SigmaSpace
EXCELLENCE IN AEROSPACE TECHNOLOGY

Impact of SLR Technology Innovations on Modern Science

Dr. John J. Degnan, Chief Scientist
Sigma Space Corporation,Lanham, MD 20706 USA
(retired from NASA Goddard Space Flight Center in 2003)
18th International Workshop on Laser Ranging
Fujishiyoda, Japan
November 11, 2013

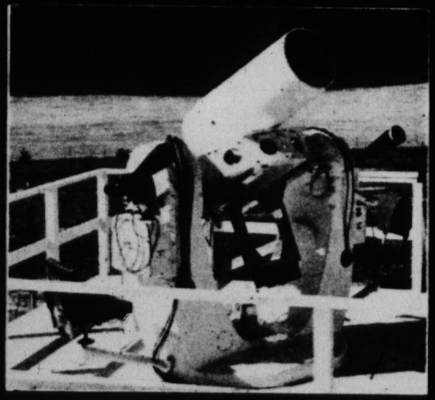
OVERVIEW

- Technology Innovations Driving Range Precision and Station Automation (Sessions 7, 8, 10, 11, 12, and 13)
- Science Applications of SLR (Sessions 1,2,4,5, and 9)
- Summary

GSFC records first SLR returns ever on Oct 31, 1964

SATELLITE LASER RANGING - 1964

GODdard LASer (GODLAS)

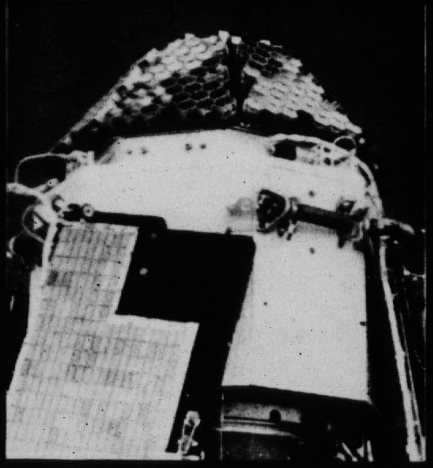


TRANSMITTING LASER AND RECEIVING TELESCOPE, MOUNTED ON A MODIFIED NIKE-AJAX RADAR PEDESTAL.

Code 524 SLR Team

Dr. Henry Plotkin
Tom Johnson*
Paul Spadin
John Moye
Walt Carrion*
Nelson McAvoy*
Sol Howard Genatt*
Louis Caudill
Peter Minott
John Degnan
Ed Reid
Charles Peruso

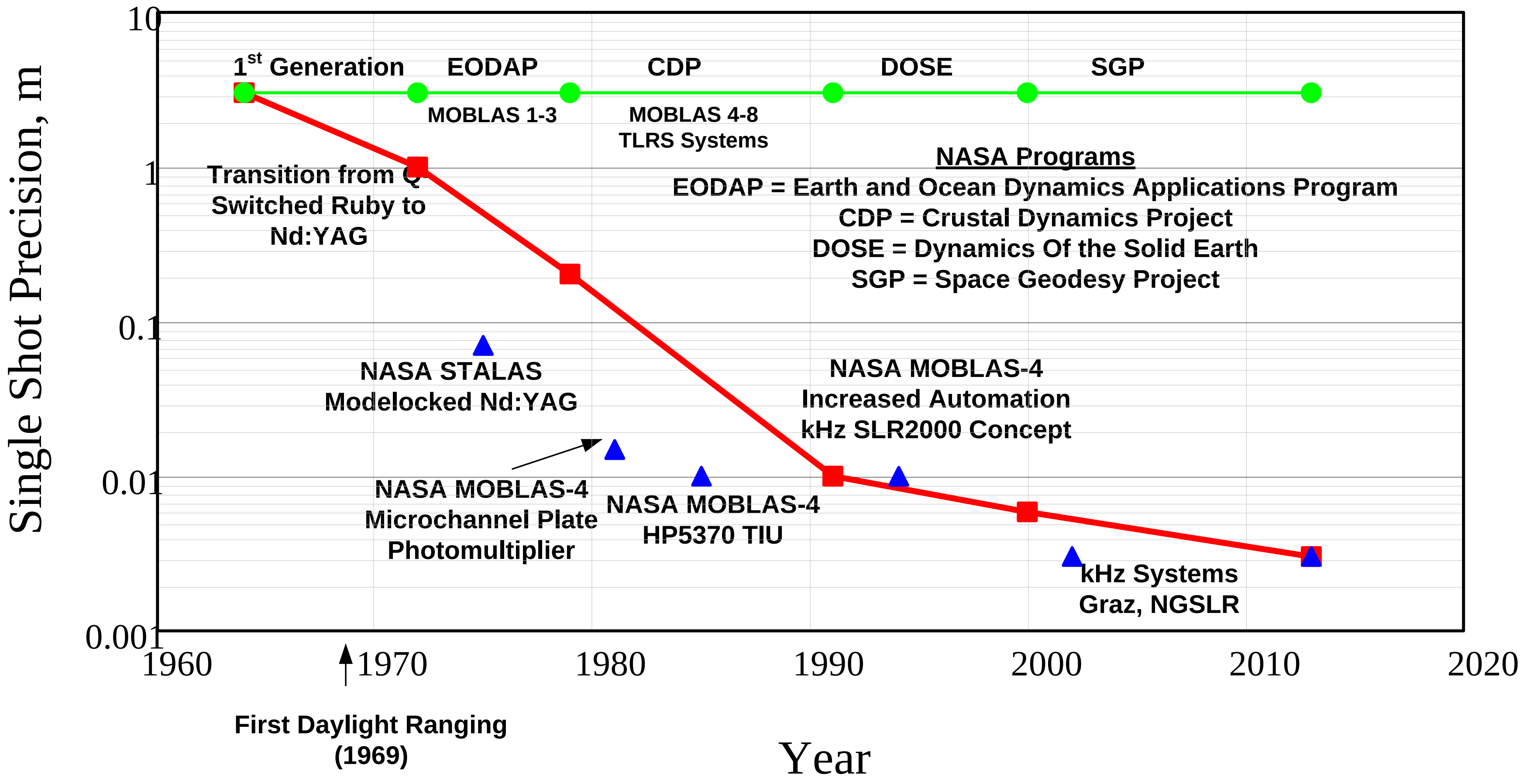
BE-B: first satellite with retro-reflectors



THE BEACON EXPLORER-B SATELLITE WITH ARRAY OF CUBE-CORNER REFLECTORS.

*** Deceased**

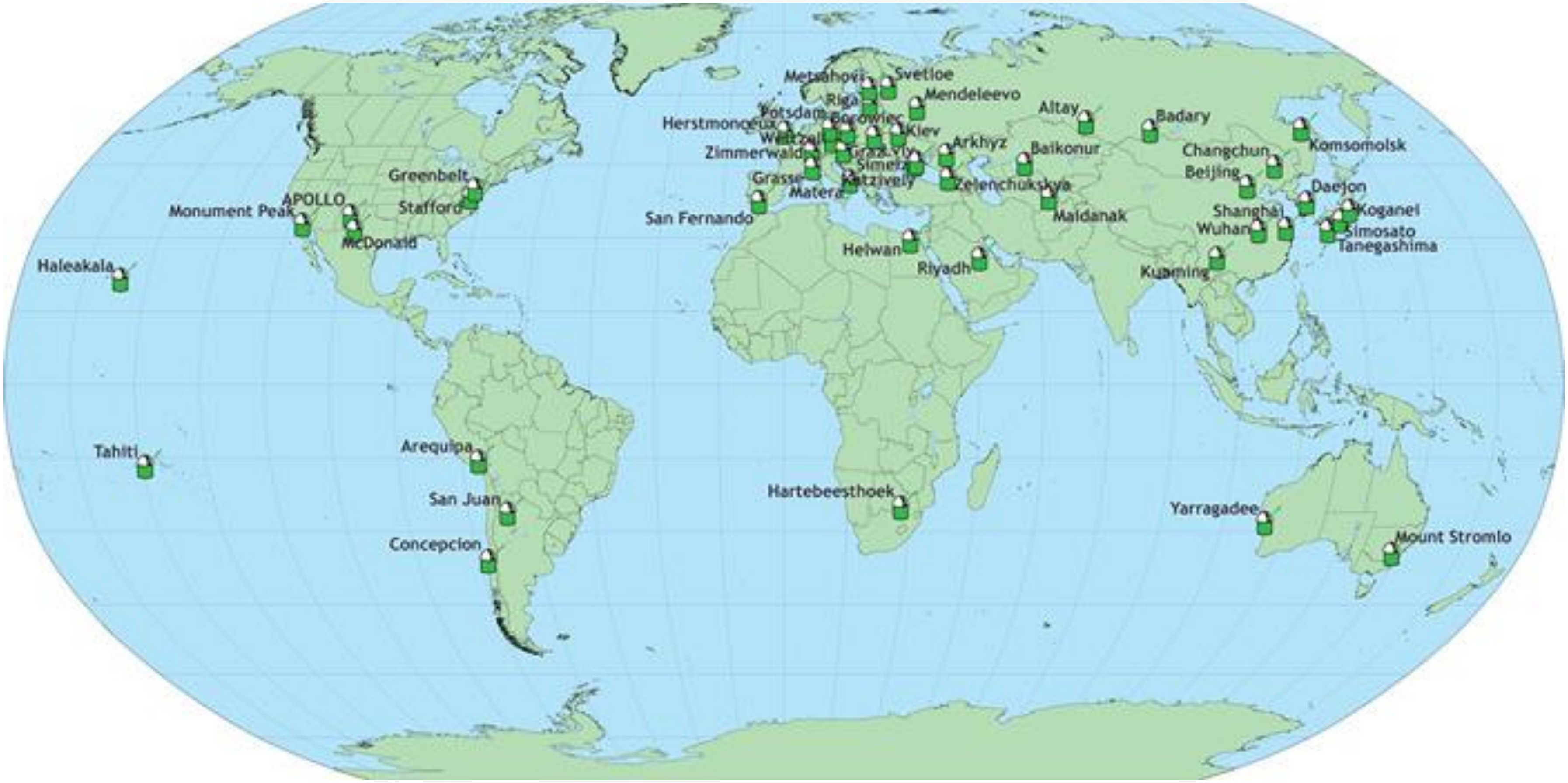
Representative SLR Precision vs Time



The 1970s also saw the launch of the first true geodetic satellites designed to support cm laser ranging. These included Starlette and Stella by France and LAGEOS by NASA. LAGEOS-2 was built by Italy and carried to orbit by the NASA Space Shuttle in 1992.

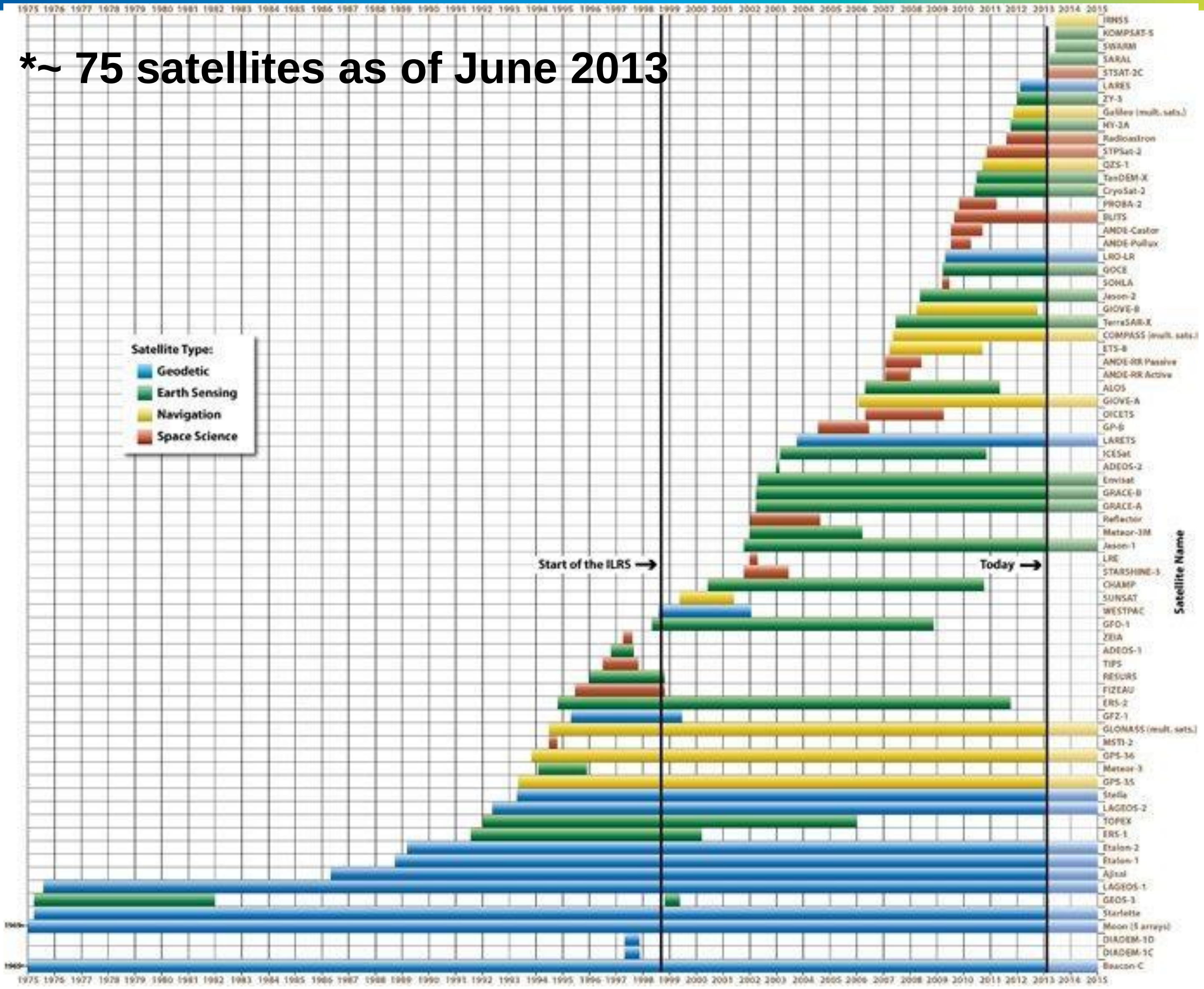
Current ILRS Network

The SLR network has grown substantially from 5 US and French stations in the late 1960s but there are still some coverage gaps in the Southern Hemisphere, Equatorial Region, and high Northern latitudes.



SigmaSpace
EXCELLENCE IN AEROSPACE TECHNOLOGY

Space Missions Tracked by SLR*

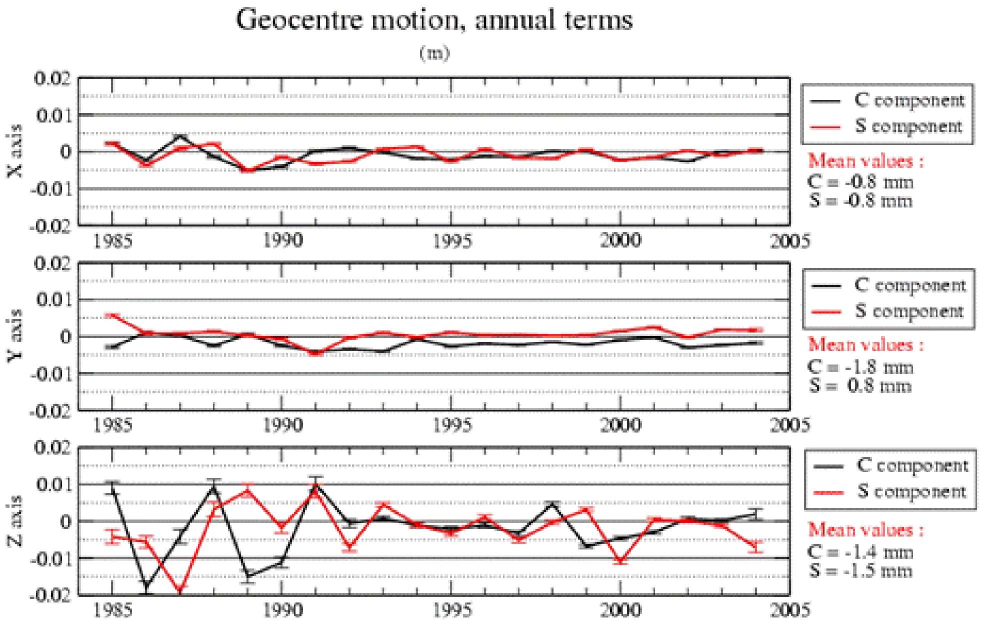


***~ 75 satellites as of June 2013**

Terrestrial Reference Frame

SLR defines the Terrestrial Reference Frame (TRF) which includes the Earth Center of Mass (Geocenter) and scale (GM)

GEOCENTER MOTION



Mean annual terms amount to :

