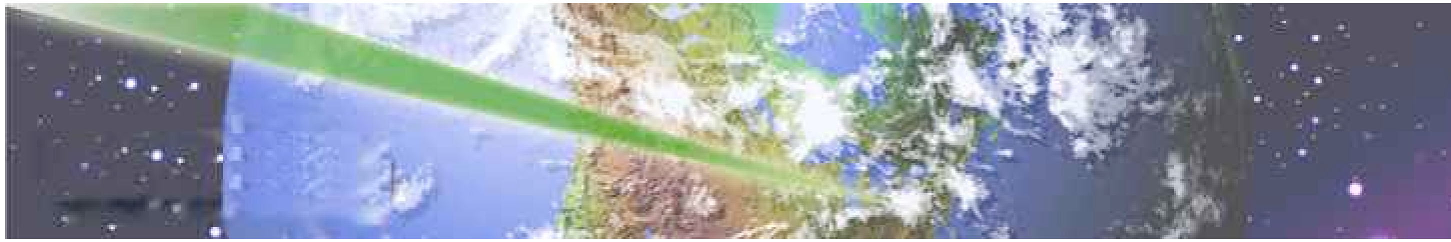


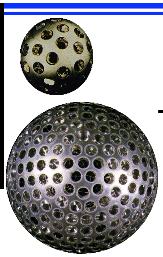
Satellite Laser Ranging Concept Review

Science Objectives and Vision for the Future
Dr. David Smith

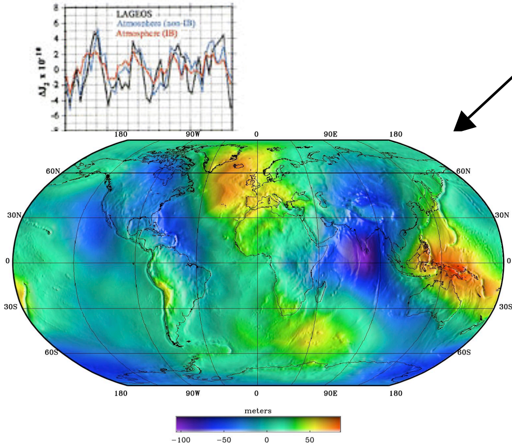
Goddard Space Flight Center
Greenbelt, Maryland
July 26, 2004

