewidth is at OSHA limit for eye safety in a 40 cm aperture. Larger telescopes would permit higher transmitted energies and shorter pulsewidths but at higher cost.

Photon Counting Detectors at 532 nm

- **Ideal detector has high quantum efficiency, fast response, minimal dead time, low dark count, and low transit time or amplitude dependent jitter.**
- **Microchannel Plate Photomultipliers (MCP/PMT)**
  - “zero” dead time, low transit time jitter, fast response
  - Low dark counts (~30 kHz)
  - New photocathode materials have high quantum efficiencies
    - GaAsP: up to 40% QE (Hamamatsu, Japan)-used in SLR2000
    - GaAs: up to 30% (Burle Industries, USA)
  - Hamamatsu tubes are available in segmented anode configurations; e.g. 2x2 for automated pointing correction and up to 10x10 for 3D imaging lidar applications
- **Single Photoelectron Avalanche Photodiodes (SPADs)**
  - Fast response, up to 55% QE, but significant dead times (50 to 100 nsec),
  - Compensated variety (C-SPAD) reduces amplitude-induced timewalk effects (QE ~ 20%) – used at Graz and Herstmonceaux
  - Ongoing work to improve QE and reduce deadtimes – especially in NIR

Space-Qualified Detectors for Transponders and Altimeters

- **Space-qualified, photon-counting PMT’s and C-SPADS exist**
- **Hamamatsu GaAsP MCP/PMT’s have been launched into space.**
- **The NASA CALIPSO atmospheric lidar is using a PMT.**
- **GLAS flew photon-counting APD’s.**
- **In Canberra, the Czech Technical University reported the latest results on their space-qualified photon counting module [Prochazka et al, 2006]. The silicon K14 SPAD has the following properties at 532 nm:**
  - Active area: 25 micron diameter
  - Quantum Efficiency: 10%
  - Timing Resolution: 75 psec
  - Dark Count Rate: < 8 kHz @ 20ºC
  - Operating Temperature Range: -30ºC to 80ºC (no cooling)
  - Power Consumption: <400 mW
  - Mass: 4 g
  - Resistant to solar and ionizing radiation (100 krad) damage
  - Expected lifetime of greater than 10 years in space

Precision Timers

- New timers dominated the technology presentations at the 2006 Canberra Workshop.
- The Riga group presented their latest timer, the A032-ET, an improved version of their previous instrument, the A031-ET.
- The Czech Technical University updated the specifications on their Portable Pico-Event Timer
- HTSI reported on a high performance ET controller designed to operate in tandem with the HTSI ET, which is currently installed in various systems (MLRO, SLR2000, GUTS).
- The Shanghai Observatory reported on a Time-to-Digital Converter (TDC) integrated onto a single Field Programmable Gate Array (FPGA) chip.
- Sigma Space Corporation reported on a 100 channel FPGA-based timing system for 3D imaging lidars.
- The French delegation described the performance of their spaceborne and ground-based timers for the Laser Link Time Transfer (L2T2) experiment.

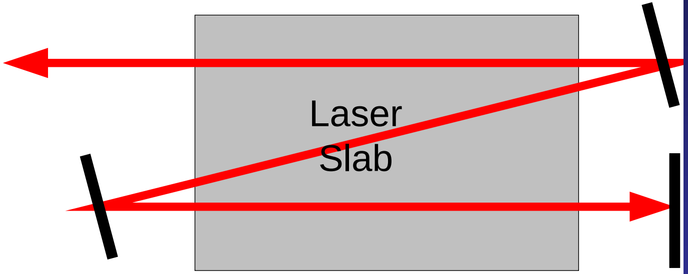
Picosecond Kilohertz Laser Oscillators

- **Modelocked lasers**
  - Workhorse of modern SLR systems since 1980’s
  - Typically large and heavy.
  - Active or passive modelocking produces ~100 MHz trains of low energy (few nJ) pulses.
  - Low energy output requires multipass or multiple amplifier stages.
  - Picosecond pulsewidths or shorter available.

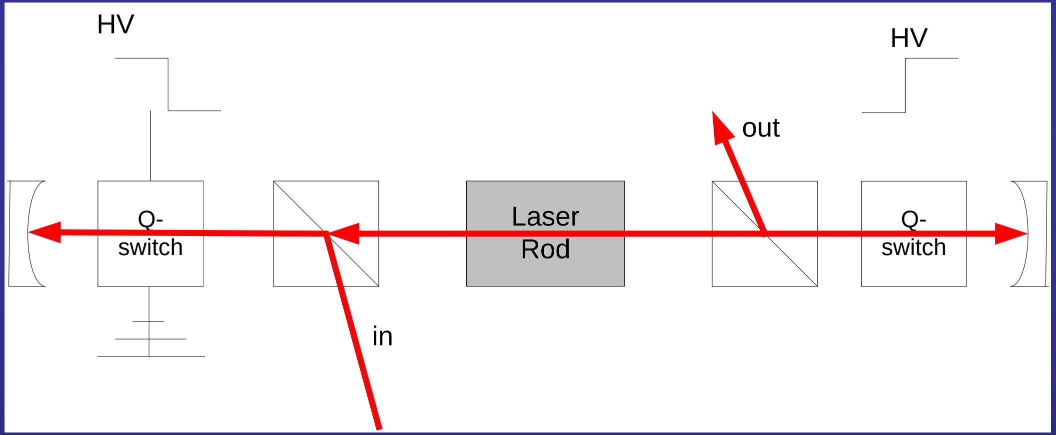
- **Passively Q-switched Microchip Lasers**
  - Small and lightweight.
  - Passive Q-switching produces multi-kHz trains of modest energy (<0.25 mJ) pulses.
  - Shortest pulses (<50 psec) are obtained with low energy SEmiconductor Saturable Absorber Mirrors (SESAM) but such low energies (~ 1 µJ) require multiple or multipass amplifier stages (≥2) for SLR
  - Devices Q-switched by Cr^{4+}YAG can generate higher energy (10 to 250 µJ) pulses but with somewhat longer pulsewidths (>200 psec)

Multipass Amplifier Approaches

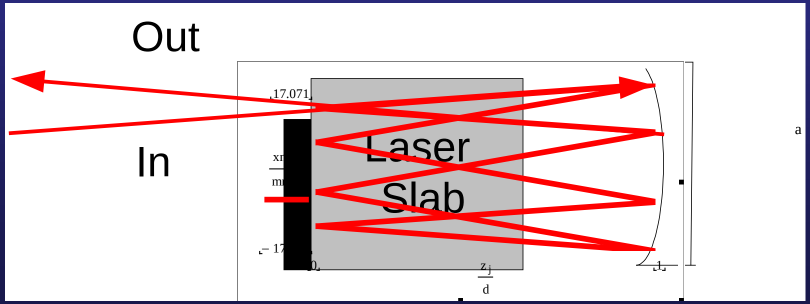
Passive Amplifier/Multiple Mirrors
(e.g. Q-Peak laser in SLR2000)



Regenerative Amplifiers
(e.g. NASA STALAS Laser
or High-Q laser at Graz)



Degenerate Optical Resonators
(J. Degnan, San Fernando, 2004.)