1.2 mm in X, with a minimum in February

2.0 mm in Y, with a minimum in December

1.8 mm in Z, with a minimum in February

corresponding to a winter loading centred on Siberia

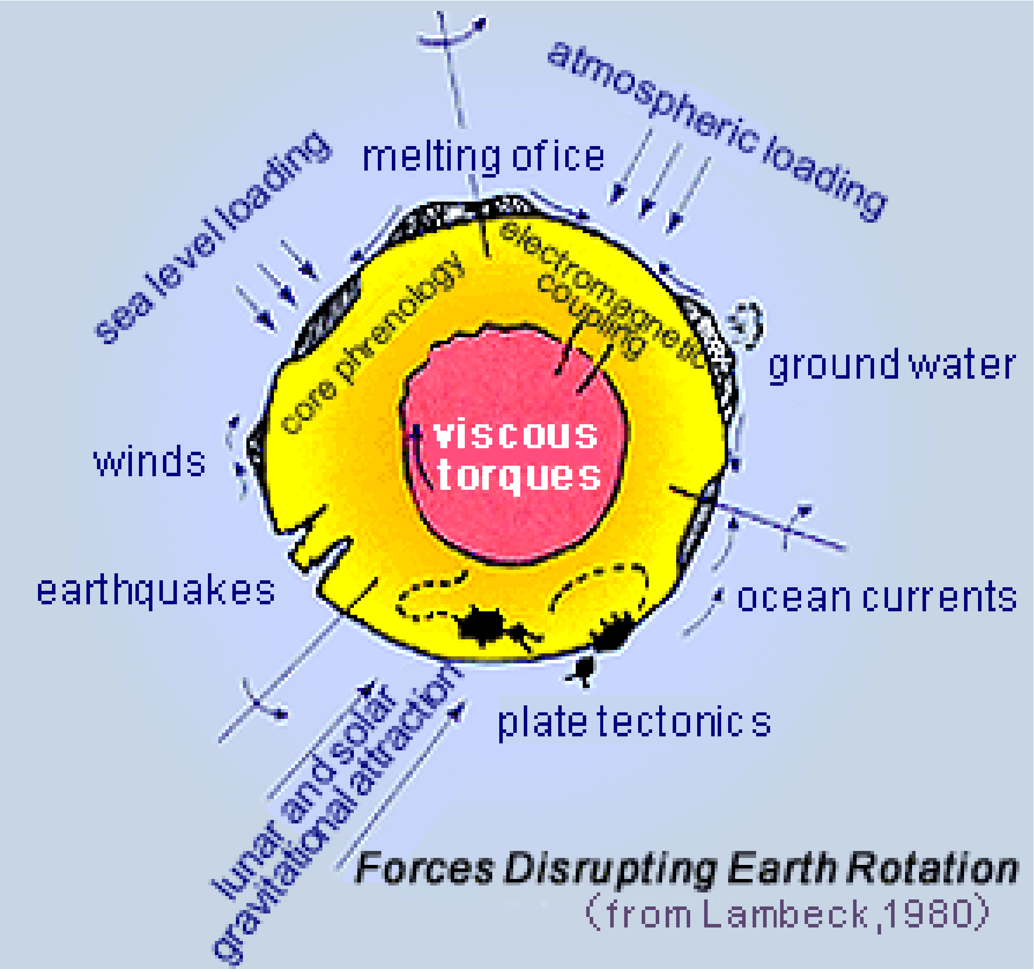
***Courtesy: Peter Dunn**

International Earth Rotation Service

Earth Orientation Parameters (EOP)

Polar motion (Chandler Wobble)
Length of Day (LOD)
High frequency UT1

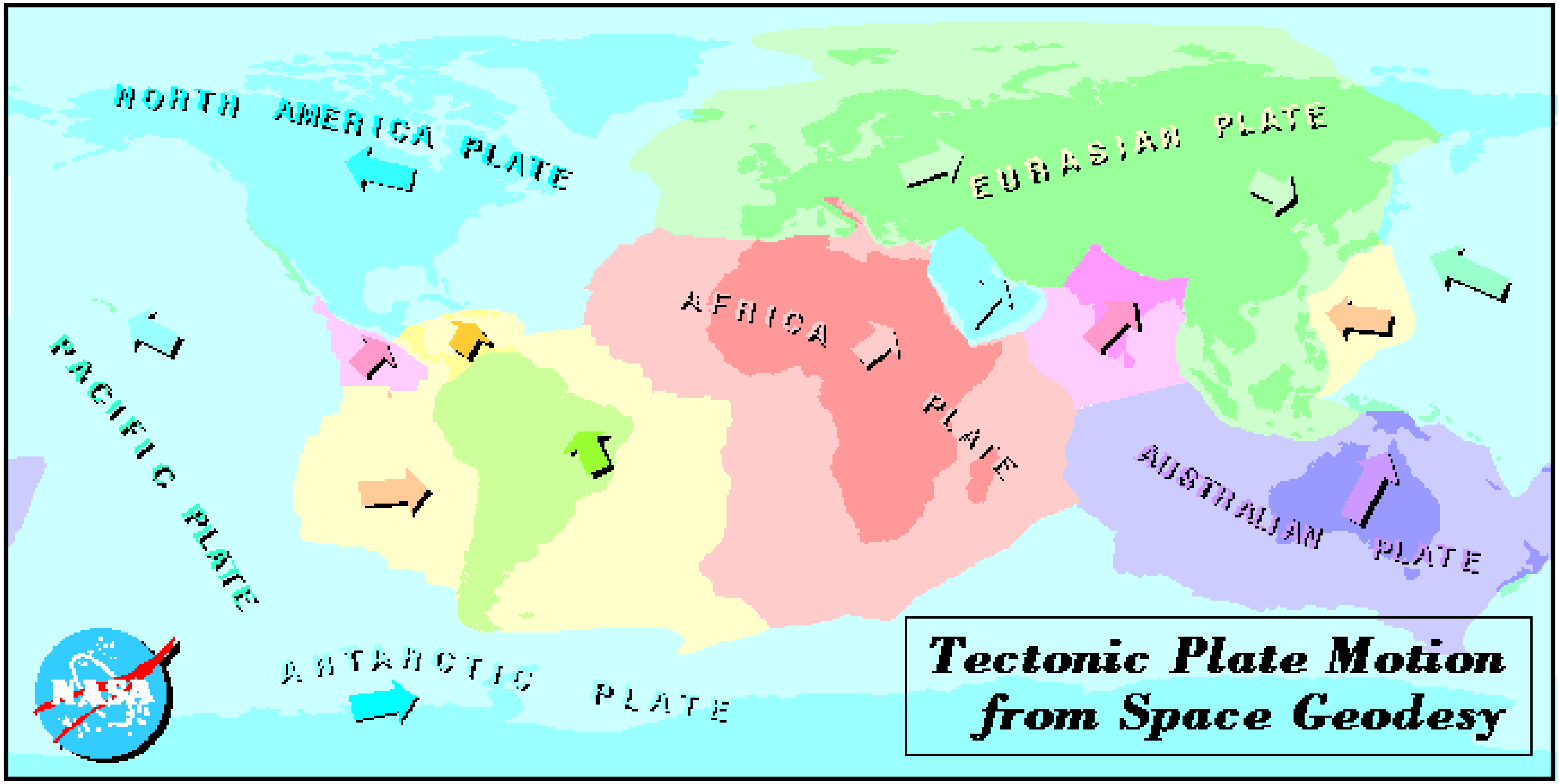
VLBI, working with distant quasars in the Celestial Reference Frame, is the primary source of EOP, but SLR interpolated the results between VLBI campaigns.



Forces Disrupting Earth Rotation
(from Lambeck, 1980)

Global Tectonic Plate Motion

High, low drag satellites, like LAGEOS in a 6000 km high orbit, provide a stable inertial reference frame which allow us to see changes in relative positions of SLR stations that track them and thereby monitor tectonic plate motion.

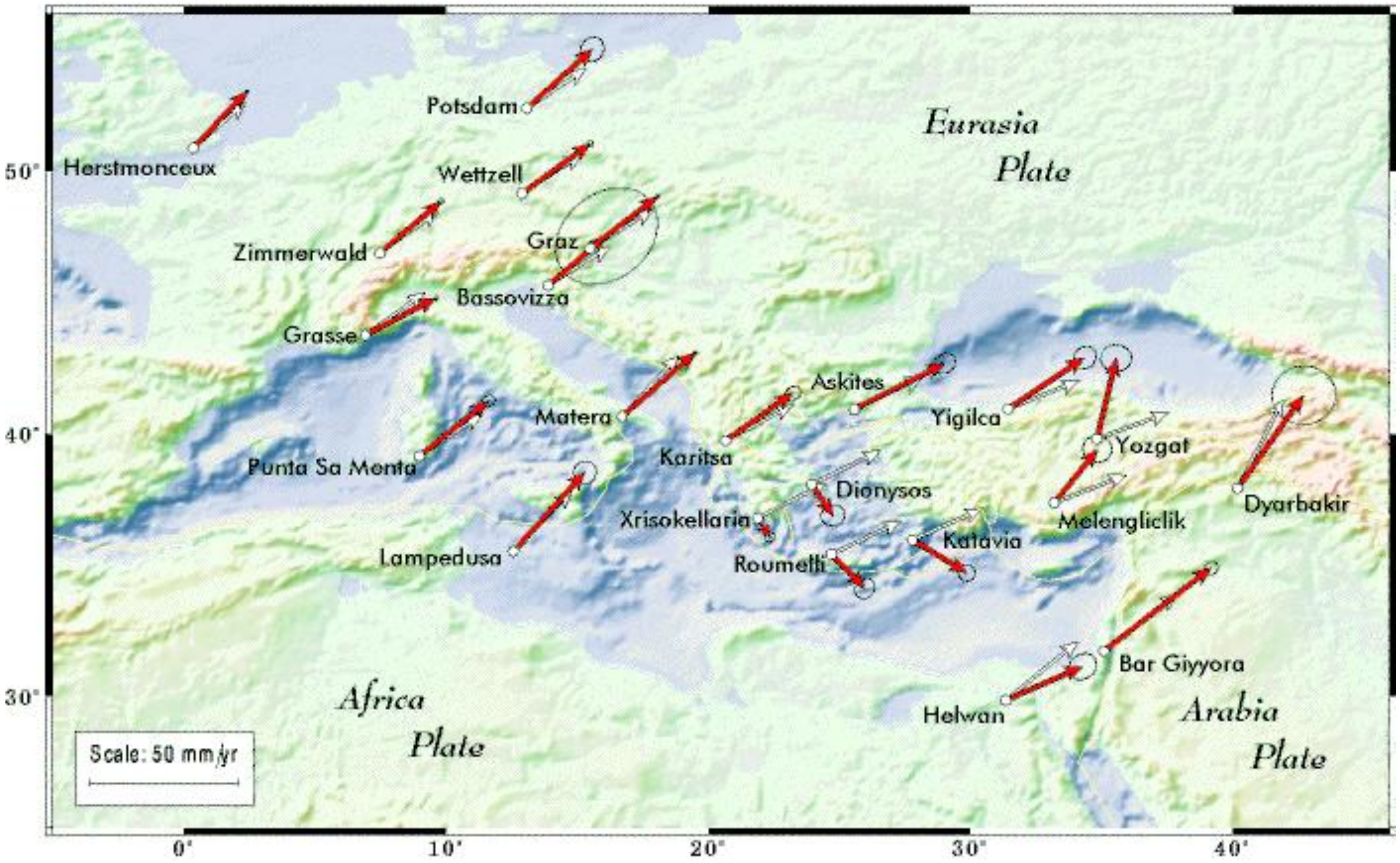


Length of the arrows are an indication of relative velocity.

SLR Site Motion in Europe

CDP/WEGENER-MEDLAS Campaigns

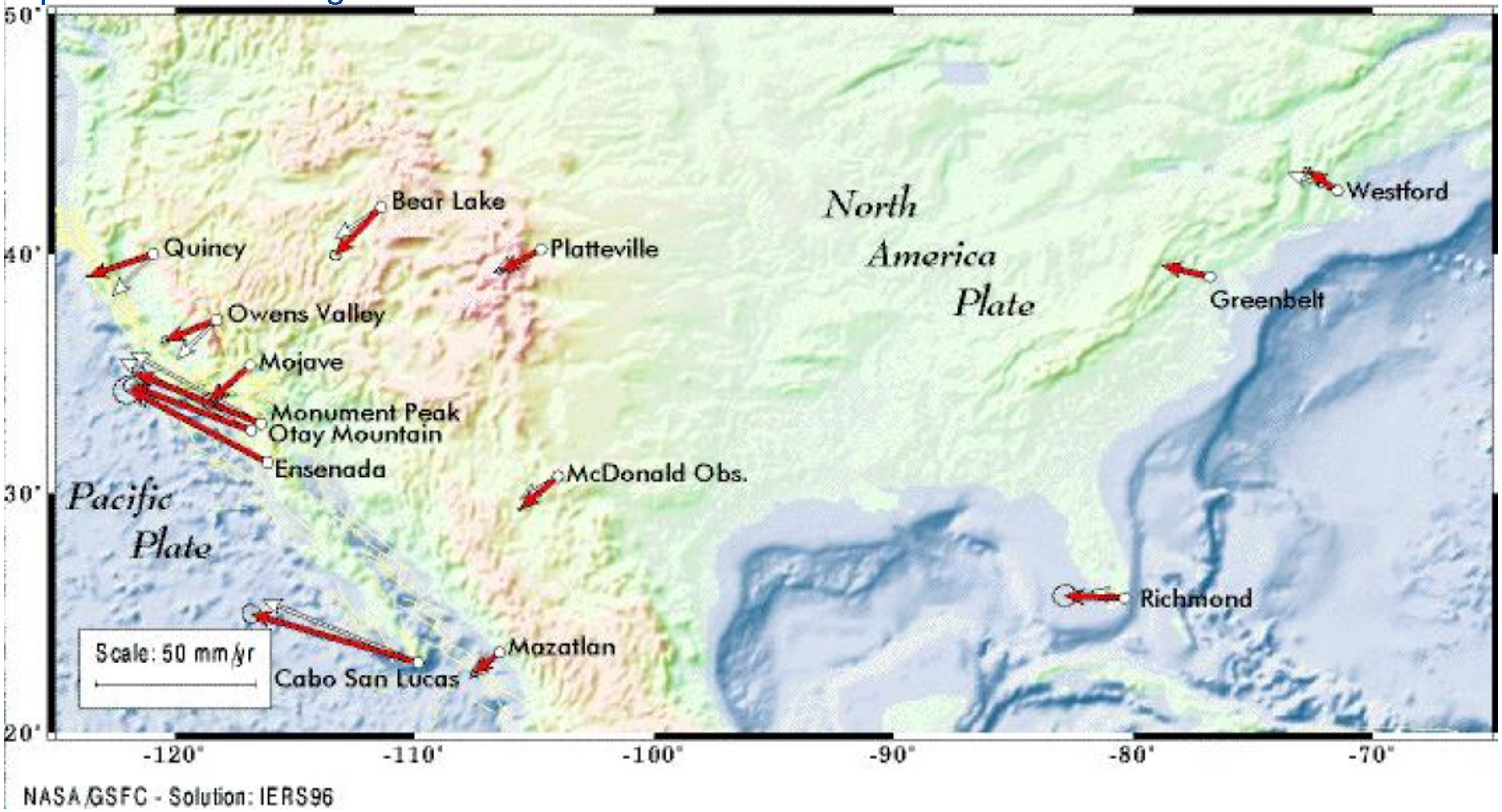
The US and European transportables routinely alternated between sites in the Western US and the Mediterranean to monitor the complex motions near major fault lines.



NASA/GSFC - Solution: IERS96

SLR Site Motion in North America CDP/WEGENER Campaigns

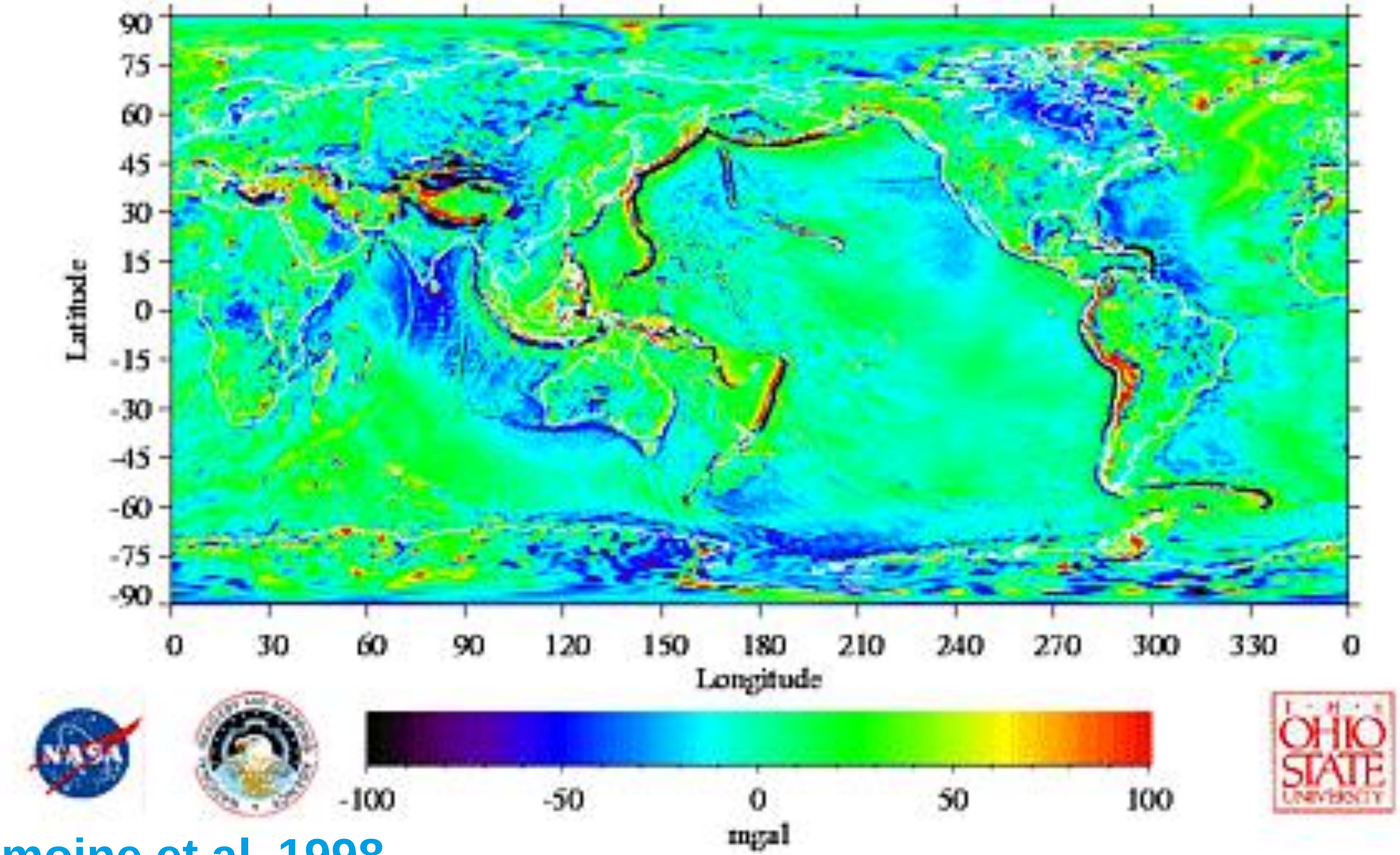
Regional deformation measurements were enabled by the development of highly transportable SLR stations in the US and Europe. This function has since been largely taken over by GPS with most SLR transportables now either in fixed locations or doing specialized investigations.