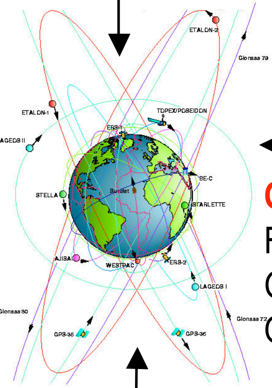
SLR Investigation Life-cycle

Satellite Form
Modeling & Frame
S/C Attitude



Atmospheric Modeling
Tropospheric Propagation Delay

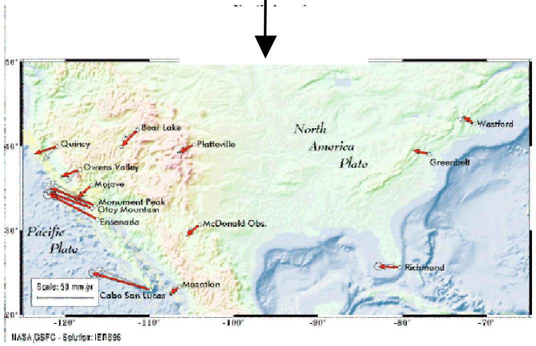




Orbit Determination
Force Modeling
Global Data Evaluation
Orbit DQ

Science Products
Geophysical Models
Analysis Methods
Science Interpretation

Tracking Data Analysis
Data QA
Tracking calibration
Instrument engineering



Reference Frame Modeling
Geocenter motion
Polar Motion and Earth Orientation

Geodetic Networks: SLR Unique Capabilities

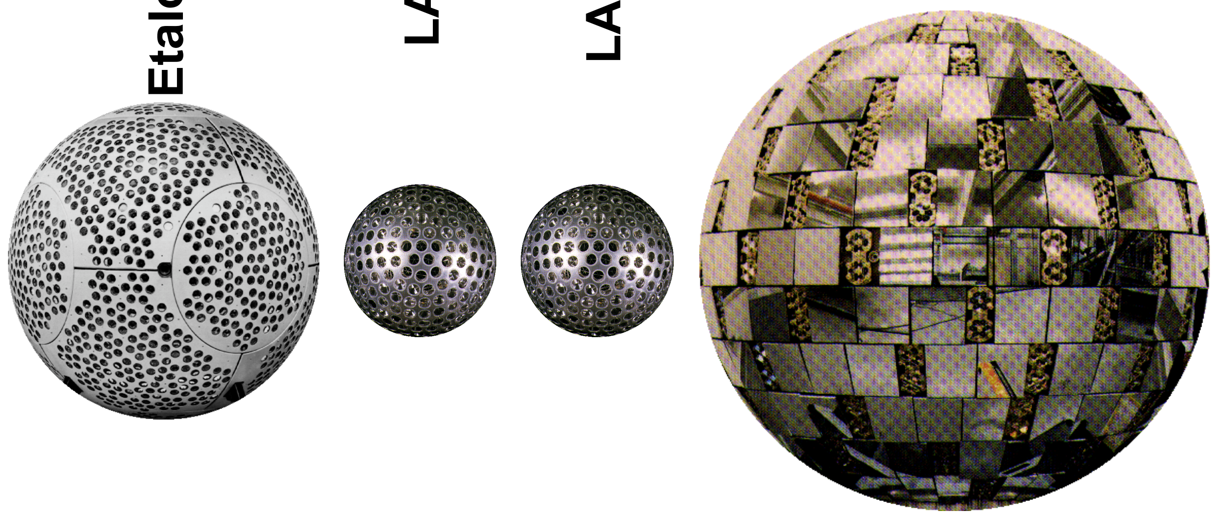
The SLR Technique

- Precise (sub cm) and unambiguous range measurements to LEO and high altitude satellites (e.g. LAGEOS, GPS)
- Small dependence on transmission media
- Passive, low cost, and fail safe space segment
- Near real-time global data availability
- Strong contributions to stable Earth reference frame

Applications

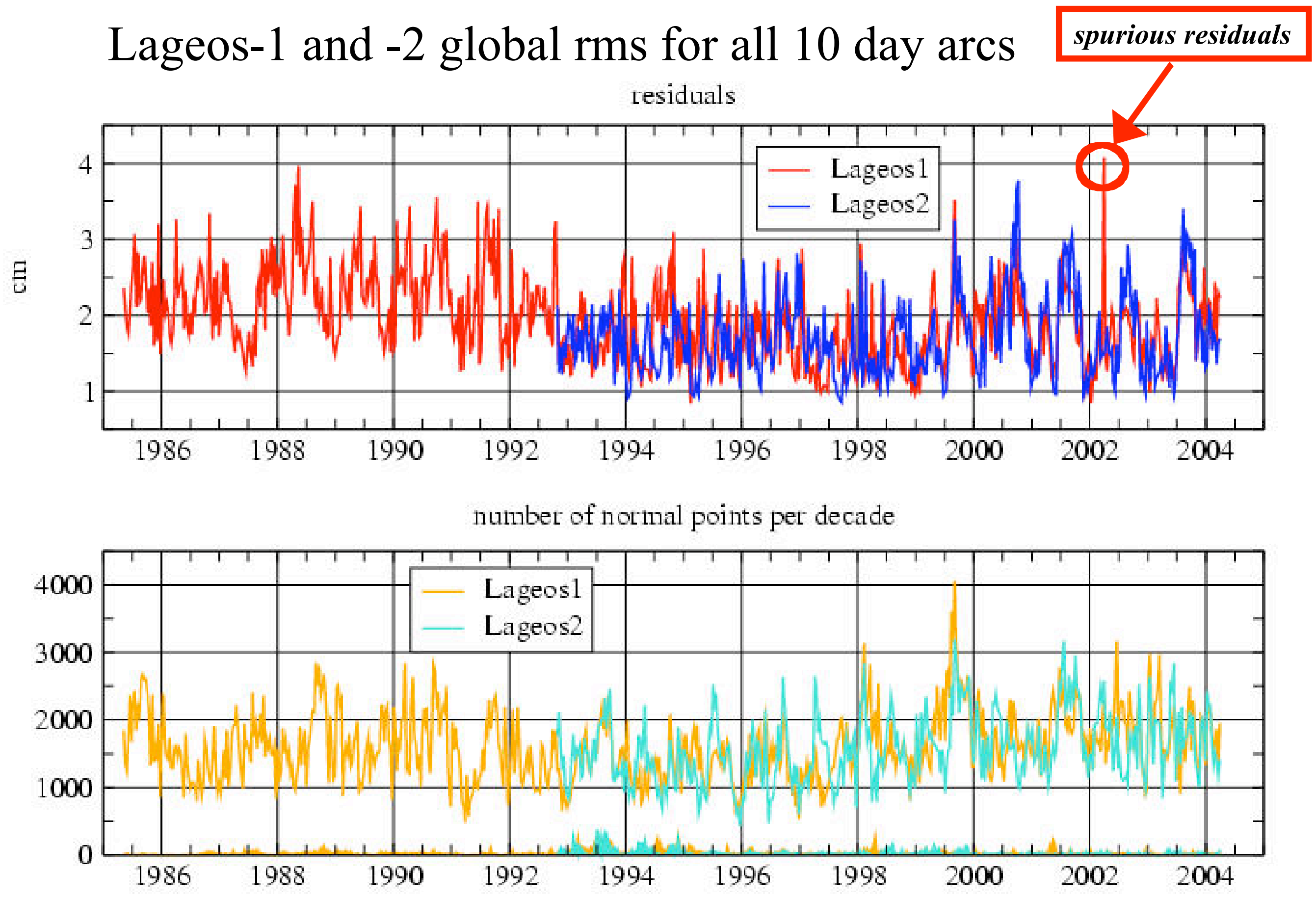
- Highly accurate satellite ephemerides: e.g. precision orbit positioning for altimeter missions
- Calibration and validation of satellite altimetry, radar pointing, astrodynamic models
- Special Missions - Tether Dynamics, etc.
- Fail-Safe Backup for Precise Orbit Determination (POD)