Kilohertz Lasers in Use

- **Graz and Herstmonceaux use the High-Q (Austria) "Pico-Regen" laser which consists of a SESAM-modelocked laser followed by a regenerative amplifier.**
  - ~0.4 mJ @ 2 kHz at 532 nm but few mJ possible
  - ~10 psec pulsewidths
  - Relatively large system and not eyesafe
- **NASA SLR2000 (NGSLR) system uses a Q-Peak (USA) microchip oscillator passively Q-switched by Cr^{4+}:YAG and followed by a bulk multipass (6) amplifier.**
  - ~0.060 mJ @ 2 kHz at 532 nm
  - ~300 psec pulsewidth
  - Relatively compact system and eyesafe for 40 cm telescope or above.

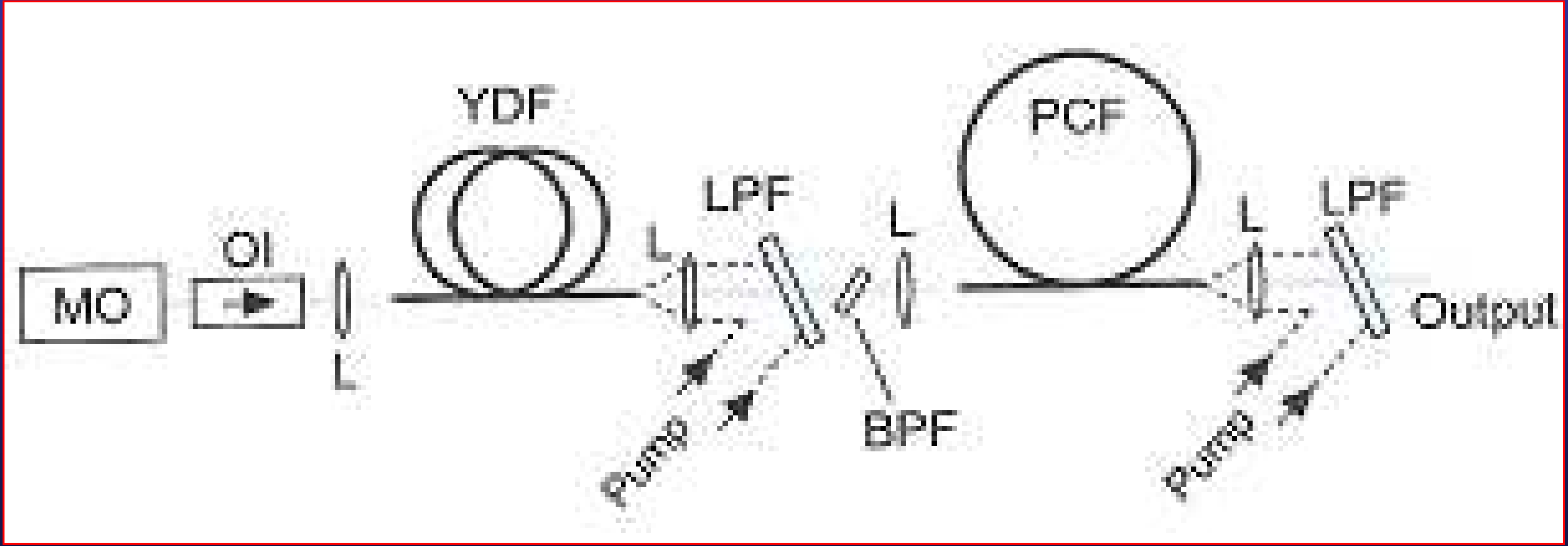
Fiber Amplifiers: The Multipass Alternative

Yt:YAG Fiber Laser Amplifiers (Acculite Inc., USA, 2005)

•Allows the gain length to be extended with high pump to output power efficiency. Fiber guides and contains pump and laser radiation.

•Measured Output: 1 mJ @ 10 kHz = 10 W

•Pulsewidth: 1 nsec but could be shorter with SESAM-switched Master Oscillator (MO). However, single mode 40 micron fiber diameter limits peak power handling capability and exacerbates nonlinear effects (e.g., self-focusing, out-of-band radiation caused by self phase-modulation)



Multiwavelength Ranging

- **The need and accuracy requirements for multiwavelength ranging are driven by the quality of the atmospheric models used to correct for the atmospheric delay in single wavelength systems.**
- **Many of the multiwavelength papers submitted to the 2006 Canberra workshop were devoted to atmospheric modeling and, in contrast with past workshops, only a few dealt with multiwavelength ranging hardware.**
- **In previous workshops, it had been demonstrated that the multicube responses of current SLR targets often produce different reflected waveforms at different wavelengths, which makes a computation of atmospheric delay difficult, if not impossible, to measure on a single pulse basis with existing multicube arrays.**
- **In Canberra, Werner Gurtner presented additional sobering material that further highlighted the difficulty in beating down dual wavelength instrument bias errors to the level required for millimeter accuracy ranging, e.g.**
    - At the Zimmerwald Ti:Sapphire wavelengths of 423 and 846 nm, the amplification factor is about 14. In order to measure the atmospheric correction to 1 mm accuracy, the calibrated range difference (423-846) must be bias-free and good to 1/14 mm, i.e. 0.07 mm.
    - This requirement is in addition to a differential time-of-flight (TOF)