NASA/GSFC - Solution: IERS96

EGM 96 Mean Gravity Anomalies*

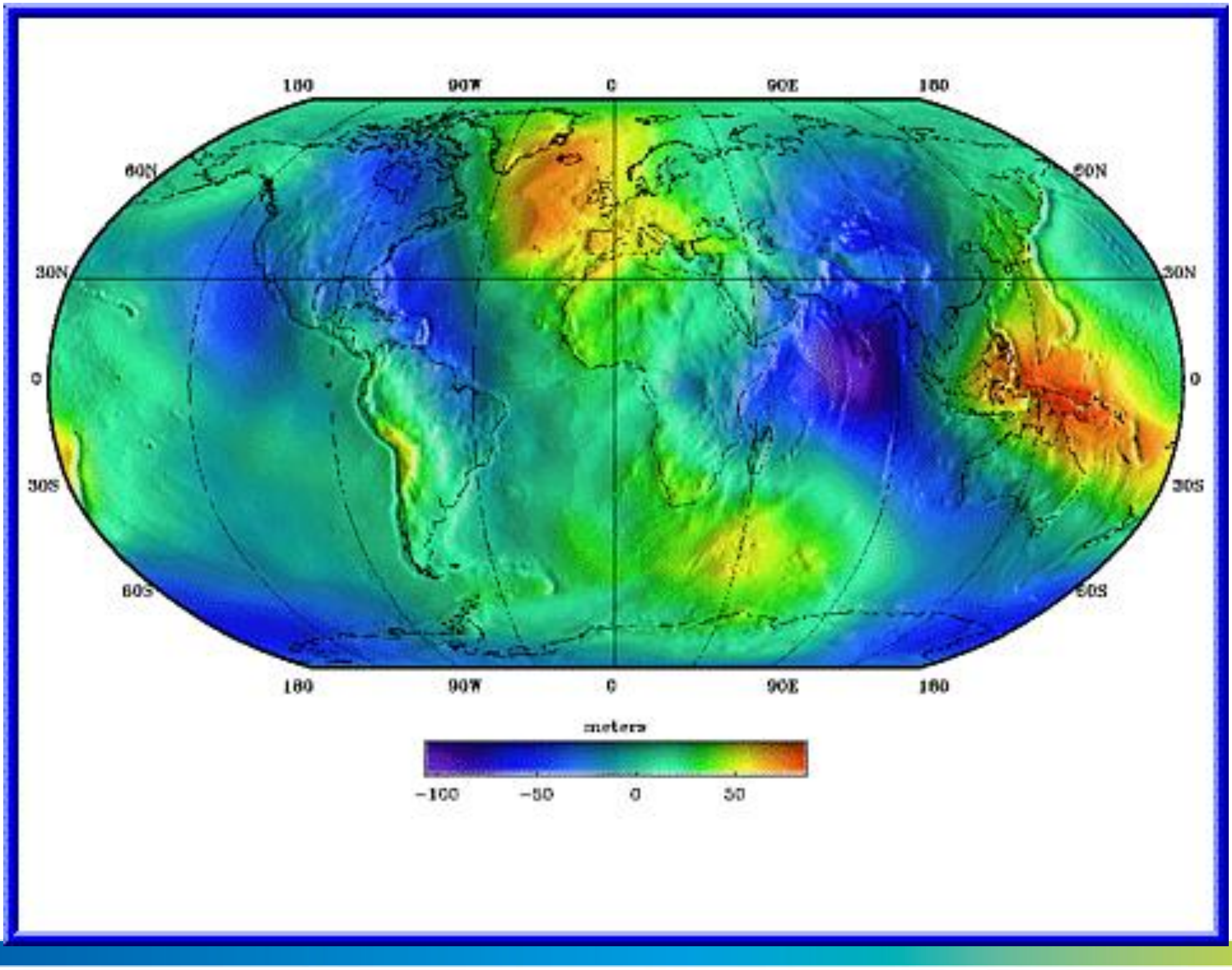
A **gravity anomaly** is the difference between the observed acceleration of a planet's gravity and a value predicted from a global model, expressed as a sum of spherical harmonics. A location with a positive anomaly exhibits more gravity than predicted, while a negative anomaly exhibits a lower value than predicted.



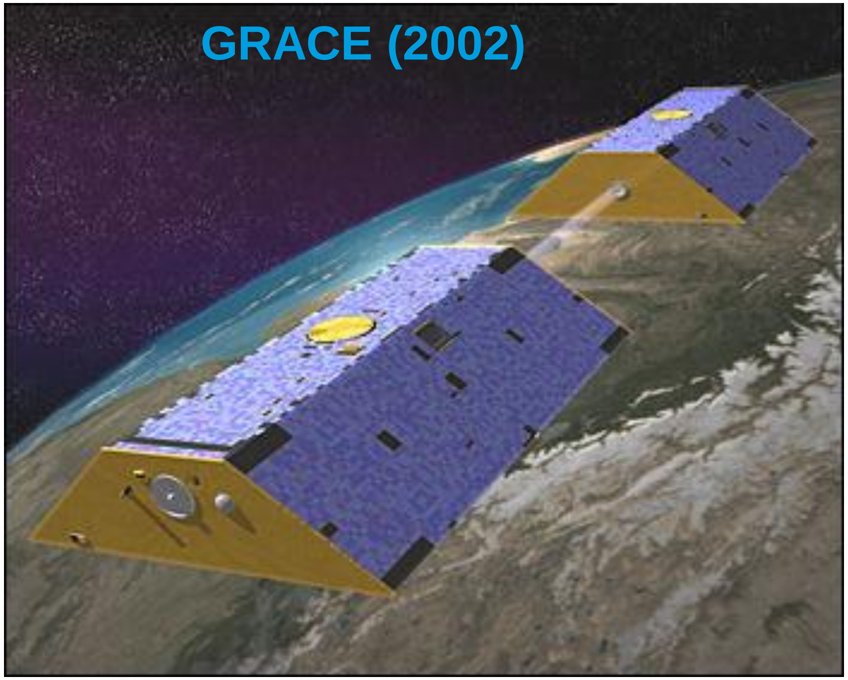
*F. Lemoine et al, 1998

JGM96 Earth Geoid

NGS Definition of “geoid”: “The equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level “



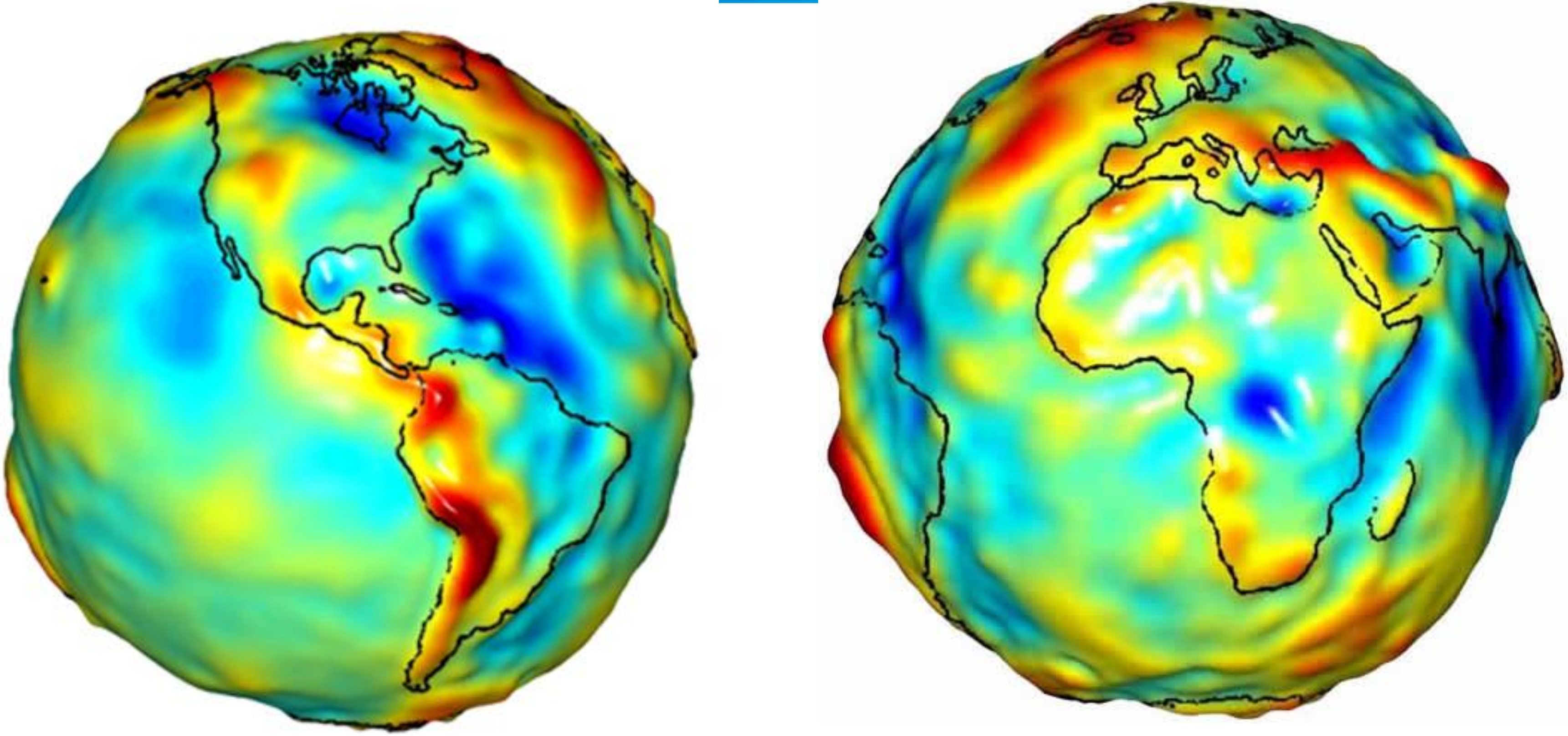
Gravity Recovery and Climate Experiment



- Two identical spacecraft (GRACE A&B) in polar orbit at 500 km altitude are tracked by GPS and SLR
- Separation (~220 km) measured by K-band microwave link
- Observed changes to separation provide high spatial frequency components in the gravity field.

- Goals:
  - Map gravity field and changes with time
  - create a better profile of the Earth's atmosphere.
- The gravity variations that GRACE studies include:
  - changes due to surface and deep currents in the ocean
  - runoff and ground water storage on land masses
  - exchanges between ice sheets or glaciers and the oceans
  - variations of mass within the Earth.
- GRACE-2 will likely have a laser –based satellite interferometer and higher resolution (100 km)

Global Gravity Field from GRACE Mission

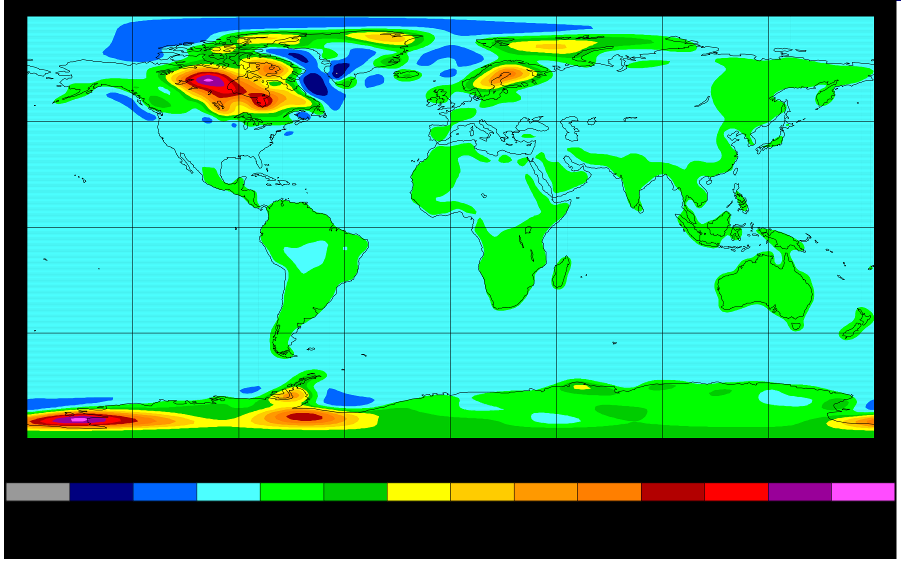


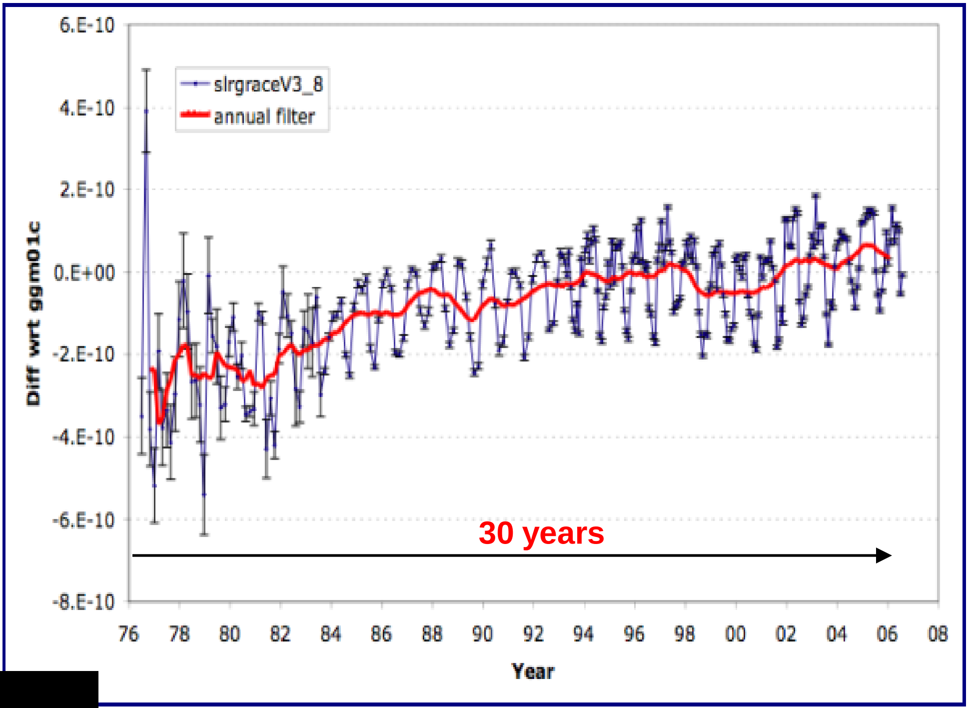
In 2002, NASA launched a pair of satellites, the Gravity Recovery and Climate Experiment (GRACE) mission, to measure precisely the gravitational field at the surface of the Earth. As the two satellites orbit the Earth, their precise velocities and the distance between them are constantly monitored. By comparing the difference between the orbits of the two satellites, GRACE mission scientists can infer how local gravity varies around the globe. The image shows the regions of strong (red, raised) and weak (blue, depressed) gravitational acceleration measured by the GRACE mission.

SLR can detect secular trends in the Earth’s gravity field

“Thr Earth is getting rounder!”