Sample of Laser Satellite Constellation

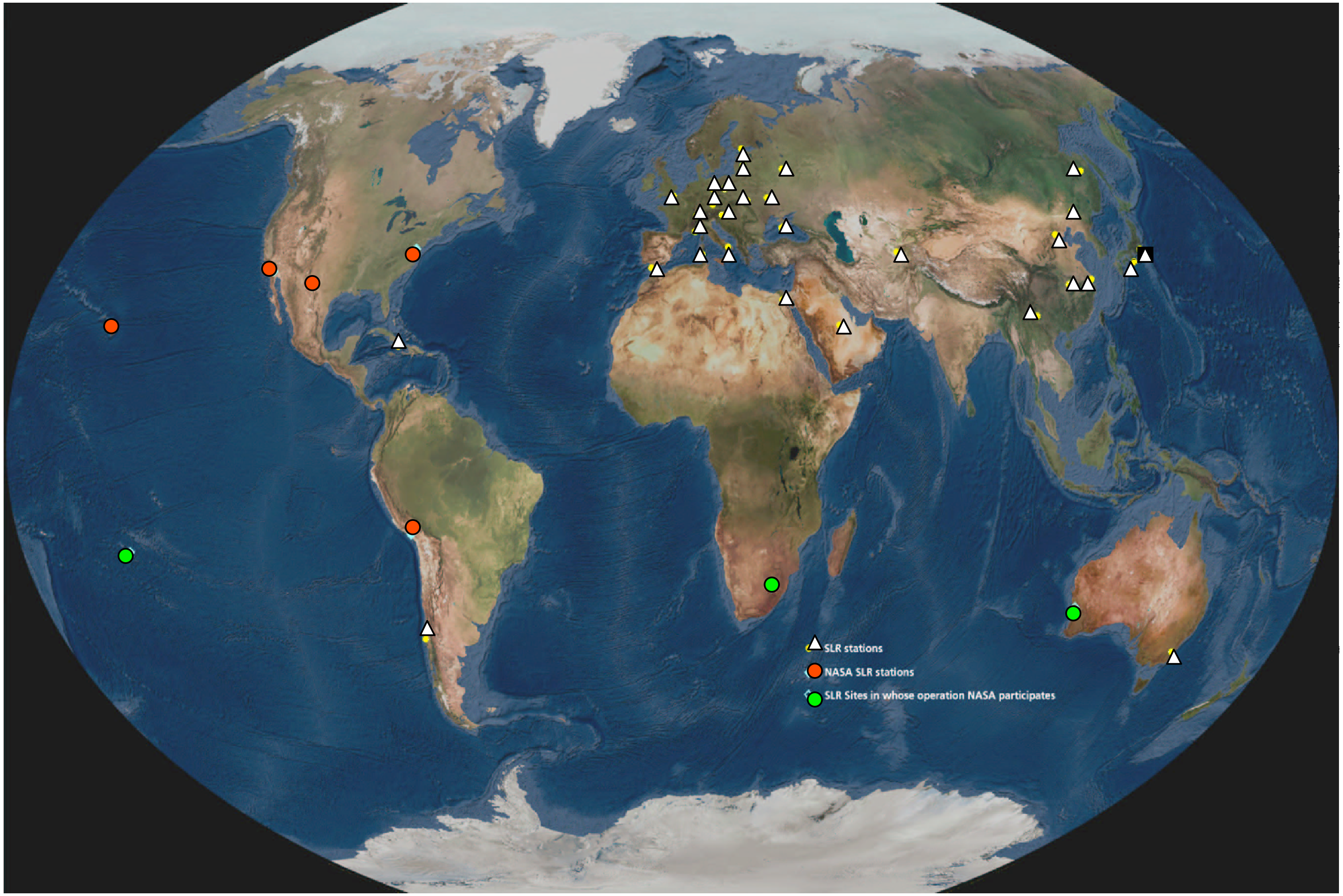


	Etalon-I & -II	LAGEOS-I	LAGEOS-II	Ajisai	Starlette	Stella	GFZ-1
Inclination	64.8°	109.8°	52.6°	50°	50°	98.6°	51.6°
Perigee height (km)	19,120	5,860	5,620	1,490	810	800	396
diameter (cm)	129.4	60	60	215	24	24	20
mass (kg)	1415	407	405.4	685	47.3	47.3	20.6