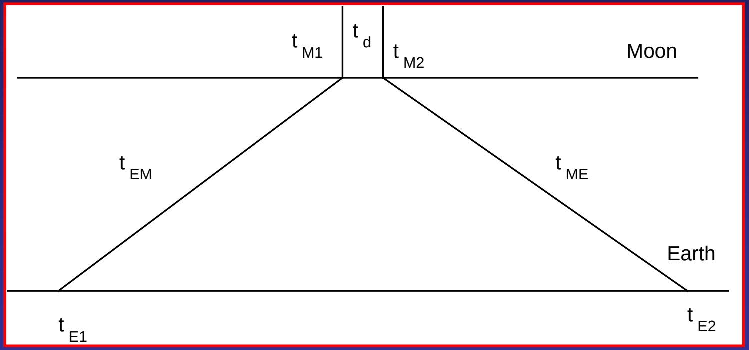
Remote or Autonomous Operation

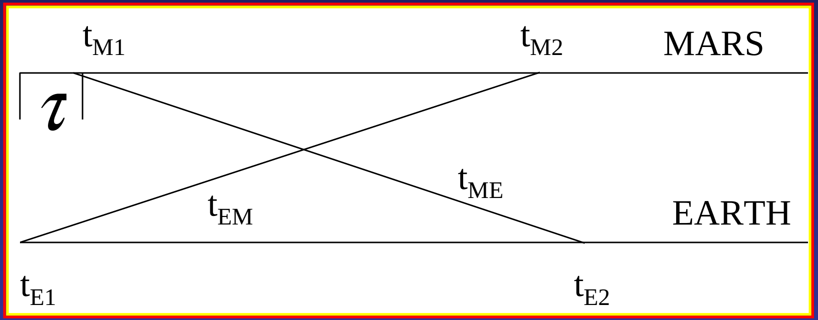
- **The drive toward remote and totally autonomous operation has not only spurred the development of increasingly sophisticated operational software at a number of stations but also a variety of new sensors and actuators to replace crucial human interactions.**
- **The special requirements of NASA's SLR2000 (NGSLR) system has resulted in the development of several new hardware subsystems including:**
  - Quadrant photon-counting photomultiplier for correcting receiver pointing errors(also necessary for future transponders).
  - Dual Risley prisms for automated transmitter point-ahead corrections (also necessary for future transponders).
  - Programmable beam expanders for controlling laser spot size and divergence as a function of satellite altitude (eye safety & signal level)
  - Computer-controlled irises for adjusting the receiver FOV
  - Liquid crystal optical gates for suppressing laser backscatter in the instrument and atmosphere by 2+ orders of magnitude.

Laser Time Transfer

- **Laser time transfer experiments are being pursued vigorously by the SLR Community.**
- **French Time Transfer by Laser Link (T2L2)**
  - After several aborted attempts since 1994, the French Time Transfer by Laser Link (T2L2) Experiment has been accepted as a payload on the Jason-2 oceanographic mission and is scheduled for launch in June, 2008 [Samain et al, 2006a].
  - The T2L2 goal is time transfer at the 100 psec level or better with possible application to fundamental physics experiments (e.g. the anisotropy of the speed of light on the downlink vs uplink) or one-way interplanetary ranging.
- **Chinese Time Transfer Experiment**
  - A second ground-to-satellite time transfer experiment between a rubidium oscillator on the ground and a second rubidium at 20,000 km is also underway [Fumin et al, 2006].
- **It has been suggested [Otsubo et al, Canberra, 2006] that the new 2 kHz systems could potentially transfer up to 30 pulses per second between SLR stations via the AJISAI mirror panels.**
  - Concept first suggested by Kunimori et al at the 1992 Annapolis Workshop.
  - Unfortunately, the proper geometry for transfer occurs only three times per AJISAI spin period (~ 2 sec) and for only 5 to 10 msec per opportunity. Thus, with the 5 to 10Hz laser fire rates (100 to 200 msec interpulse periods) of the current network, the probability of a pulse transfer between stations was greatly reduced but is significantly enhanced for kHz systems.

Transponders: Ranging Beyond the Moon





- *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 single shot detection probability at both terminals is high.

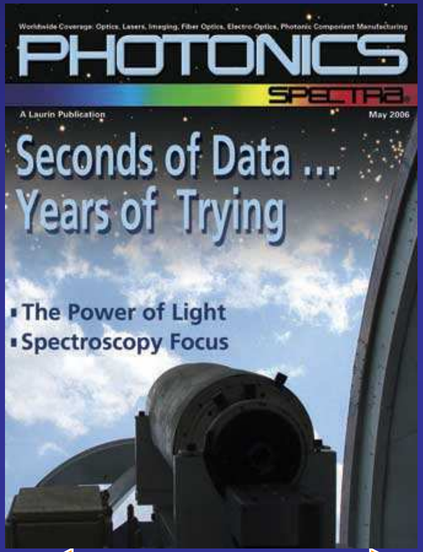
***J. Degnan, *J. Geodynamics*, Nov. 2002.**

- *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

Two-Way Asynchronous Transponder Experiment to the Messenger Spacecraft

(May/June 2005)*

GSFC 1.2 Meter Telescope



Worldwide Coverage: Optics, Lasers, Imaging, Fiber Optics, Electro-Optics, Photonic Component Manufacturing