Rate of Radial Displacement Predicted from PGR Model Developed from ICE-5G (Peltier)



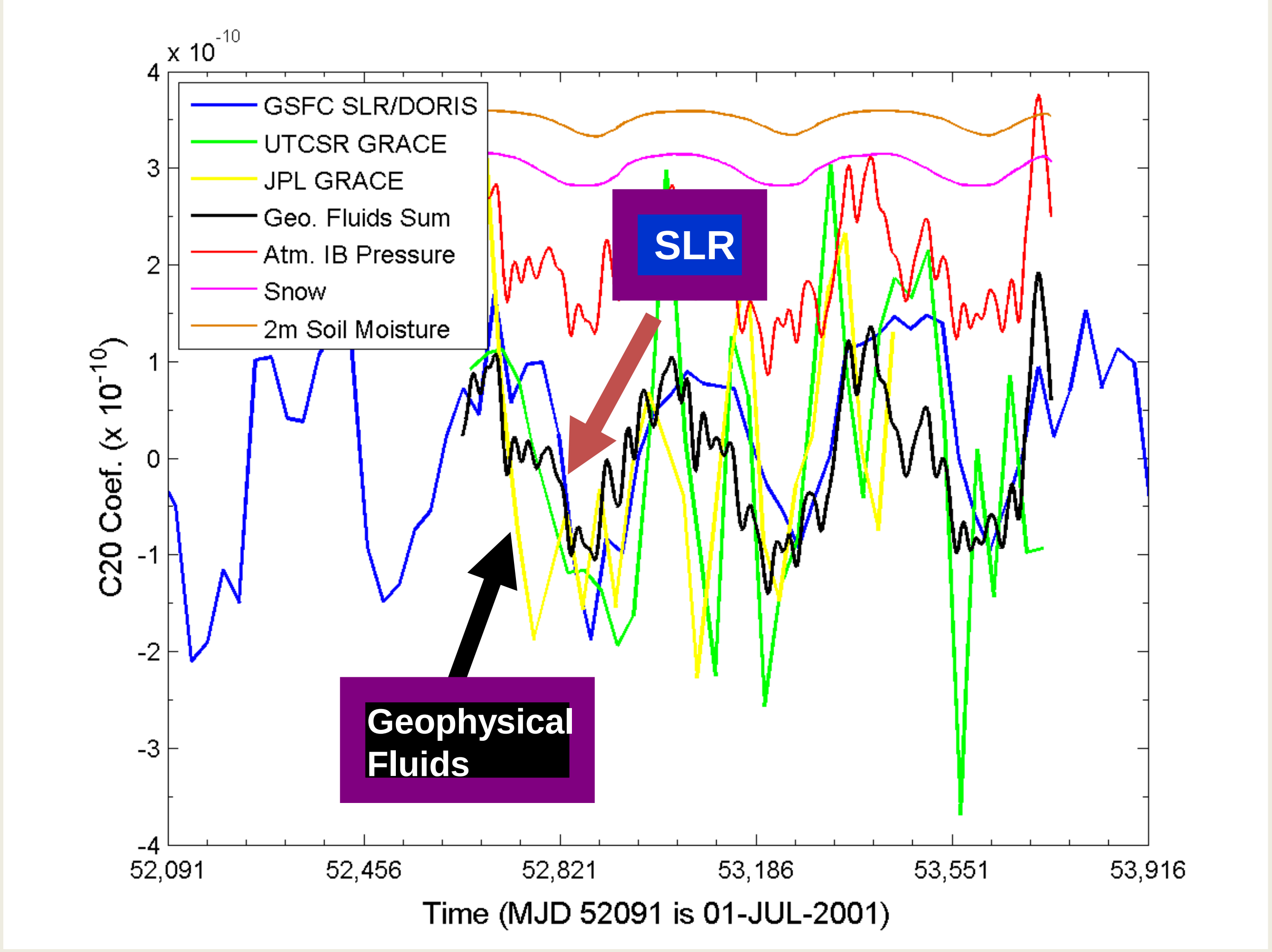


C_{20}: SLR 30 yr Evolution (Lemoine)

Post Glacial Rebound

Courtesy: Steve Klosko, SGT Inc.

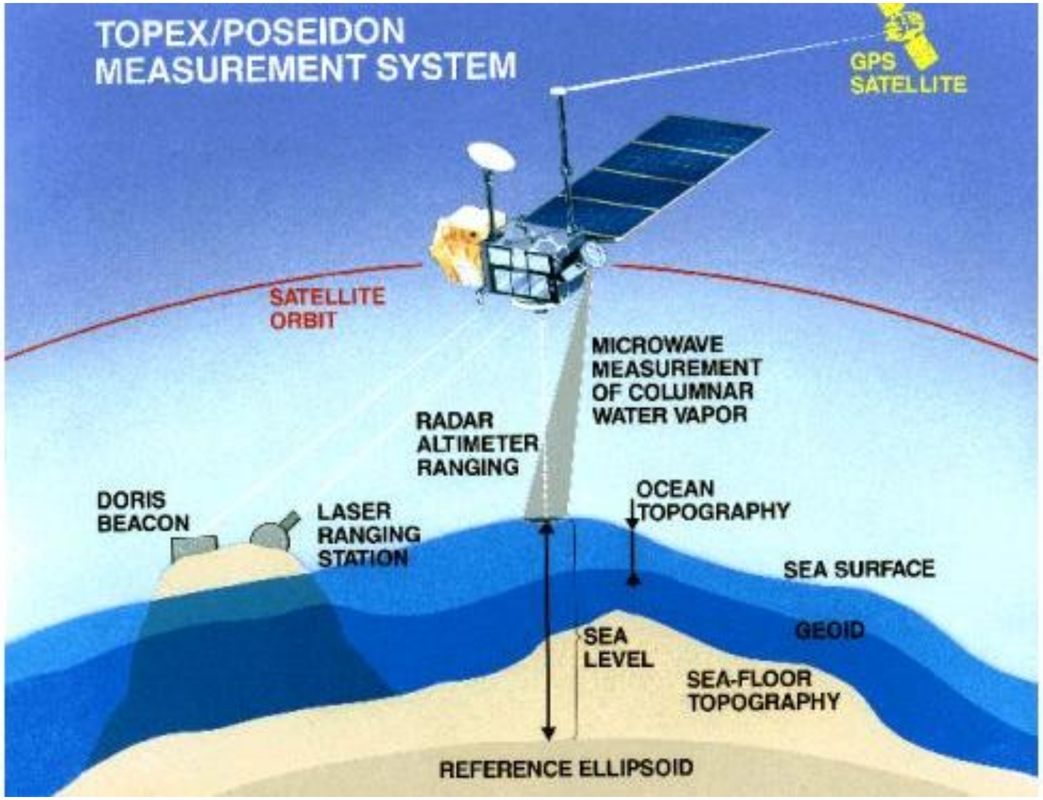
$C_{2,0}$: Comparison: SLR vs GRACE monthly (Lemoine)



As SLR precision and our knowledge of the Earth gravity field improved, analysts were able to better model other forces affecting satellite orbits, such as atmospheric drag and radiation pressures (Sun and Earth albedo).

Global Sea Level & Circulation

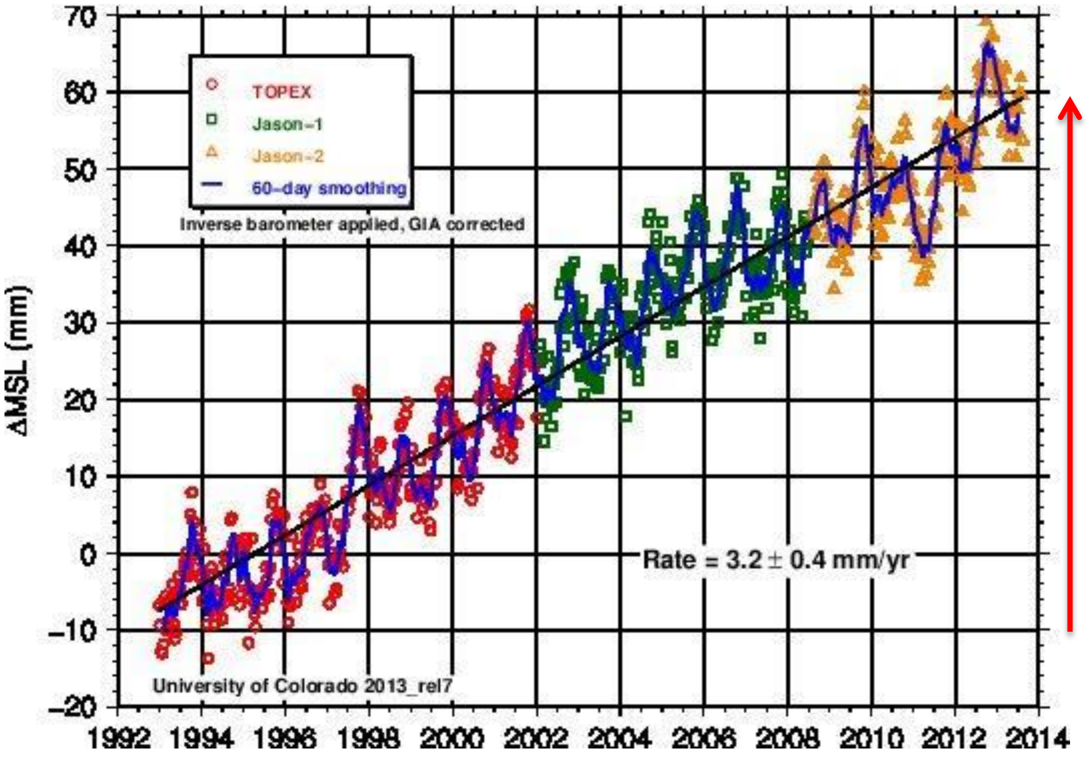
Radar altimetry on GeoSat, ERS-1, TOPEX/Poseidon, ERS-2, GFO,and JASON satellites, all tracked by SLR



- "Ocean Topography" (OT) is defined as the height difference between the sea surface and the geoid (sum of gravity and Earth rotation effects)
- In the Northern hemisphere, currents flow CW around topographic highs and CCW around lows. The reverse is true in the Southern Hemisphere
- Height of the SST is proportional to the speed of the surface currents.
- Radar altimeter measures the distance between the sea surface and the spacecraft on a global scale
- SLR provides:
  - Cm accuracy SLR station locations relative to Geocenter
  - Moderate to long wavelength geoid surface relative to geocenter
  - Cm accuracy positioning of the TOPEX/Poseidon satellite in geocentric reference frame

OT = Satellite Distance from Geocenter (SLR)-Local Geoid (SLR/Alt)-Altimeter Range

Mean Sea Level (MSL) and Sea Surface Temperature (SST)



(Topex/Poseidon, Jason-1, and Jason-2 –1992 through 2013)

70 mm rise in Mean Sea Level from 1992 to 2013 (21 years) yields rate of 3.2 ± 0.4 mm/yr

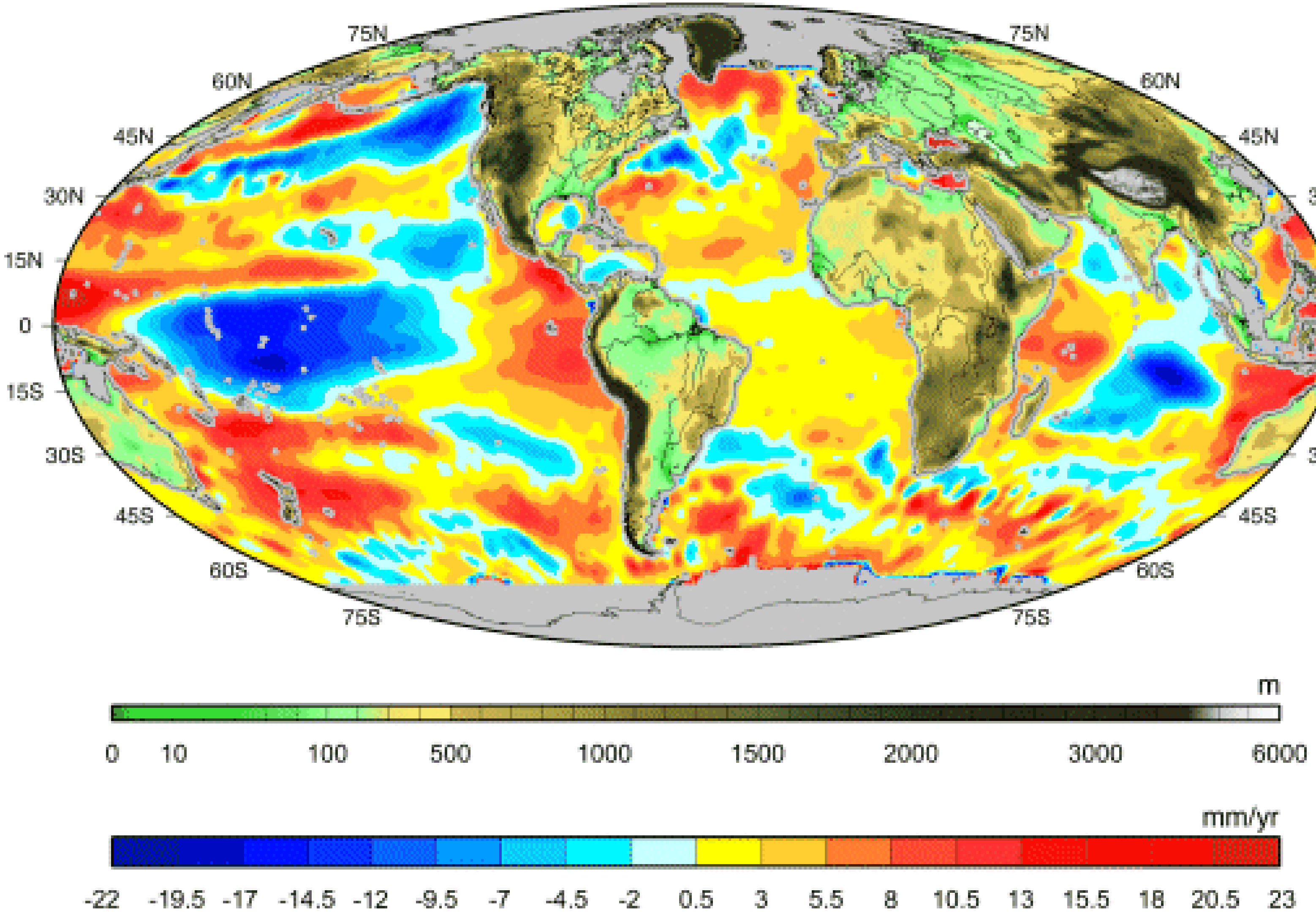
Contributors to Sea Level Change

•variations in sea water temperature and salinity at all depths
•Tectonic changes to the water basin "shape"
•change of the ocean mass as a result of exchanges of water with the other surface reservoirs (atmosphere, continental waters, glaciers and ice sheets).

Tide Gauge Drawbacks

•Prior to the launch of the oceanographic satellites, tide gauges were used to estimate sea level rise
•geographical distribution provides very poor sampling of the ocean basins,
•measure sea level relative to the land, hence recording vertical crustal motions that may be of the same order of magnitude as the sea level variation.

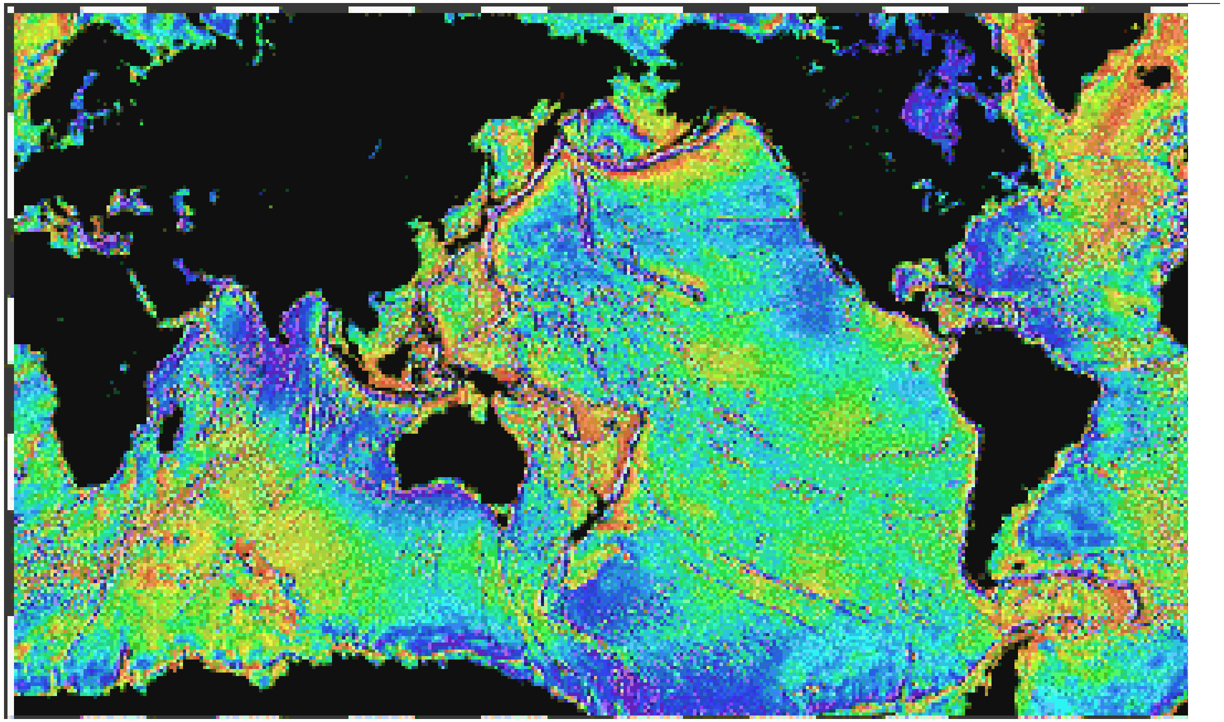
Spatially Resolved Global Sea Level Rise



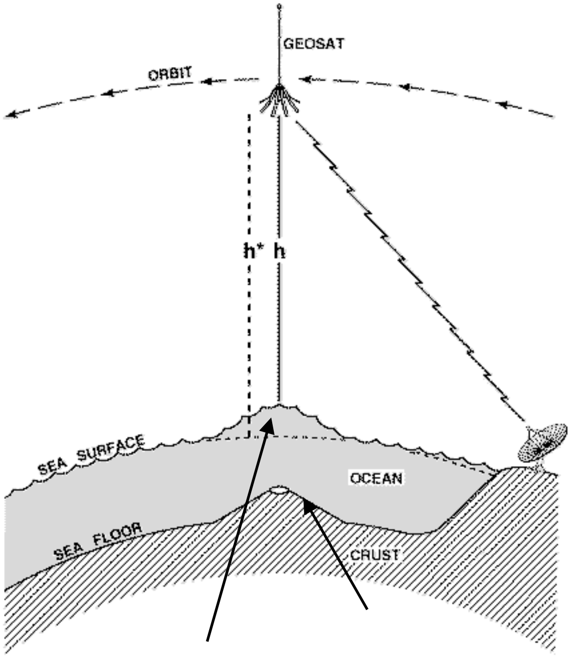
SigmaSpace
EXCELLENCE IN AEROSPACE TECHNOLOGY

Sea Floor Topography from Sea Surface Altimetry*

* The 2nd keynote address by Dr. M Fujita will discuss the relation to earthquakes.