Lageos-1 and -2 global rms for all 10 day arcs



Geodetic Networks: SLR Site Map



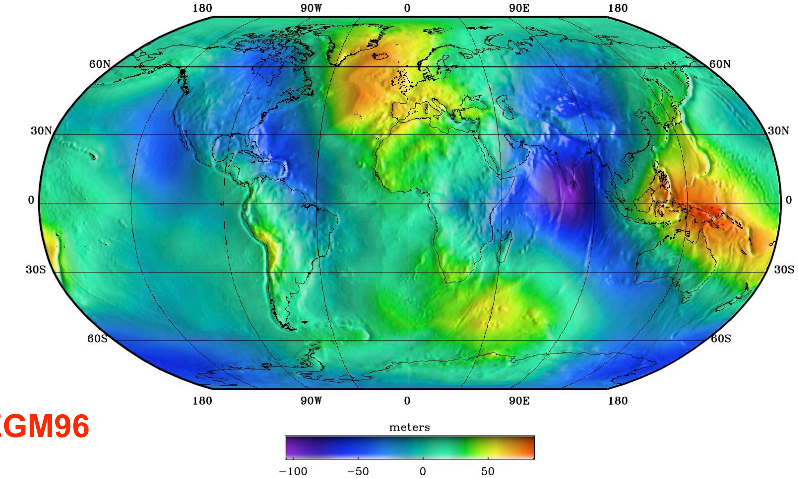
Major SLR Science Contributions

➢Science Products

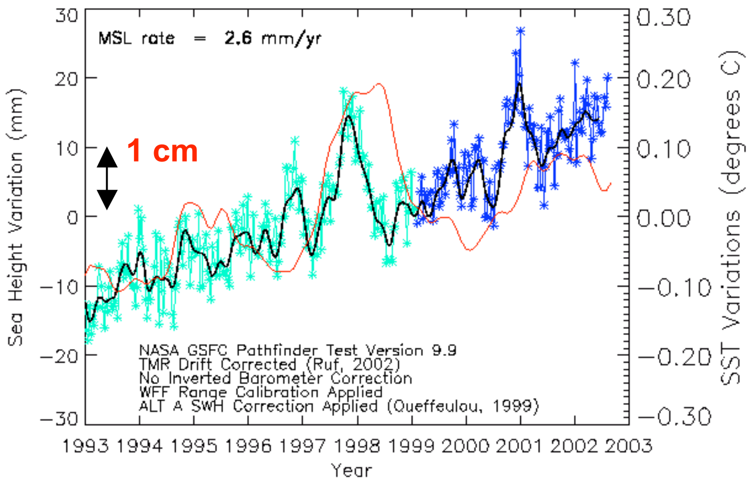
- Global gravity models
- Temporal gravity changes
- Dynamic tides
- Lunar science
- Fundamental physics and tests of relativity
- Earth scale: GM

➢Applications

- GPS independent orbit/model assessment
- Altimeter calibration
- Precise orbit determination
- Fail-safe precision tracking