PHOTONICS SPECTRA

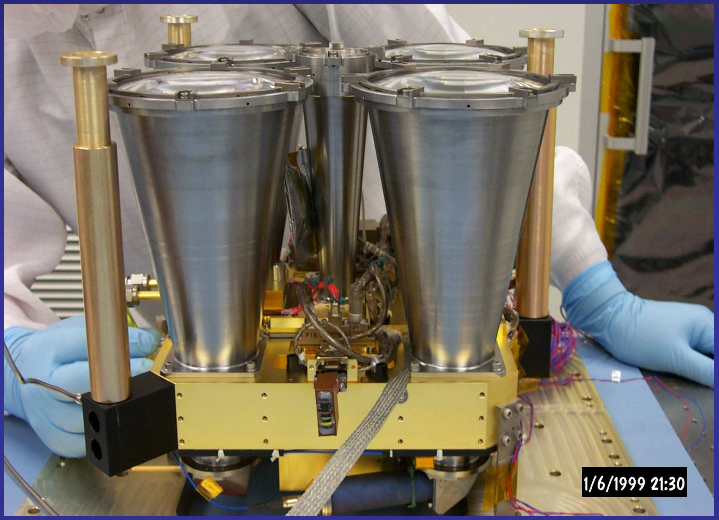
A Laurin Publication

May 2006

Seconds of Data ... Years of Trying

- The Power of Light
- Spectroscopy Focus

24.3 Million Km



Messenger Laser Altimeter (MLA) enroute to Mercury

<u>Ground Station</u>

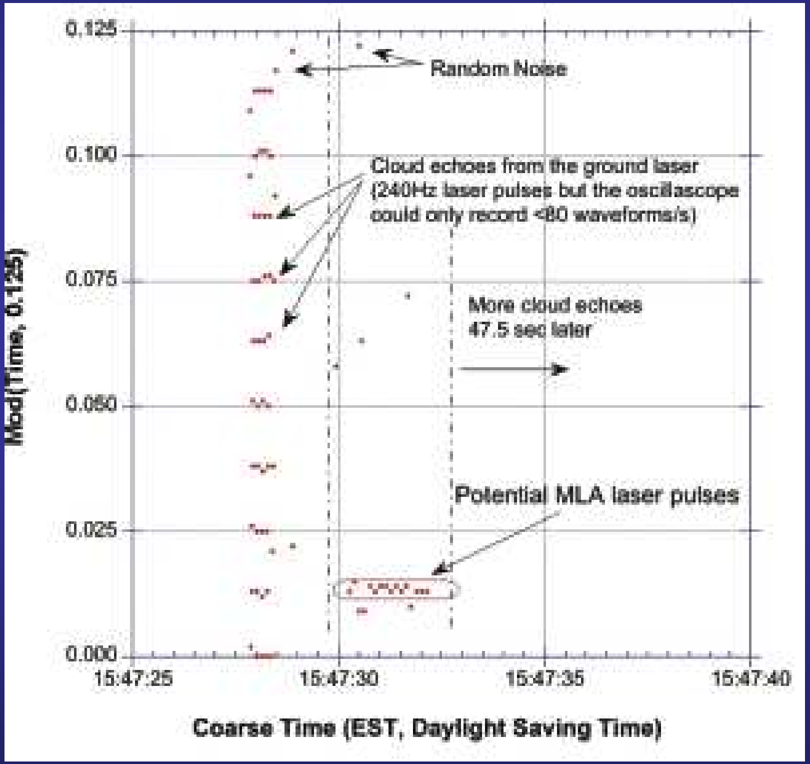
Xiaoli Sun	Jan McGarry
Tom Zagwodzki	John Degnan
D. Barry Coyle	

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

David Smith	Maria Zuber
Greg Neumann	John Cavenaugh

*D. E. Smith et al, *Science*, January 2006.

Two Way Laser Link between Earth and Messenger Spacecraft



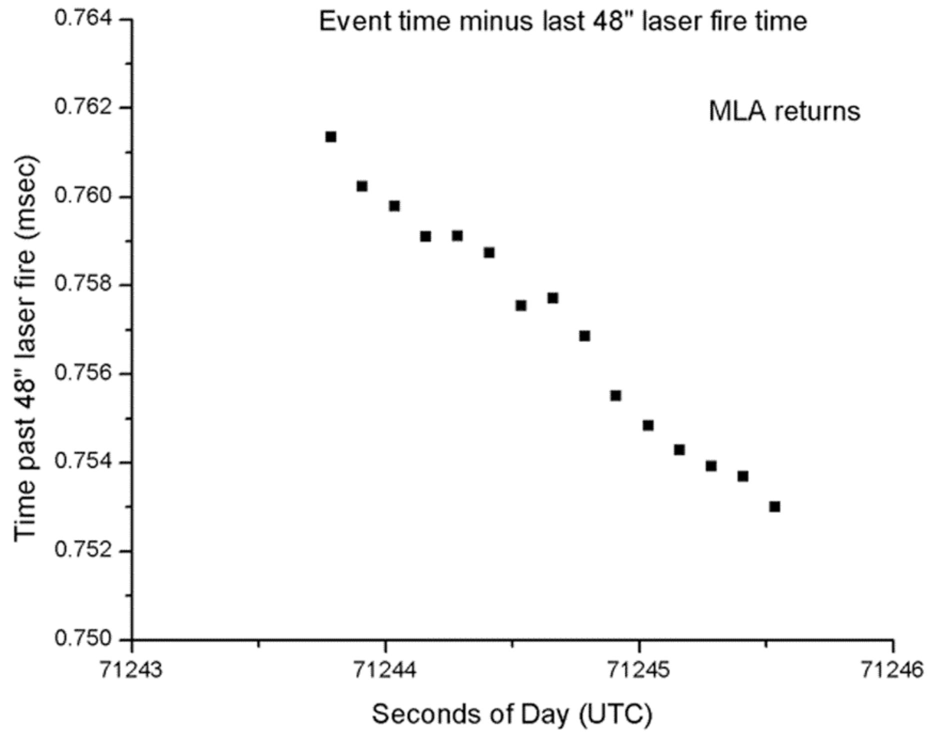
Random Noise

Cloud echoes from the ground laser (240Hz laser pulses but the oscillascope could only record <80 waveforms/s)

More cloud echoes 47.5 sec later

Potential MLA laser pulses

Downlink – Space to Earth


Event time minus last 48" laser fire time

MLA returns

Uplink – Earth to Space

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

GSFC 1.2 Meter Telescope

80 Million Km!

~500 laser pulses observed at Mars!

Mars Orbiter Laser Altimeter (MOLA)