Ocean floor topography from Geosat and ERS-1 radar altimetry obtained with SLR tracking only
(David Sandwell and Walter Smith)



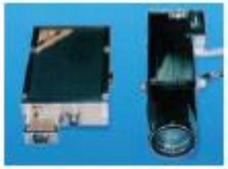
Approximately 1000:1 ratio in heights
(1 km sea mount creates ~1 m bump in sea level)

Spaceborne Laser Altimetry

Compared to microwave altimeters, lasers have much better spatial resolution and range precision. All spaceborne laser altimeters to date have been based on 2nd generation SLR technology.

Apollo, - Moon
NASA (1971-1972)
Ruby laser,
5,000 shots

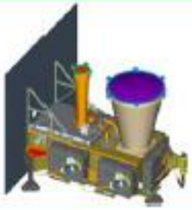
Clementine - Moon
LLNL/NRL (1994)
Nd:YAG laser,
~72,000 shots



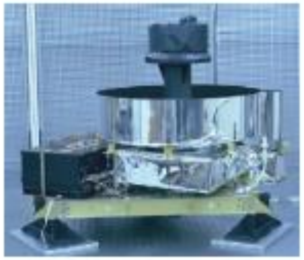
SELENE/LALT - Moon
Japan (2007-present)
Nd:YAG laser,

Chang'E - Moon
China (2007-present)
Nd:YAG laser

LRO/LOLA - Moon
NASA GSFC (2008-now)
Nd:YAG laser,
>1 Billion shots



MGS/MOLA - Mars
NASA GSFC (1992, 1996 -2000)
Nd:YAG laser,
670 Million shots

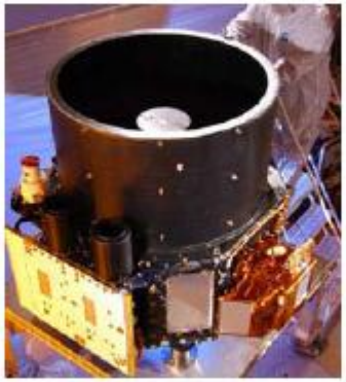


NEAR/NLR - Eros
JHU/APL (96-2001)
Nd:YAG laser,
11 Million shots

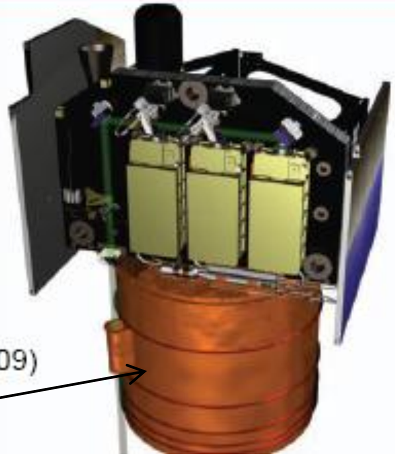
MESSENGER/MLA - Mercury
NASA GSFC (2004-2012)
Nd:YAG laser,
12M shots (planned)

Hayabusa -Itokawa
Japan (2003)

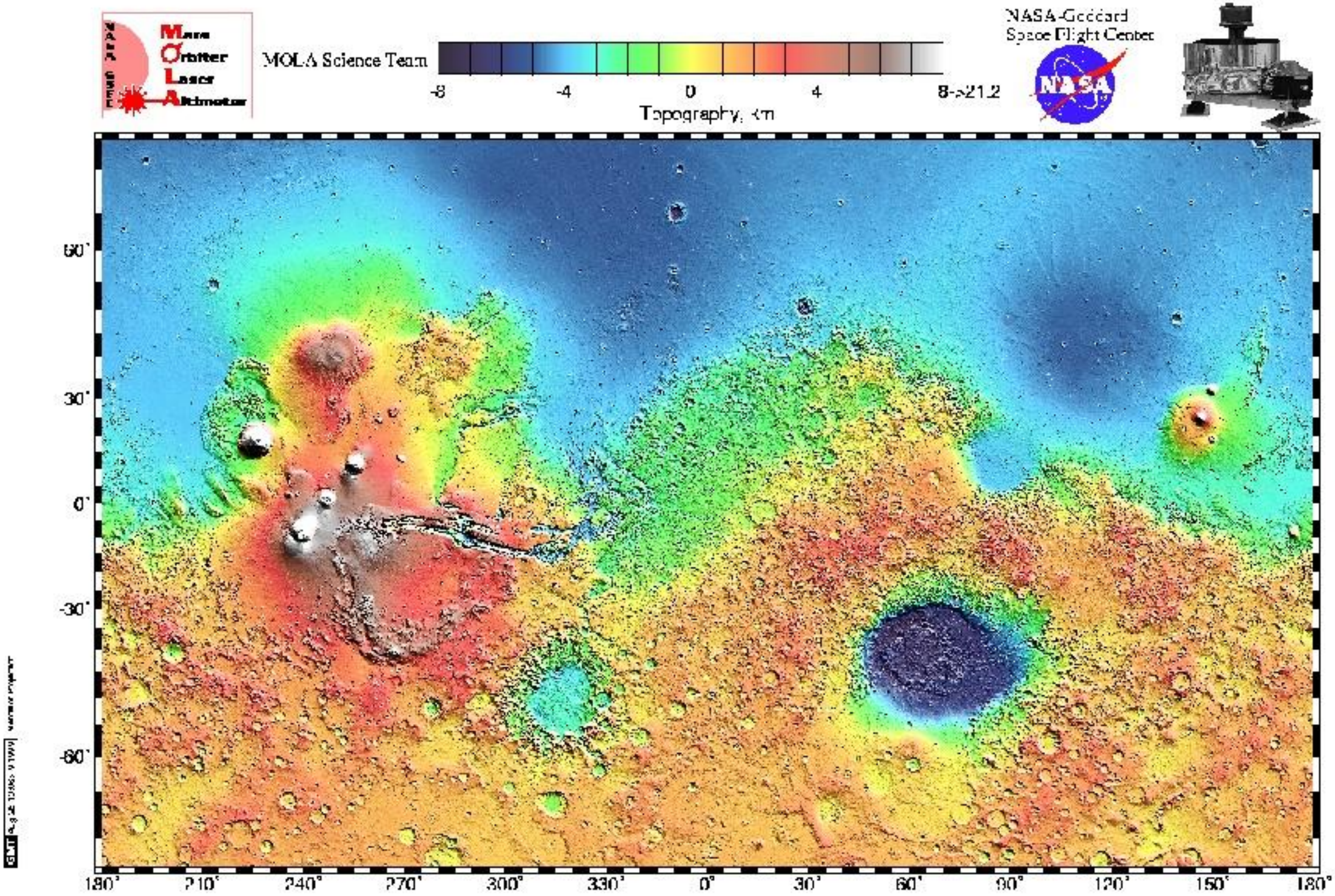
CALIPSO/CALIOP - Earth
NASA LaRC/ Ball Aerospace
(2006-present)
2 Nd:YAG lasers,
> 2B shots to date



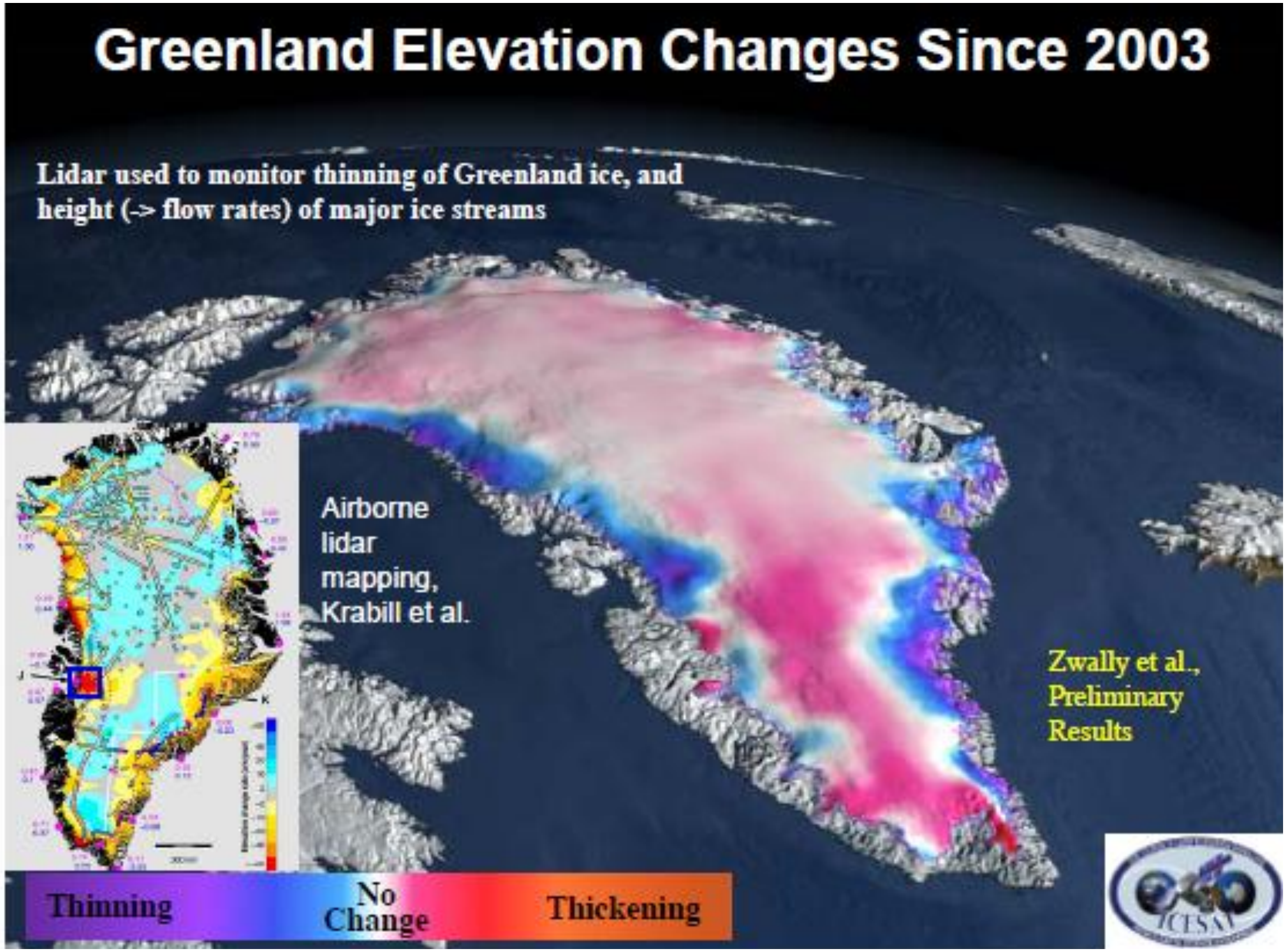
ICESat/GLAS - Earth
NASA GSFC (2003-2009)
3 Nd:YAG lasers
1.98 Billion shots



Mars Surface Topography from MGS/MOLA (10 Hz)



Geoscience Laser Altimeter System (GLAS) on ICESat-1 (2003) -40 Hz



Greenland Elevation Changes Since 2003

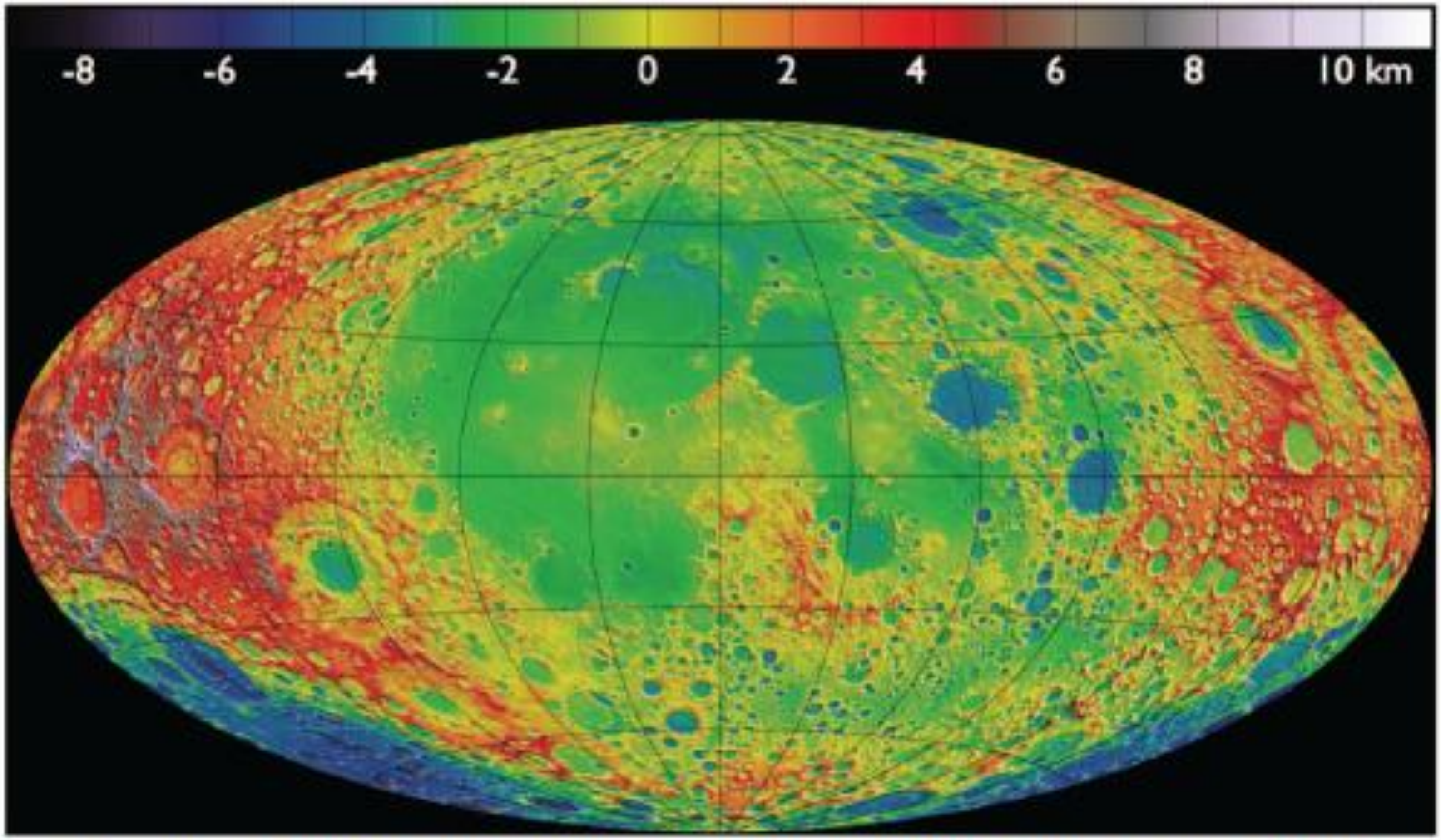
Lidar used to monitor thinning of Greenland ice, and height (-> flow rates) of major ice streams

Airborne lidar mapping, Krabill et al.

Zwally et al., Preliminary Results

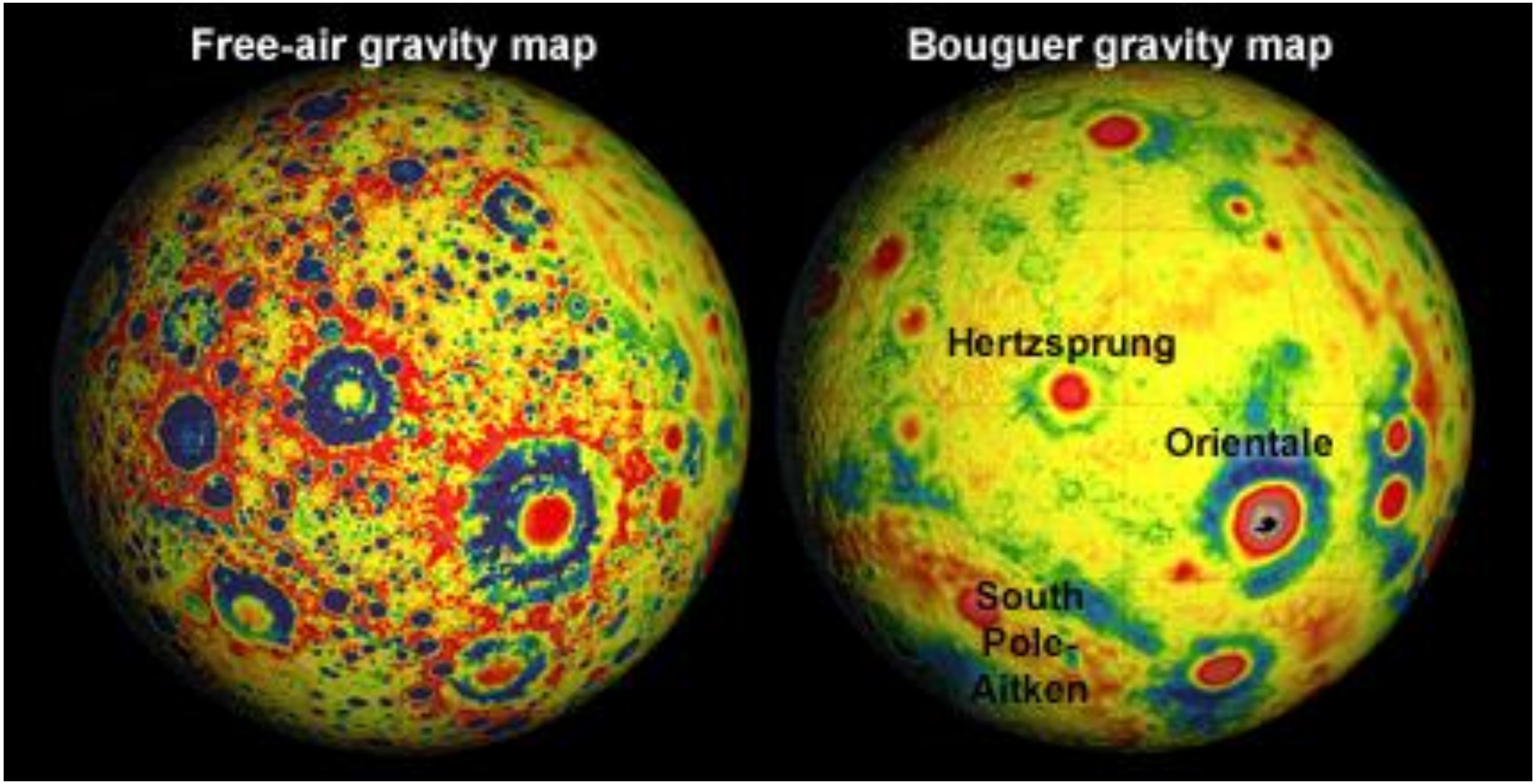
Almost 2 billion range measurements worldwide studying ice elevations, biomass, cloud heights, aerosols, etc.