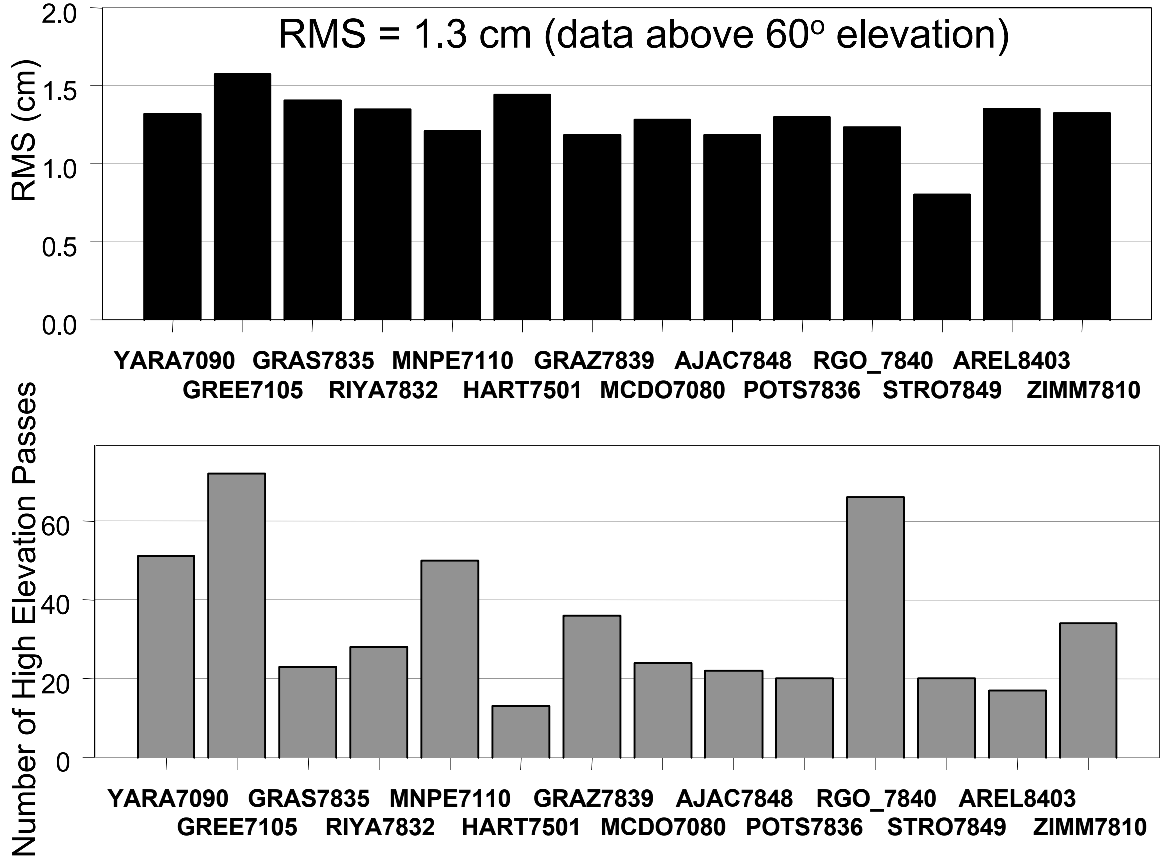


EGM96



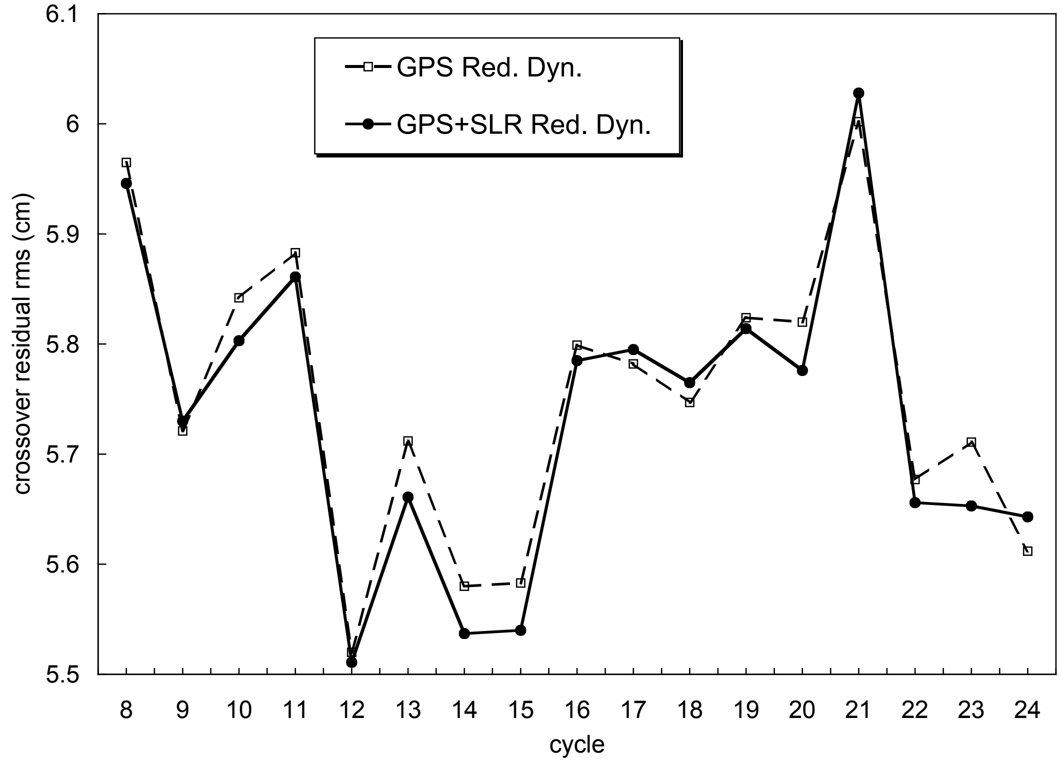
Calibrated altimeters needed to monitor mm level sea level rise

Verification of GPS-derived Jason orbits using SLR



SLR was used to both validate and assess the optimization strategy for GPS determined orbits for Jason. SLR alone provided independent orbit accuracy assessments.