Ground Station

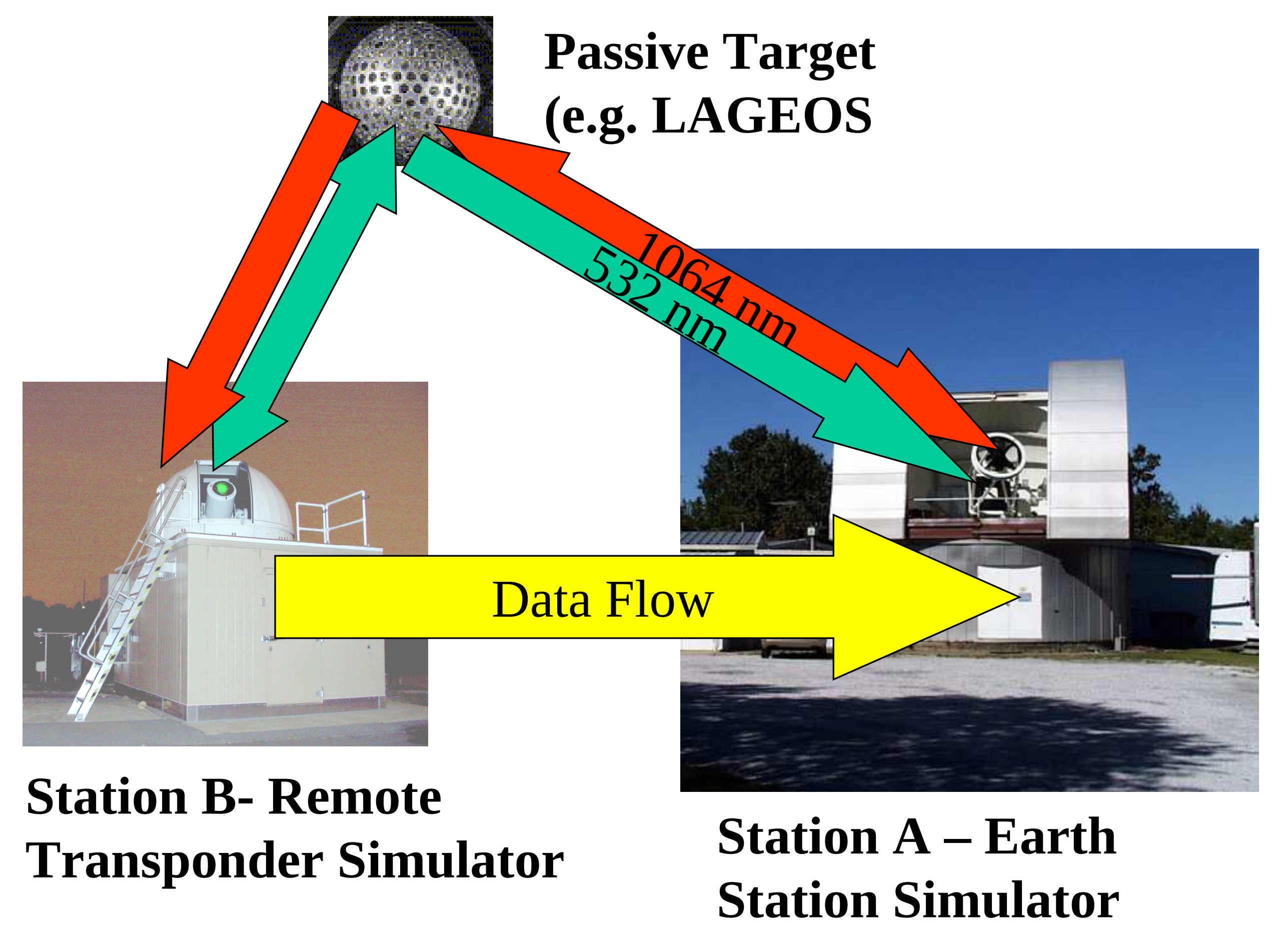
Xiaoli Sun Jan McGarry
Tom Zagwodzki John Degnan