Lunar Orbiter Laser Altimeter (LOLA)



Equal-Area projection of lunar topography developed from1 billion LOLA measurements
Resolution: N/S ~20m; E/W ~0.1 deg (4.5km at equator, 200m at >85 Lat)

Bouguer Gravity from NASA's Gravity Recovery and Interior Laboratory (GRAIL) and Lunar Reconnaissance Orbiter (LRO) Missions



GRAIL's "free-air" gravity map *(left)* shows deviations caused by both the Moon's bumpy surface and its lumpy interior. Compare that to the Bouguer gravity map *(right)*, which removes effects of topography to reveal density variations underneath the surface (such as *mascons* underlying large impact basins). These views show the lunar far side, centered on 120° west.

NASA / GSFC / Science Visualization Studio

Future Spaceborne Altimetry Missions

Earth*

Advanced Topographic Laser Altimeter System (ATLAS) on ICESat-2 (NASA-2016)

- – 6 beams@10 kHz =60,000 surface measurements per second

Mercury*

Bepi-Colombo Altimeter on Mercury Planetary Orbiter (ESA/JAXA - 2023)

Asteroid

OSIRIS-Rex Laser Altimeter (OLA) on Origins Spectral Interpretation Resource Identification Security Regolith Explorer (Univ. of Arizona, CSA/NASA)

*These missions will use some 5th generation photon-counting technology, but future spaceborne systems will have orders of magnitude higher surface measurement rates (~1 Million pixels per sec) and correspondingly higher horizontal resolution. (see my 3D Imaging Lidar paper in Session 12).

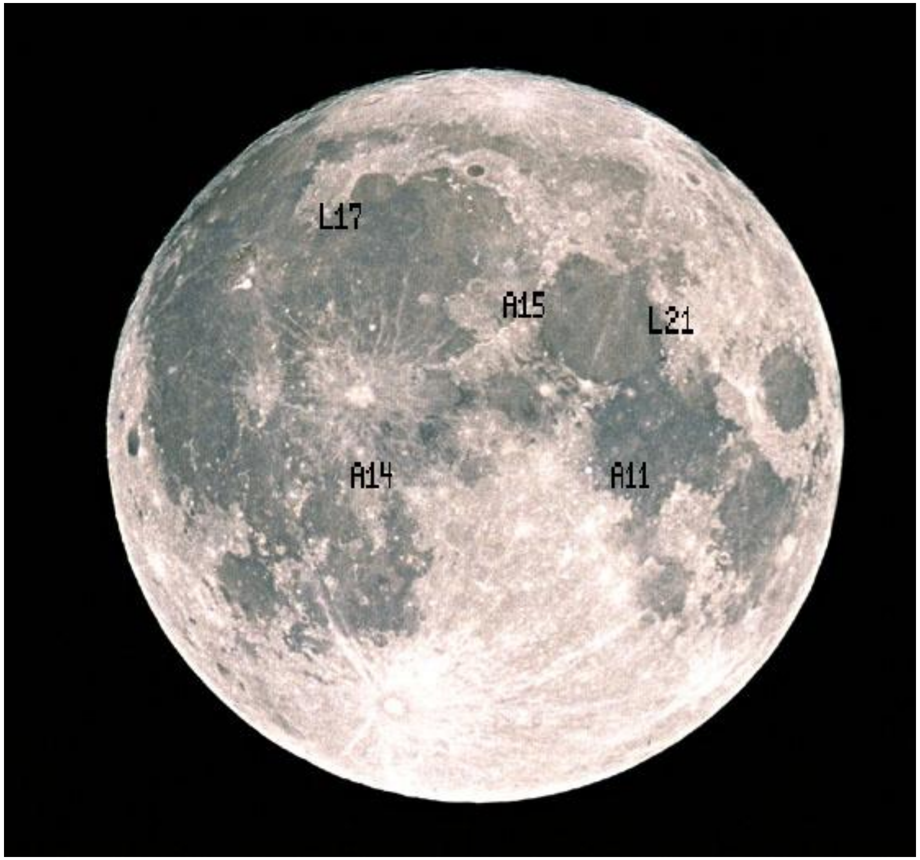
Lunar Laser Ranging

MLRS ranging to the Moon

- Currently five passive retroreflector arrays were landed on the Moon by
  - 3 NASA manned Apollo missions (11,14, and 15)
  - 2 Soviet Lunakhod missions (1 and 2)
- For over 30 years, the LLR data set was provided by three sites:
  - MLRS, McDonald Observatory, Texas, USA
  - CERGA LLR, Grasse, France
  - Mt. Haleakala, Hawaii, USA (decommissioned in 1992)
- New LLR systems have since come online:
  - MLRO, Matera, Italy
  - Apollo, Arizona, USA (multiphoton, 3.5 m telescope)

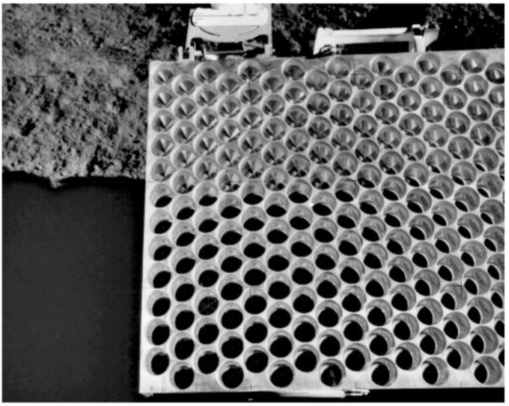
Lunar Retroreflector Arrays

Five retroreflector arrays were placed on the lunar surface beginning with Apollo 11 in 1969. Two other manned Apollo missions (14 and 15) also left arrays with Apollo 15 being the largest (300 vs 100 cubes) to strengthen the return signal. Two unmanned Soviet Lunakhod (17 and 21) missions landed additional arrays provided by France.



Retroreflector Array Sites

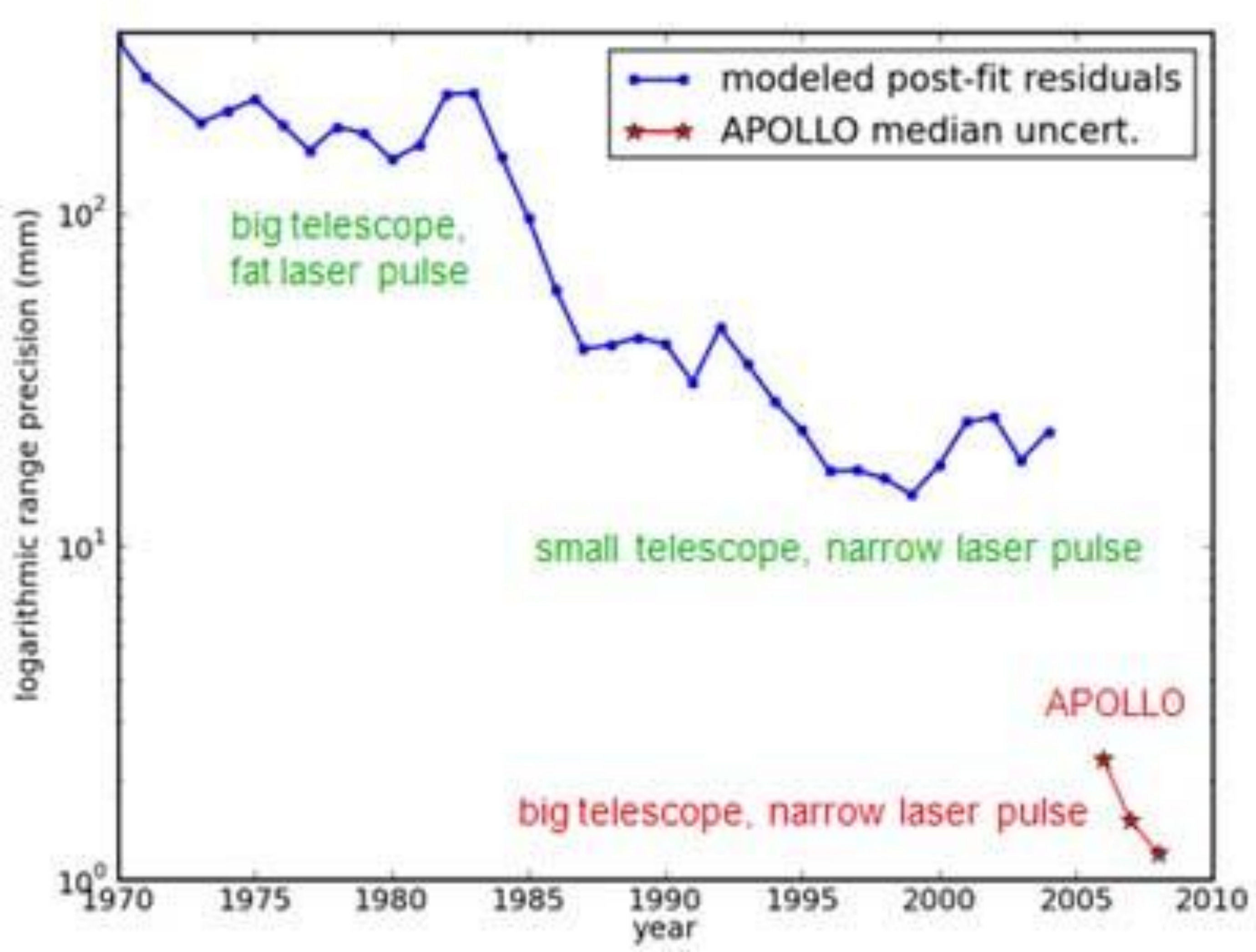
Apollo 11, 1969



Apollo 15

Lunakhod

LLR Range Precision vs Time

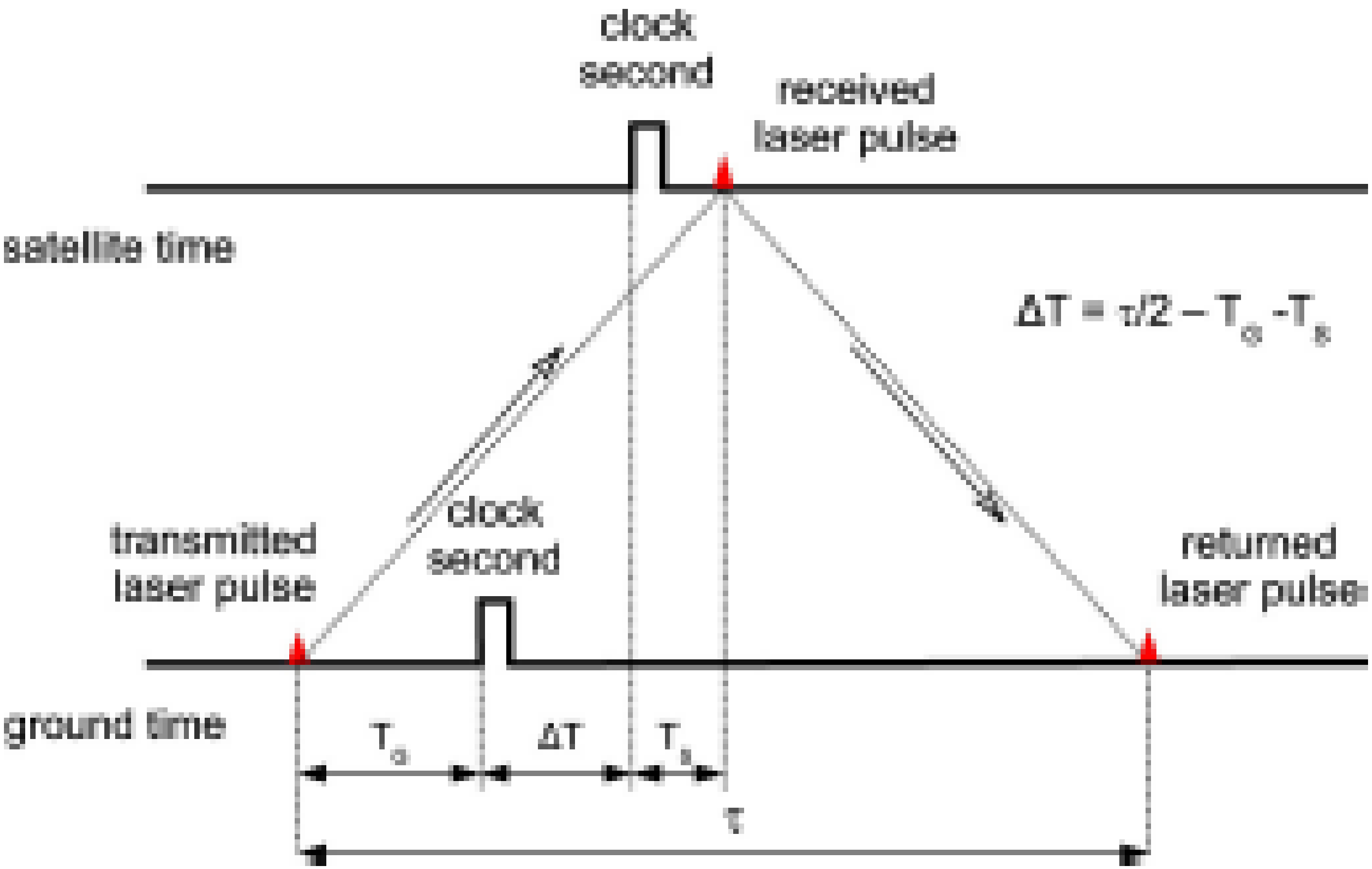


Some LLR Applications

- 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 $G(M_E + M_M)$
- Solar System Reference Frame (LLR)
  - Dynamic equinox
  - Obliquity of the Ecliptic
  - Precession constant
- General Relativity/Fundamental Physics
  - Test/evaluate competing gravitational and relativistic theories
  - **LLR validates Strong Equivalence Principle (SEP), which states that an** object's movement in a gravitational field does not depend on its mass or composition.
  - Constrain β parameter in the Robertson-Walker Metric
  - Constrain time rate of change in G (G-dot)

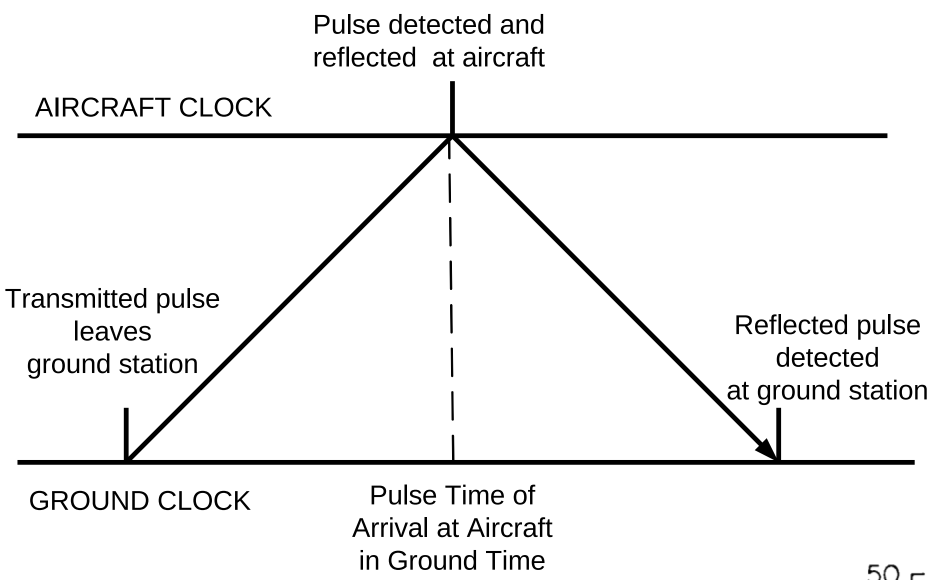
See Session 9 for the latest LLR results.