Combination of SLR and GPS produces significant Jason orbit improvements



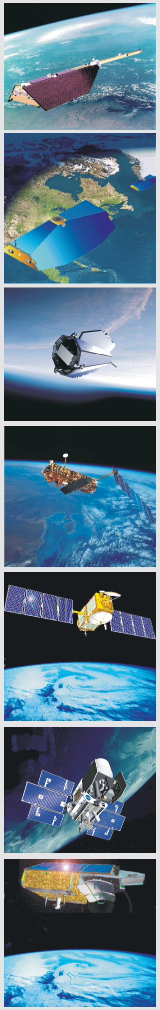
Jason crossover RMS per 10-day repeat cycle for both GPS and GPS+SLR reduced dynamic solutions. The results demonstrate the SLR data can improve radial orbit accuracy when properly combined with GPS data.

Fundamental questions in Geosciences:

Context for SLR Science Support:

- What are the causes of the observed global and regional sea level changes?
- What are their relations to the variations in the heat and mass content of the oceans?
- How do the polar ice sheets vary in size and thickness?
- Are there variations in the continental hydrosphere and what are their influences on the climate changes?
- Which geodynamic convective processes cause deformations and motions of the Earth‘s surface?

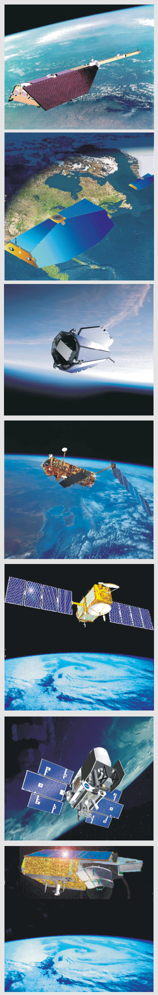
International Program for Geodetic Monitoring: "Decade of Geopotential"



mission	2000 – 2010	
CHAMP	static and time variable long wavelength gravity field, atmosphere sounding, magnetic and electrical field	gravity field
GRACE	static and time variable long and medium wavelength gravity field atmosphere sounding	gravity field
GOCE	high resolution, high precise gravity field	gravity field
ENVISAT	continuation of ERS1/2 missions ocean / ice environmental parameter atmosphere and ocean	sea surface
JASON-1	mean ocean topography ocean circulation and seasonal changes climate development (El-Nino, etc.) sea level changes, ocean tidal models	sea surface
ICESAT	topography of the polar ice masses and changes of it, vertical aerosol distribution, land / water topography	ice regions
CRYOSAT	trends of continental ice masses, sea level variations, reg. trends of sea ice, seas. ice mass variations	ice regions

Years: 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010

Role of SLR in Geodetic Monitoring

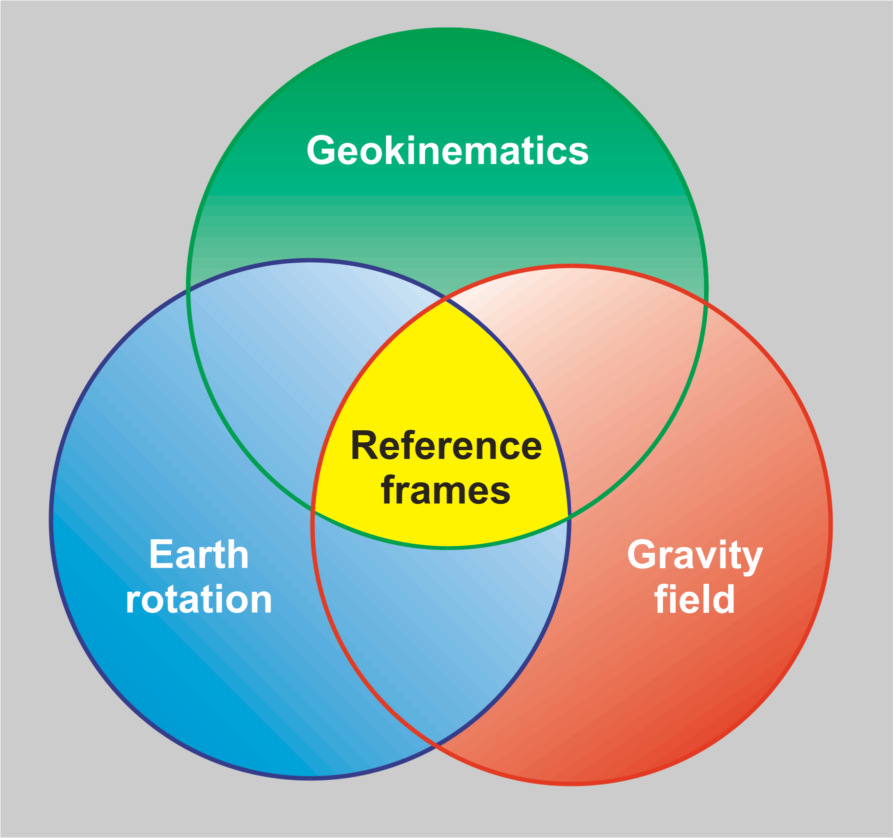
mission		Role of SLR	
	CHAMP	2,3,4	gravity field
	GRACE	3,4	
	GOCE	2,3,4	
	ENVISAT	1,2,3,4,5	sea surface
	JASON-1	1,2,3,4,5	
	ICESAT	1,2,3,4,5	ice regions
	CRYOSAT	1,2,3,4,5	