Science/Analysis/Spacecraft

David Smith Maria Zuber
Greg Neumann Jim Abshire

Dual Station Laser Ranging*

Experiments being prepared at GSFC and Wettzell



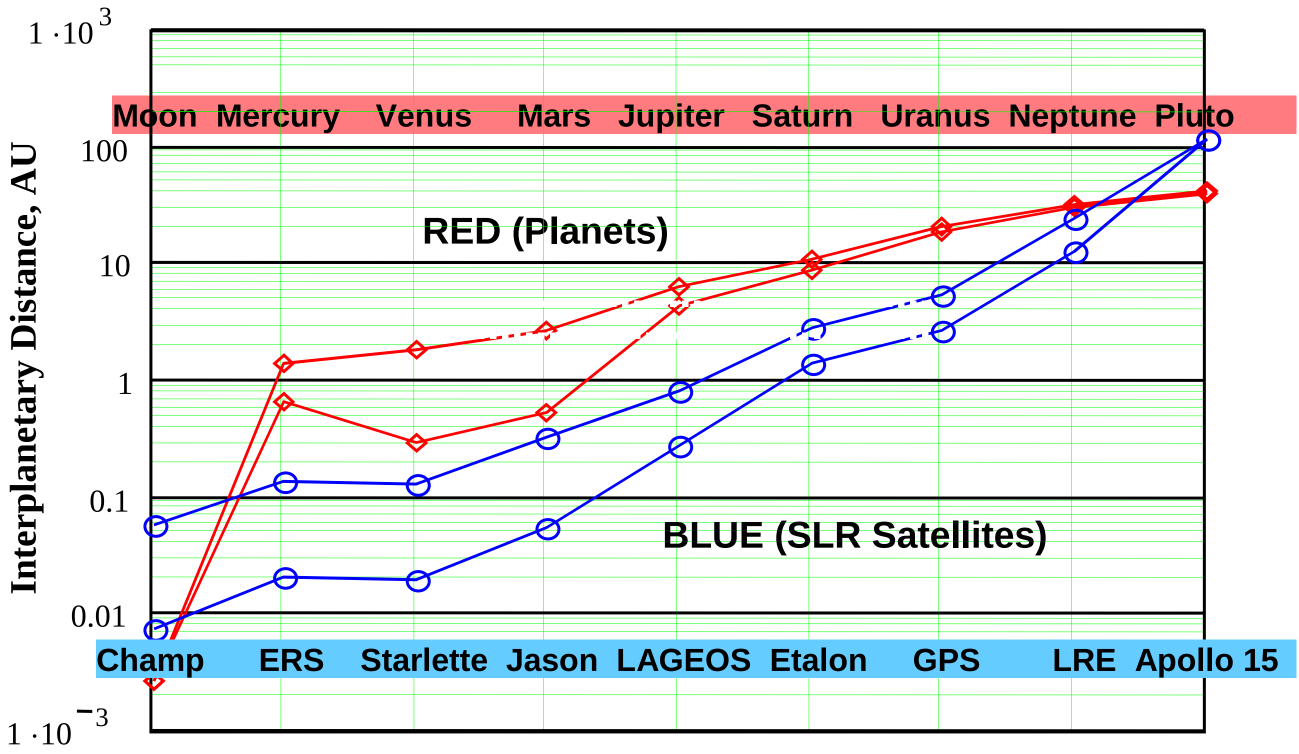
Passive Target (e.g. LAGEOS

Station B- Remote Transponder Simulator

Station A – Earth Station Simulator

*** J. Degnan, Canberra Workshop, 2006**

Satellite Simulations of Transponder/Lasercom Links Throughout the Solar System*



Red curves bound the Earth-planetary distance

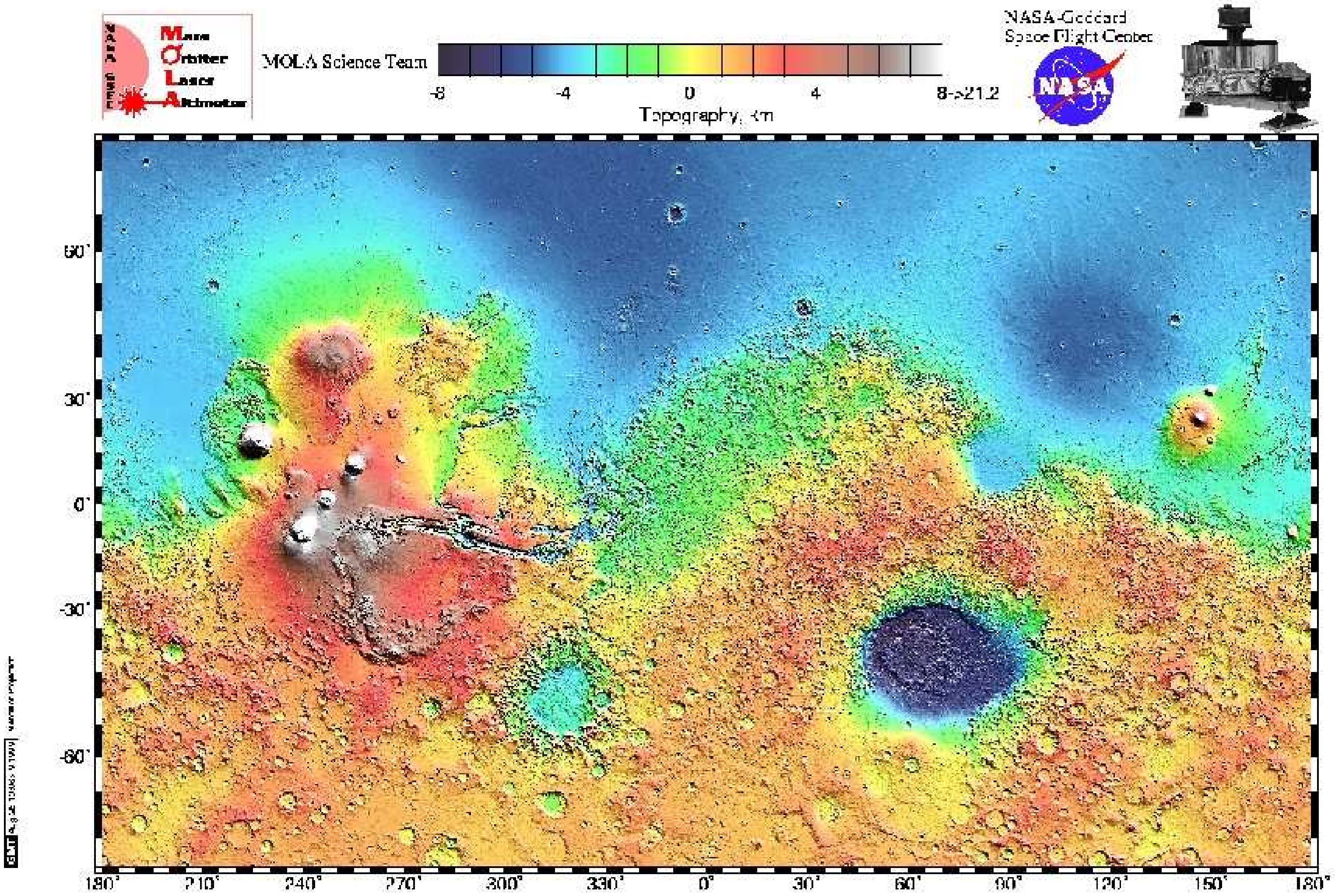
Blue curves bound the equivalent transponder range at satellite elevations of 90 and 20 degrees respectively.

*** J. Degnan, Canberra Workshop, 2006**

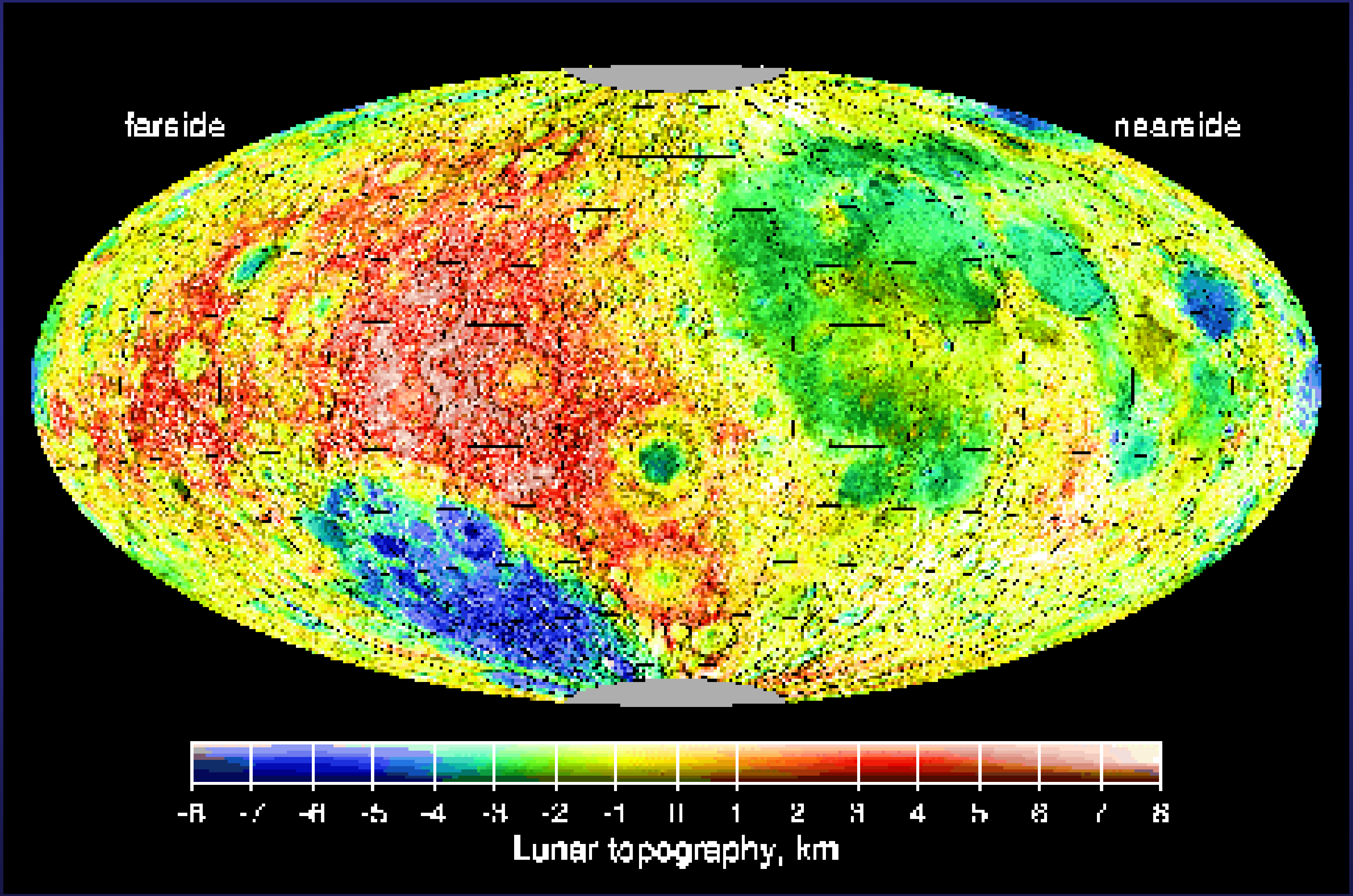
LASER ALTIMETRY
Past and Current Spaceborne Lidars