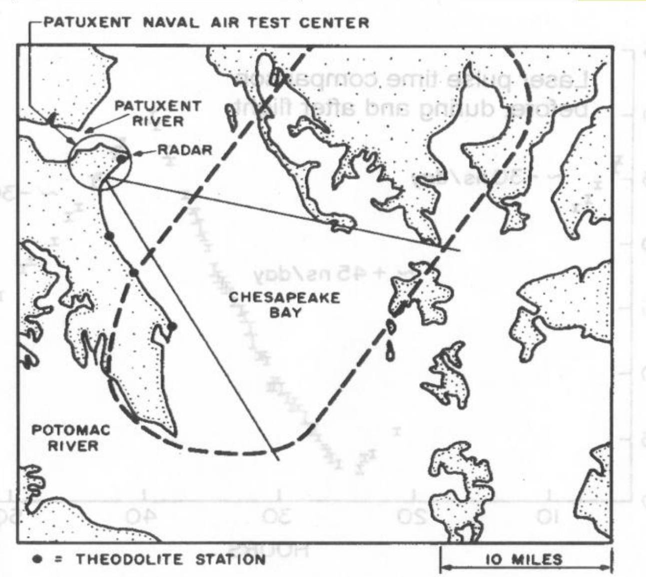
Laser Time Transfer

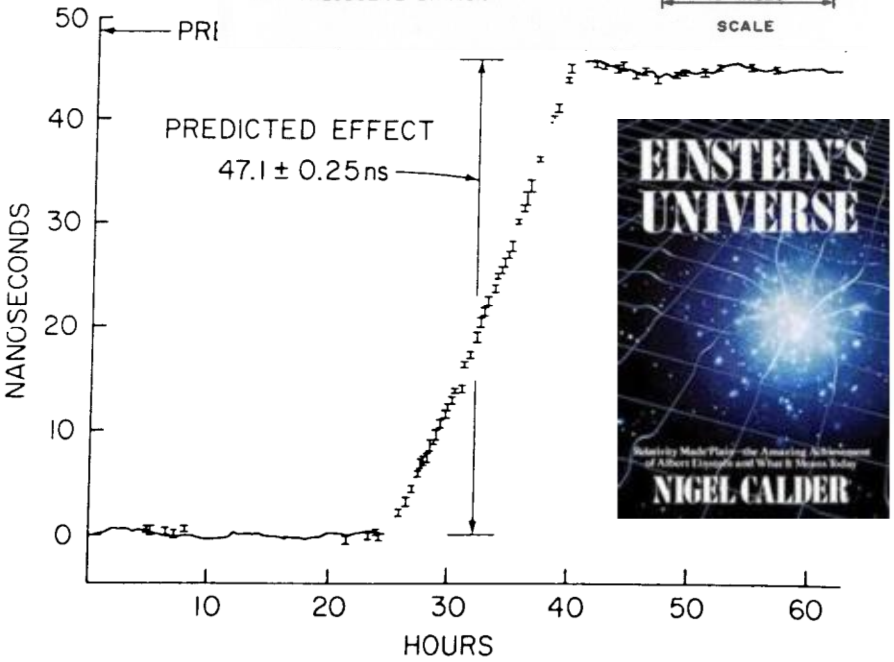


The pulse time of arrival at the satellite coincides with the midpoint of the recorded ground start and stop times which allows one to compute the offset ΔT between the two clocks. If a second ground station performs the same experiment to the satellite, the time offset between the two ground clocks can be determined . Global laser time transfer experiments include L2T2 (France), Compass (China), ELT/ACES (ESA), SOTA (Japan). See Session 5.

Univ. of Maryland Airborne Atomic Clock Experiment (C. O. Alley et al, 1975)





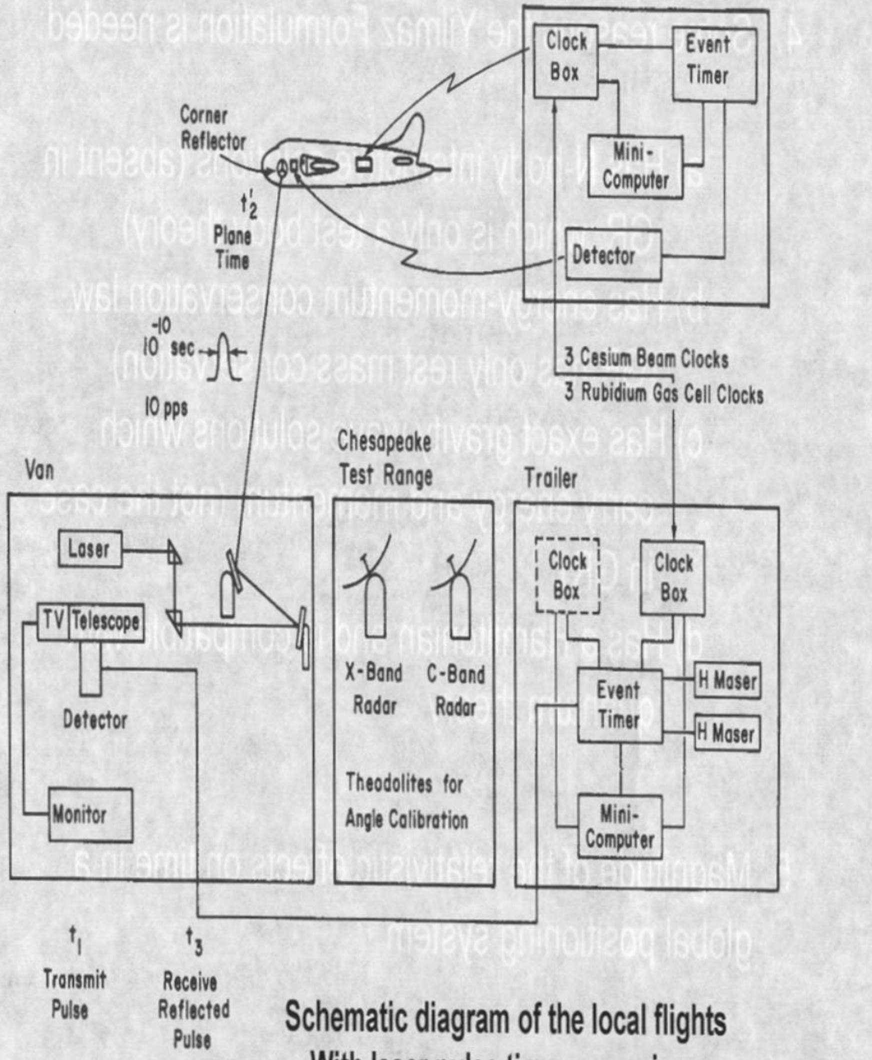


Gravitational redshift **52.8 ns**

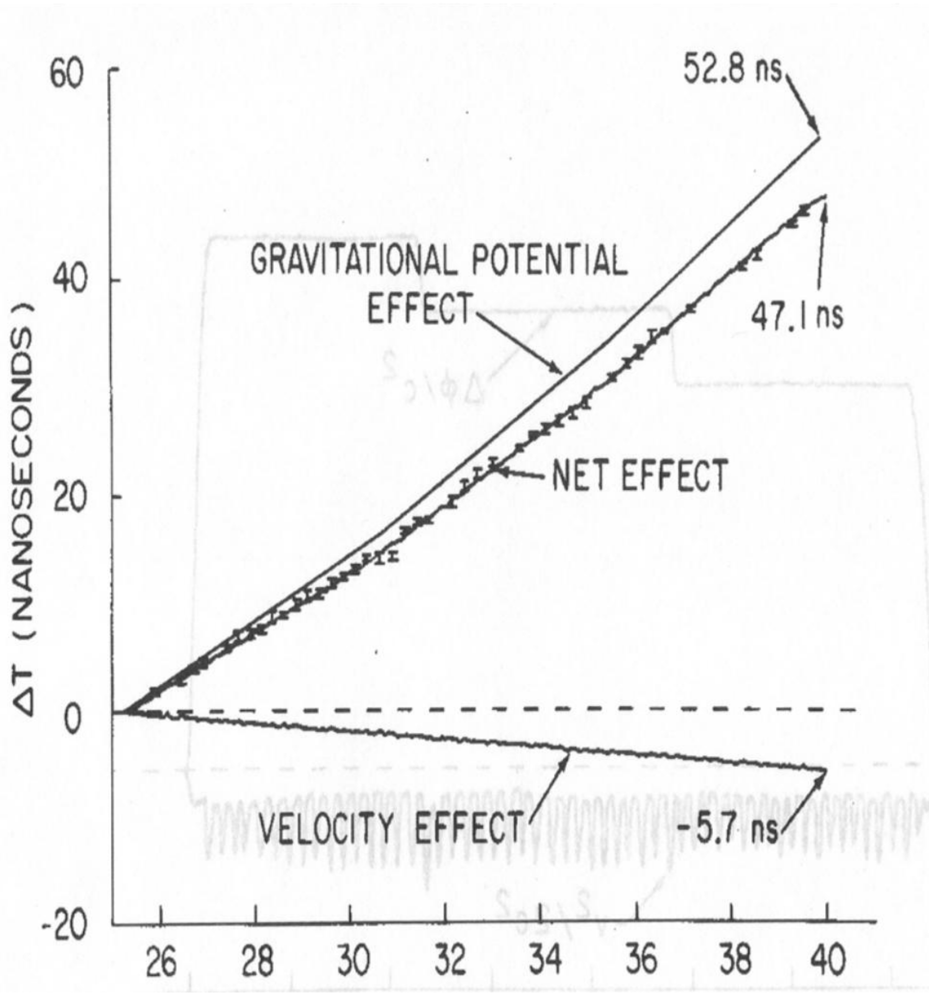
Time dilation **-5.7 ns**

Net effect **47.1 ns**

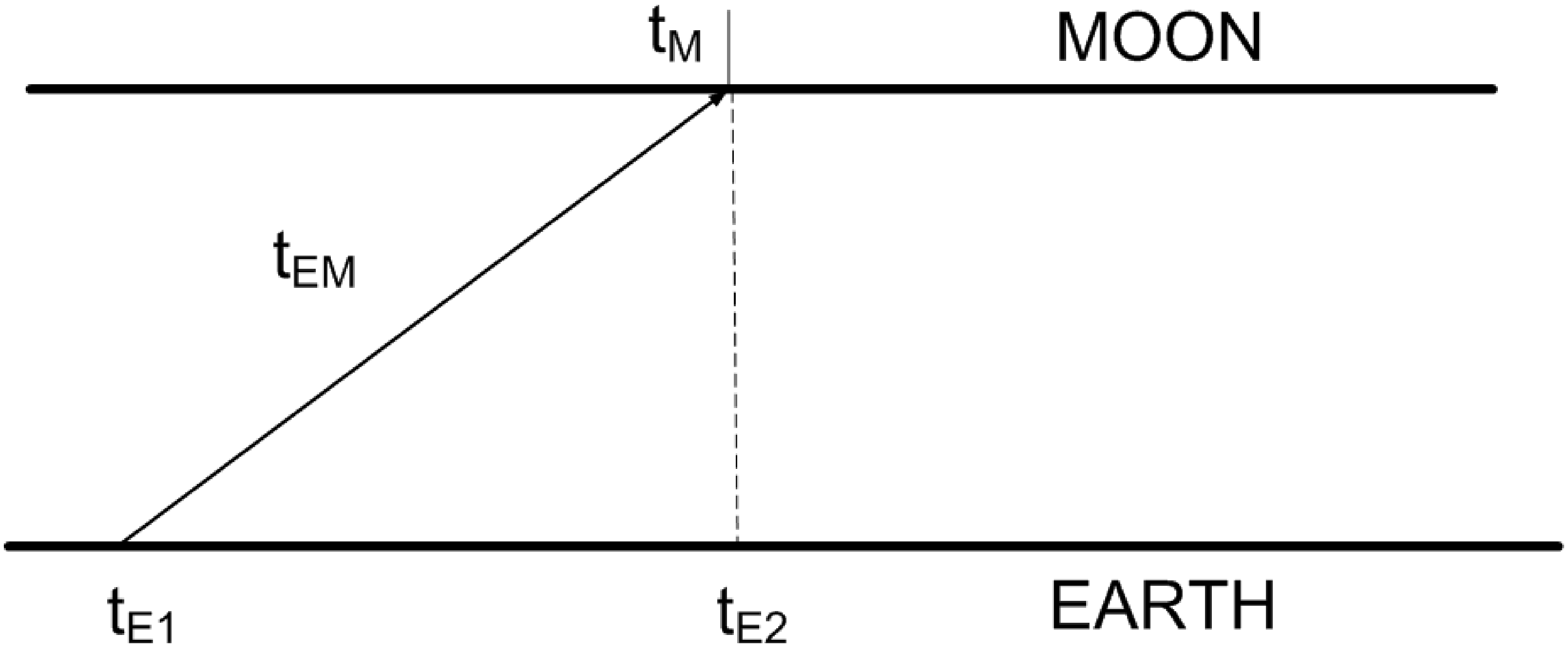
World’s Most Expensive Altimeter



Schematic diagram of the local flights
With laser pulse time comparison



One Way Transponder (e.g. LRO)



Actual Range $R = c(t_{E2} - t_{E1})$

Measured Range $R_m = c(t_M - t_{E1})$

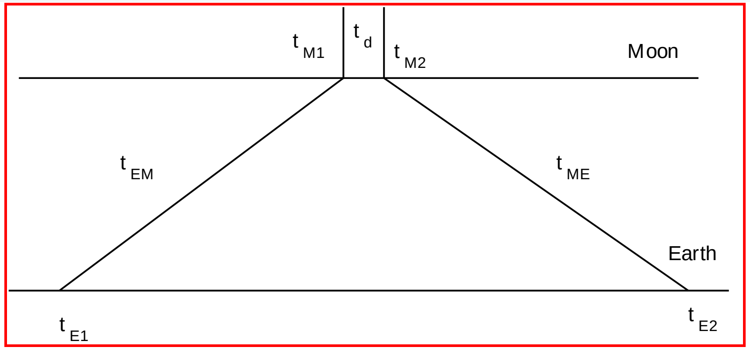
Range Error $\Delta R = R_m - R = c(t_M - t_{E2}) = c\Delta t$

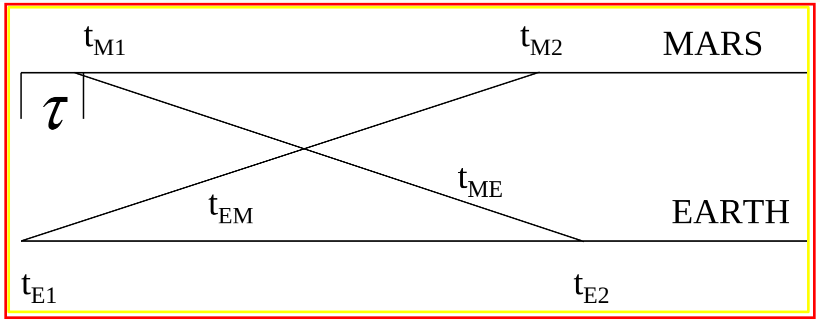
One-way ranging requires good synchronization between the Earth and spaceborne clocks
(Δt=33 psec for 1 cm ranging)

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*



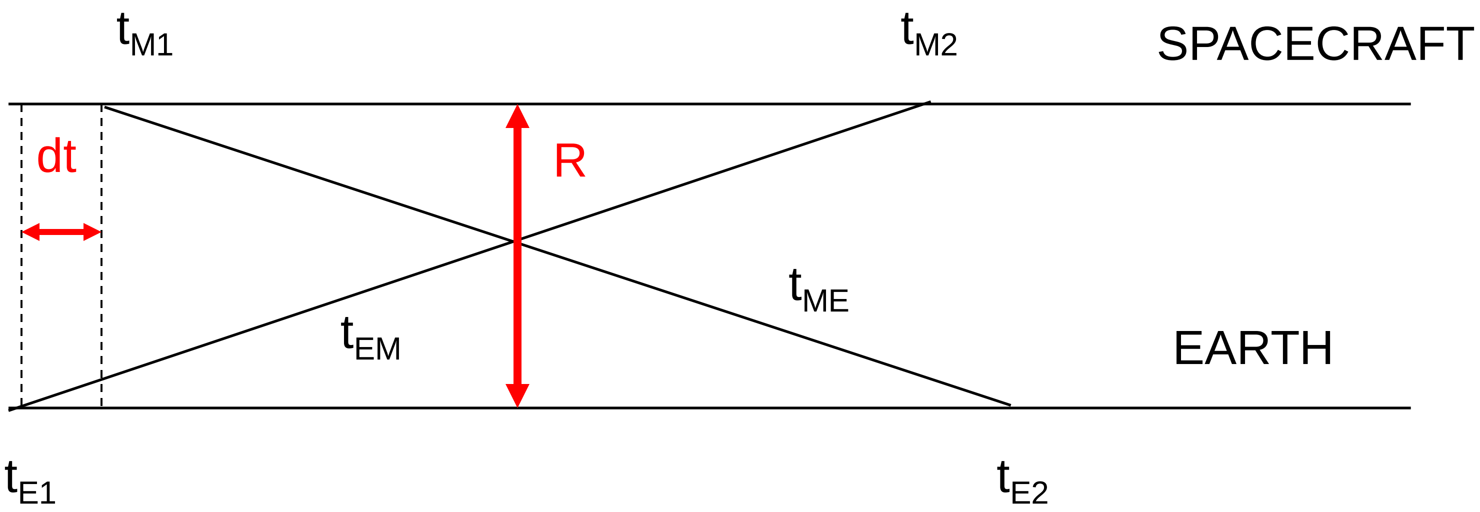


- ***Echo Transponders (R <<1 AU)***
  - Spacecraft transponder detects pulses from Earth and fires a reply pulse back to the Earth station.
  - To determine range, the delay t_d must be known a priori (or measured onboard and communicated back to Earth) and subtracted from the measured round-trip time-of-flight 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

*J. Degnan, J. Geodynamics, 34, pp. 551-594 (2002).

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

*J. Degnan, J. Geodynamics, 34, pp. 551-594 (2002).

Some Transponder Applications

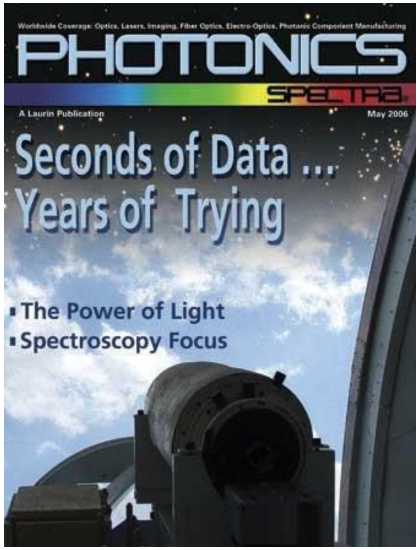
- **Solar System Science**
  - Solar Physics: gravity field, internal mass distribution and rotation
  - Few mm accuracy lunar ephemerides and librations
    - Improves ranging accuracy and temporal sampling over current lunar laser ranging (LLR) operations to Apollo retroreflectors on the Moon with small, low energy, ground stations
  - Decimeter to mm 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 (1×10^{-12} from LLR)
    - Gravitational and velocity effects on spacecraft clocks
    - Shapiro Time Delay
- **Lunar and Planetary Mission Operations**
  - Decimeter to mm 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 ($\sim\lambda/D$)
    - 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, as in SLR.
- **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 already operated in Earth, Lunar, Mars, and Mercury orbits.