2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

Role of SLR:

1- Altimeter calibration
2- Precision Orbit Determination
3- Independent model verification
4- Independent orbit verification
5- Back-up tracking system

Constituents of an integrated geodetic-geodynamic monitoring system

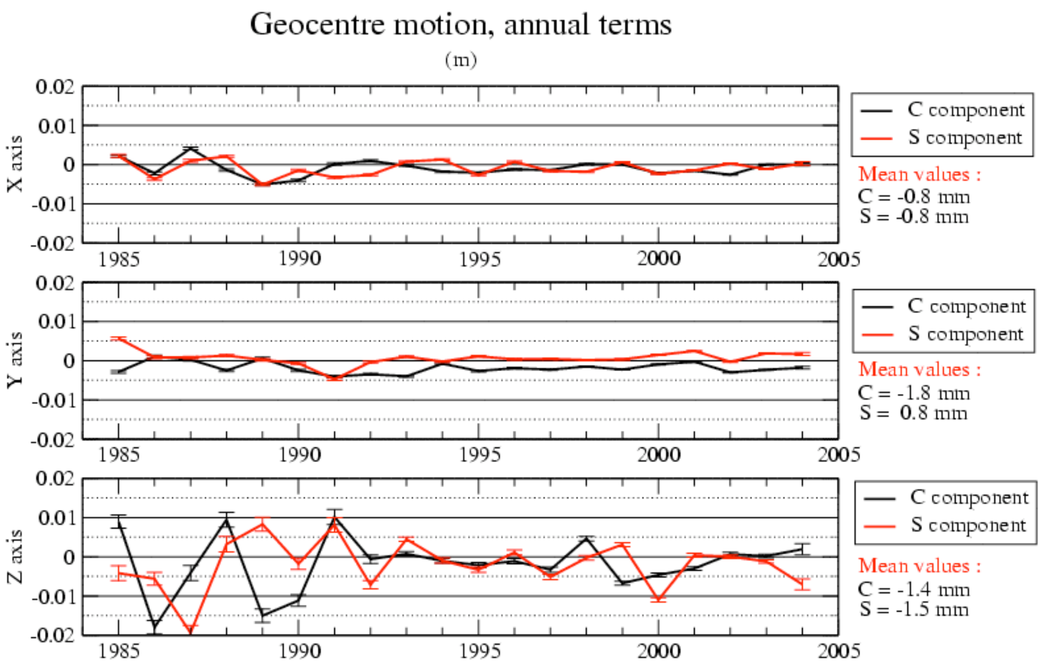


Why do we have three techniques?

- **High precision geodesy is very challenging**
  - Accuracy of 1 part per billion
- **Fundamentally different observations with unique capabilities**
- **Together provide cross validation and increased accuracy**

Technique Signal Source Obs. Type	VLBI Microwave Quasars Time difference	SLR Optical Satellite Two-way range	GPS Microwave Satellites Range change
Celestial Frame UT1	YES	No	No
Scale	Yes	YES	Maybe
Geocenter	No	YES	Yes
Geographic Density	No	No	YES
Real-time	Yes	No	YES
Decadal Stability	YES	YES	YES