- **NASA's Mars Orbiter Laser Altimeter (MOLA) mapped the surface topography of Mars from the Mars Global Surveyor spacecraft (~666 million ranges)**
- **Earth's moon has been visited by two lidars with another on the way.**
  - NASA's Apollo 11 altimeter collected about 77,000 range measurements in 1969
  - DoD's Clementine mission collected about 700,000 ranges.
  - Lunar Observer Laser Altimeter (LOLA) will be launched in 2008 on NASA's Lunar Reconnaissance Orbiter (LRO)
- **The Earth is currently being mapped by the Geoscience Laser Altimeter System (GLAS) on NASA's ICESat (~2 billion ranges since March 2006 launch)**
- **NASA's Calipso mission has been mapping cloud and aerosol heights since June 2006.**
- **Johns Hopkins Applied Physics Lab's Near Earth Asteroid Rendezvous (NEAR) spacecraft mapped the asteroid EROS prior to landing on the surface.**
- **Mercury Laser Altimeter (MLA) on NASA's Messenger spacecraft is enroute to Mercury. Will possibly be joined by a lidar on ESA's Bepi-Colombo mission.**

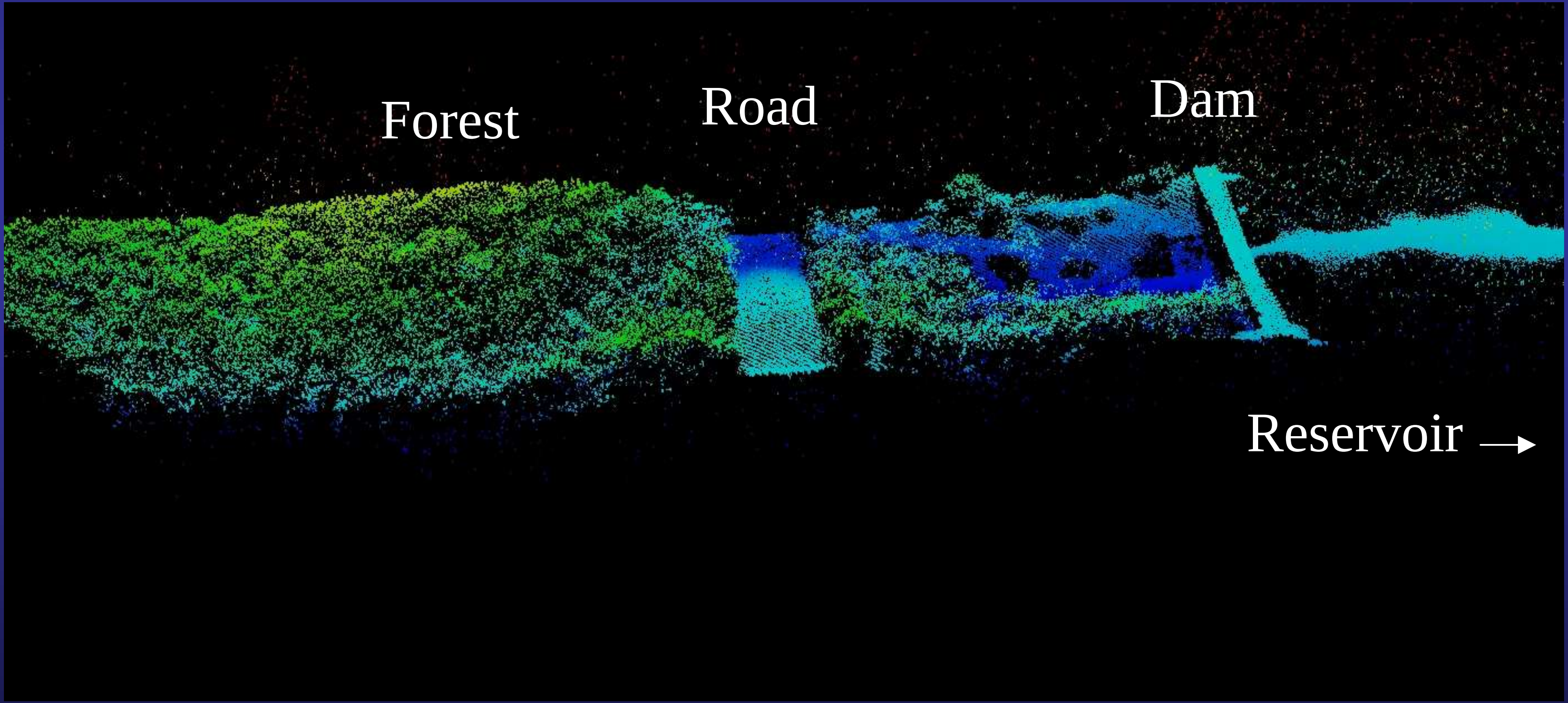
Mars Surface Topography from MGS/MOLA



Lunar Topography from Clementine



3D Lidar View of Triadelphia Reservoir, MD (single overflight)



NASA's Jupiter Icy Moons Orbiter (JIMO)