Two-Way 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

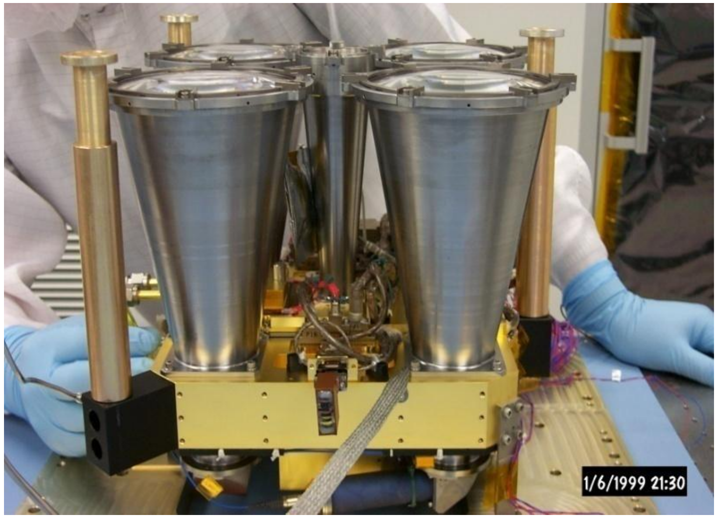
A Laurin Publication

May 2006

Seconds of Data ... Years of Trying

- The Power of Light
- Spectroscopy Focus

24.3 Million Km



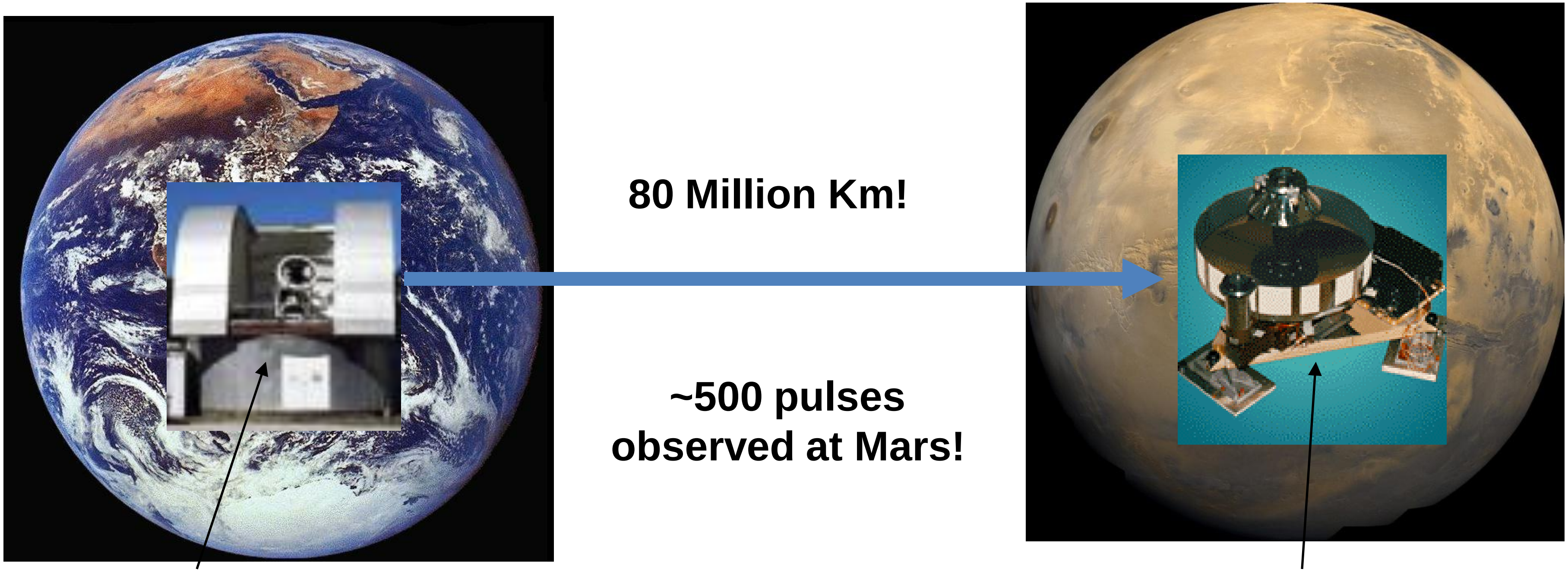
Messenger Laser Altimeter (MLA) enroute to Mercury

<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.

One-Way Earth-to-Mars Laser Transponder Experiment (Sept. 2005)



80 Million Km!

~500 pulses
observed at Mars!

GSFC 1.2 Meter Telescope

MOLA at Mars

Ground Station

Xiaoli Sun Jan McGarry Tom
Zagwodzki John Degnan

Science/Analysis/Spacecraft

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.

*J. Degnan, Int. J. Modern Physics D, 16, pp. 1-14 (2007).

SigmaSpace
EXCELLENCE IN AEROSPACE TECHNOLOGY

The Road Forward

- **Messenger and MOLA were experiments of opportunity rather than design.**
  - Since the spacecraft had no ability to lock onto the opposite terminal or even the Earth image, the spaceborne lasers and receiver FOV's were scanned across the Earth terminal providing only a few seconds of data.
  - Detection thresholds were relatively high due to the choice of wavelength (1064 nm) and the use of analog detectors
  - Precision was limited to roughly a decimeter or two by 2nd generation SLR technology, i.e. 6 nsec laser pulsewidths and comparable receiver bandwidths.
- **The physical size, weight, and accuracy of future interplanetary transponder and laser communications experiments will benefit from current SLR photon counting technology, such as:**
  - Multi-kHz, low energy, ultrashort pulse lasers (10 to 50 psec)
  - Single photon sensitivity, picosecond resolution, photon-counting receivers
  - Autonomous tracking with transmitter point ahead and receiver pointing correction via photon-counting multi-anode detectors.
- **The SLR satellite constellation can accurately mimic interplanetary links (including the Earth's atmosphere). for inexpensive, pre-mission testing of laser transponder and communications concepts.**

Simulating Interplanetary Ranges Using the SLR Constellation*

*J. Degnan, Int. J. Modern Physics D, 16, pp. 1-14 (2007).

Link Equations (A to B)

Transponder/Lasercom System:

$$n_T^{AB} = \frac{4\eta_q^B \eta_t^A \eta_r^B T_A^{\sec\theta_A} T_B^{\sec\theta_B}}{h\nu_A \left(\theta_t^A\right)^2 (4\pi)} \frac{E_t^A A_r^B}{R_T^2}$$

One/Two-Station Ranging to a Satellite:

$$n_R^{AB} = \frac{4\eta_q^B \eta_t^A \sigma_s \eta_r^B T_A^{2\sec\theta_A}}{h\nu_A \left(\theta_t^A\right)^2 (4\pi)^2} \frac{E_t^A A_r^B}{R_R^4}$$

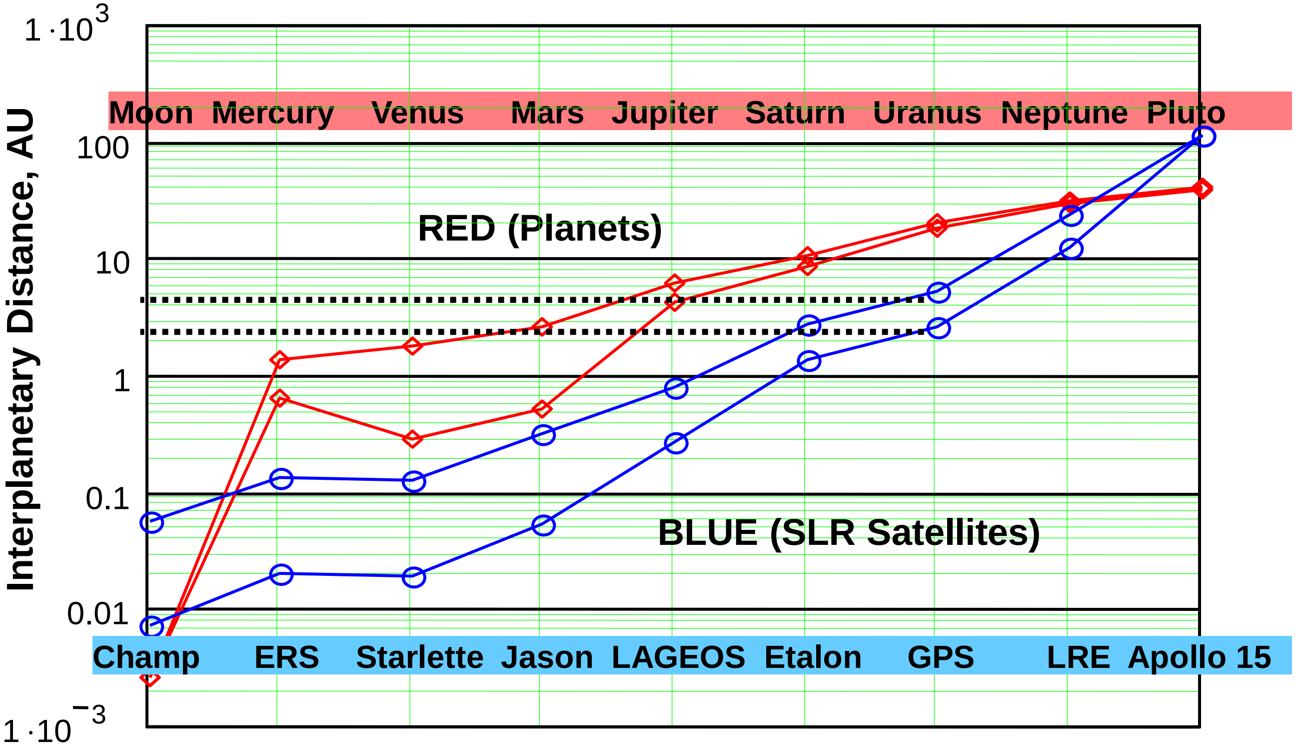
Setting $n_T^{AB} = n_R^{AB}$ gives us an equivalent transponder range for the two-station SLR experiment

$$R_T\left(h,\theta_A,\sigma_s\right) = R_R^2\left(h,\theta_A\right)\sqrt{\frac{4\pi}{\sigma_s}\left(\frac{T_B^{\sec\theta_B}}{T_A^{\sec\theta_A}}\right)}$$

$$\cong R_R^2\left(h,\theta_A\right)\sqrt{\frac{4\pi}{\sigma_s}\frac{1}{T_A^{\sec\theta_A}}}$$

Simulations can be carried out from a single SLR station (e.g. Wettzell) or two adjacent stations (e.g. GSFC 1.2 m and NGSLR) located within the far field pattern of the retroreflector array.

Planet/Satellite Equivalence*



Red curves bound the Earth-planetary distance
Blue curves bound the equivalent transponder range
at satellite elevations of 90 and 20 degrees respectively.

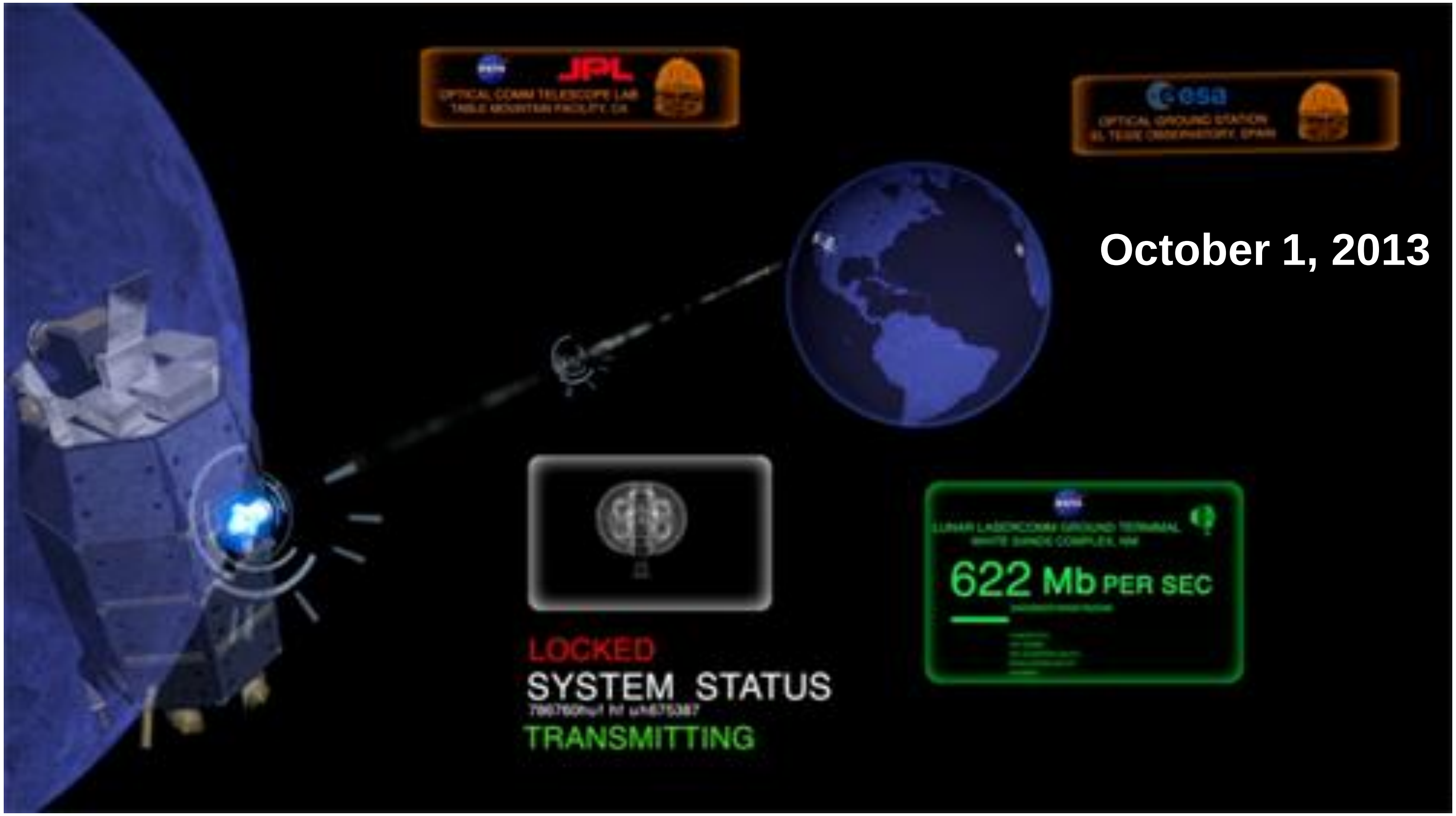
*J. Degnan, Int. J. Modern Physics D, 16, pp. 1-14 (2007).

Summary of Equivalent Links

- Moon (~0.0026 AU) and Trans-lunar
  - Champ, ERS, Starlette, Jason
- Mercury, Venus, Mars (0.28 to 2.52 AU)
  - LAGEOS (near planetary PCA)
  - Etalon, GPS-35, 36 (Full planetary synodic cycle)
- Jupiter, Saturn, Uranus (4.2 to 18.2 AU)
  - GPS-35, 36 (Jupiter PCA); LRE @25,000 km
- Neptune, Pluto, Kuiper Belt (30 to 50 AU)
  - Future retro-equipped GEO satellites?
- Beyond our Solar System
  - Apollo 15 (~100 AU)

Lunar Laser Communications Demonstration (LLCD)

Over the past two decades, there have been several high bandwidth lasercom experiments between Earth-orbiting spacecraft or between spacecraft and a ground station carried out or currently planned by various countries. A low bandwidth link between LOLA/LRO and NGSLR successfully transmitted an image of the Mona Lisa over lunar distances, but the LLCD on the lunar LADEE mission recently demonstrated a bandwidth of 622 Mbps!



October 1, 2013

Summary:Science Impact of SLR/LLR

- **Centimeter Accuracy Orbits**
  - Test/calibrate microwave navigation techniques (e.g., GPS, GLONASS, DORIS, PRARE)
  - Supports microwave and laser altimetry missions for global land topography, sea level, polar ice, and tree biomass measurements. (TOPEX/Poseidon, ERS 1&2, GFO, JASON, ICESat)
  - Support gravity missions (e.g. CHAMP, GRACE, Gravity Probe B)
- **Terrestrial Reference Frame**
  - Geocenter motion
  - Scale (GM)
  - 3-D station positions and velocities
- **Earth Gravity Field**
  - Static medium to long wavelength components
  - Time variation in long wavelength components due to mass redistributions within the solid Earth, oceans, cryosphere, and atmosphere
  - Free Air/Bougher gravity
  - Atmospheric Drag & Radiation Pressure Models
- **Geodynamics**
  - Tectonic plate motion
  - Regional crustal deformation
- **Earth Orientation Parameters (EOP)**
  - Polar motion
  - Length of Day (LOD)
  - High frequency UT1
- **Global Time Transfer**
- **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
  - LLR validates Strong Equivalence Principle (SEP)
  - Constrain β parameter in the Robertson-Walker Metric
  - Constrains time rate of change in G (G-dot)
  - Measure Lense-Thirring Frame Dragging Effect (LAGEOS 1 and 2)
- **Solar System Reference Frame (LLR)**
  - Dynamic equinox
  - Obliquity of the Ecliptic
  - Precession constant
- **Interplanetary Laser Transponders and Communications**
  - Two-way interplanetary ranging and time transfer for improved navigation/control of spacecraft
  - Solar System Science and improved General Relativity Experiments
  - Stations and SLR constellation support interplanetary laser communications efforts