JIMO 3D Imaging Goals

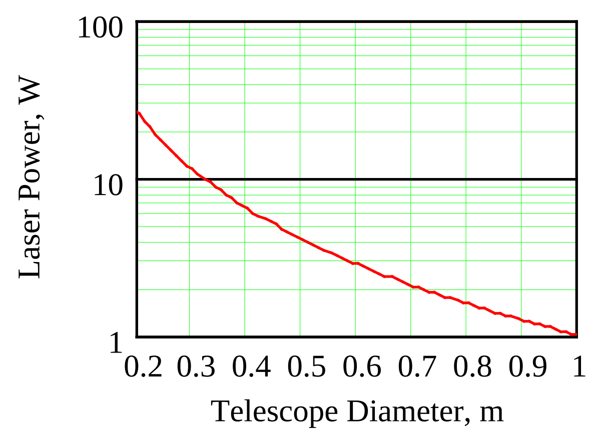
- Globally map three Jovian moons
- Horizontal Resolution: <10 m
- Vertical Resolution: < 1 m

Worst Case Constraints

- Europa (last stop) map must be completed within 30 days
  - 348 orbits at 100 km altitude
  - 14.5 km mean spacing between JIMO ground tracks
- Surface Area: 31 million km^2

Photon-Counting Lidar

- >95% probability of detection per pixel
- Power-Aperture Product: 1.12 W-m^2

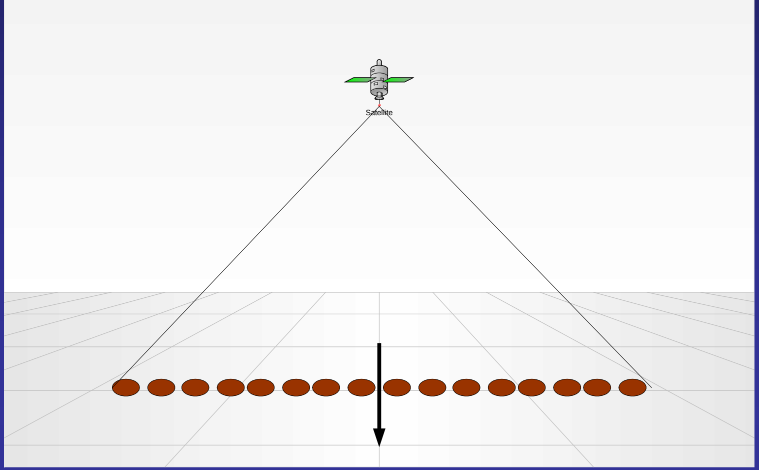


What is Swath Mapper*?

- A 16 beam photon-counting lidar which has been proposed by Sigma Space to fly with the primary ICESat-II lidar in 2011
- Serves as a “pathfinder” for the NASA LIST mission which seeks 5 m resolution, globally contiguous, Earth topography in the 2016 time frame.
- A Diffractive Optical Element (DOE) generates 16 parallel beamlets from a single, multikilohertz, passively Q-switched laser transmitter (nominally 1 mJ @ 10 KHz = 10W at 1064 nm; 4W at 532 nm or 0.25W per beamlet)
- 16 fiber bundles in the GLAS telescope focal plane relay photons reflected from the surface within each beamlet to a single microchannel plate photomultiplier with 16 anodes arranged in a 4x4 pattern.
- The multistop, single photon sensitive detector and Sigma’s multistop, multichannel timing receiver record the photon times of flight with a resolution of ±93 psec (±1.4 cm range) and a deadtime of less than 2 nsec.

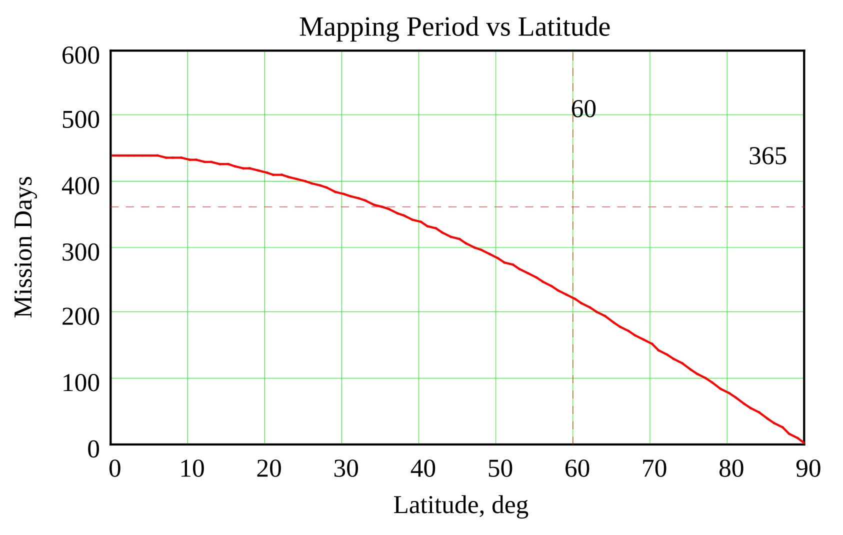
*Also referred to as a “pushbroom lidar” in J. Degnan, “A Conceptual Design for a Spaceborne 3D Imaging Lidar”, J. e&i Elektrotechnik und Informationstechnik (Austria), April, 2002.

Swath Mapper Concept



- A single 10 W laser transmitter is within the state-of-the-art and can support up to 16 channels with 82% surface return rate over ice and snow in a standard clear atmosphere and provides some signal margin for poorer atmospheres.
- Sixteen beams is “optimum” since reducing the number of channels only marginally increases the return rate while significantly reducing the spatial coverage.

- Assuming 16 beams over 3 km oriented at 45º to flight accomodates periodic spacecraft yaw rotations while providing:
  - 16 tracks 141 m apart = 2.1 km actual swath
  - Latitudes above 80º are mapped seasonally (>4 times/yr)
  - Latitudes below 35º are mapped less than once per year



Concluding Remarks

- Photon-counting kilohertz SLR systems appear to offer significant benefits but eyesafe requirements severely compromise performance.
- Multiwavelength ranging for atmospheric refraction correction appears to be stalled due to technical difficulties and/or inadequacy of existing targets; current research emphasis is on better atmospheric modeling.
- With modest technology investments, laser transponders will permit centimeter ranging and subnanosecond time transfer over most of the solar system in the near future. System concepts can be tested inexpensively via dual station laser ranging to artificial satellites. NASA’s Lunar Reconnaissance Orbiter (LRO) will conduct a “half-transponder” experiment following a 2008 launch.
- Photon-counting 3D imaging lidars offer a viable way to globally map planets and moons at high spatial resolution.