GEOCENTER MOTION



<u>Mean annual terms amount to :</u>

1.2 mm in X, with a minimum in February

2.0 mm in Y, with a minimum in December

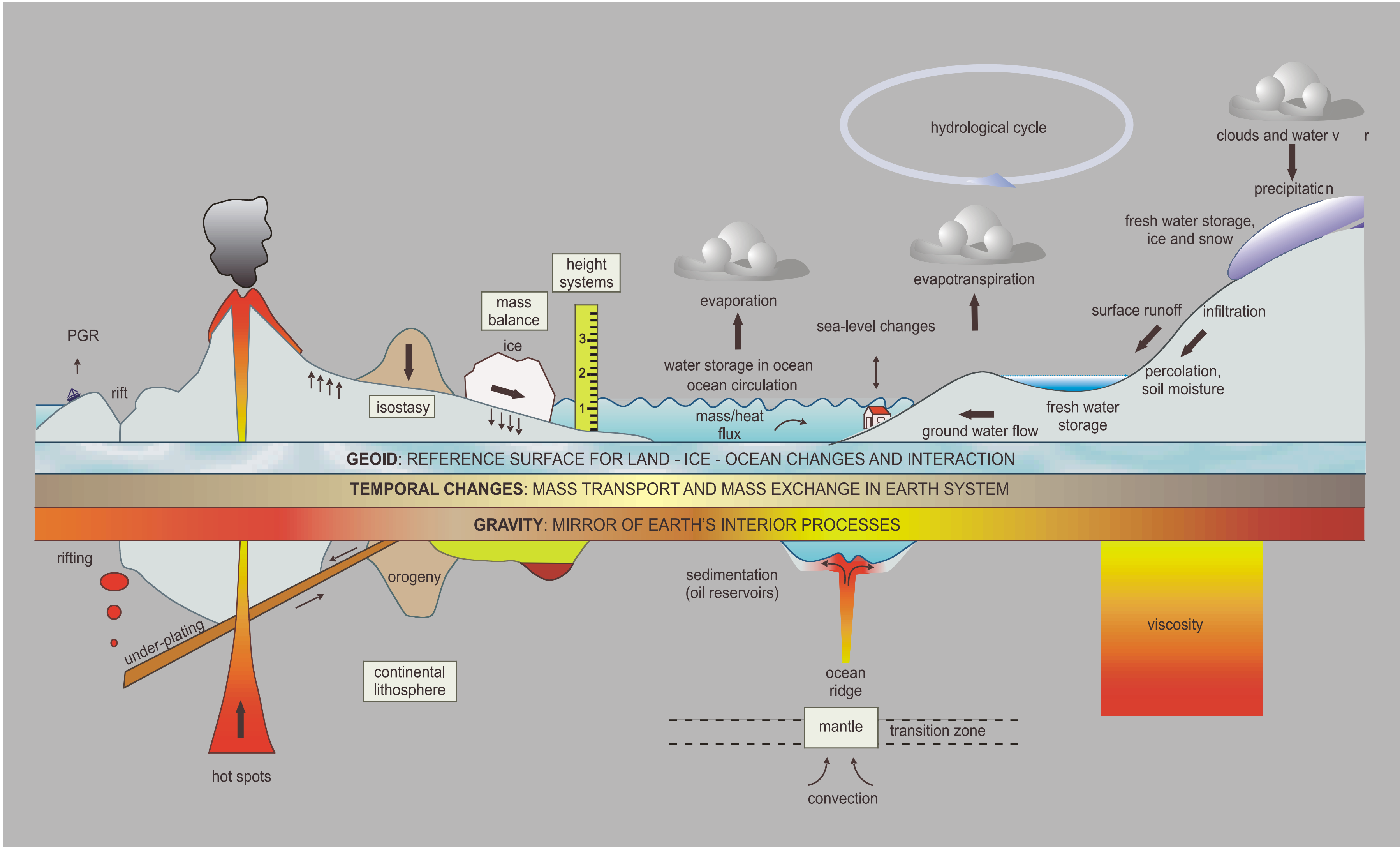
1.8 mm in Z, with a minimum in February

- mm-level Geodesy requires understanding of the reference frame and its distortions to acute levels of precision.
- Shown here is the change in the origin of the crust-fixed frame w.r.t. the center of mass due to non tidal mass transport in the atmospheric and hydrospheric systems.

GEODETIC MONITORING OF EARTH

	Atmosphere	Hydrosphere/ Cryosphere	Crust	Earth Interior
Gravity Field	Temporal monitoring of mass redistribution throughout Earth system as form of remote sensing		Lithosphere strength, PGR, isostatic behavior	Mantle rheology, convection, core-mantle boundary
Tides	Thermal/gravity forces mass displacements	Ocean tides, ocean circulation, Earth/Moon system	Tidal loading and lithosphere strength	Inelasticity of solid Earth
Earth Rotation & Polar Motion	Atmospheric angular momentum, air-ocean coupling	Ocean momentum, bottom friction, ice sheet mass balance	Secular changes due to deglac-iation & long term processes	Core-mantle coupling/ reson-ance, ties to geomagnetism
Crustal Motions	Atmospheric loading	Ocean loading, non-tidal deformation	Strain in seismic zones, tectonics, subsidence, mountain building	Lithosphere-mantle coupling, crustal cooling
Topographic Mapping	Loading, baro-metric ocean response	Ocean circulation, ocean wind interaction	Gravity anom-alies, ice sheet loading	Small scale convection, mantle rheology

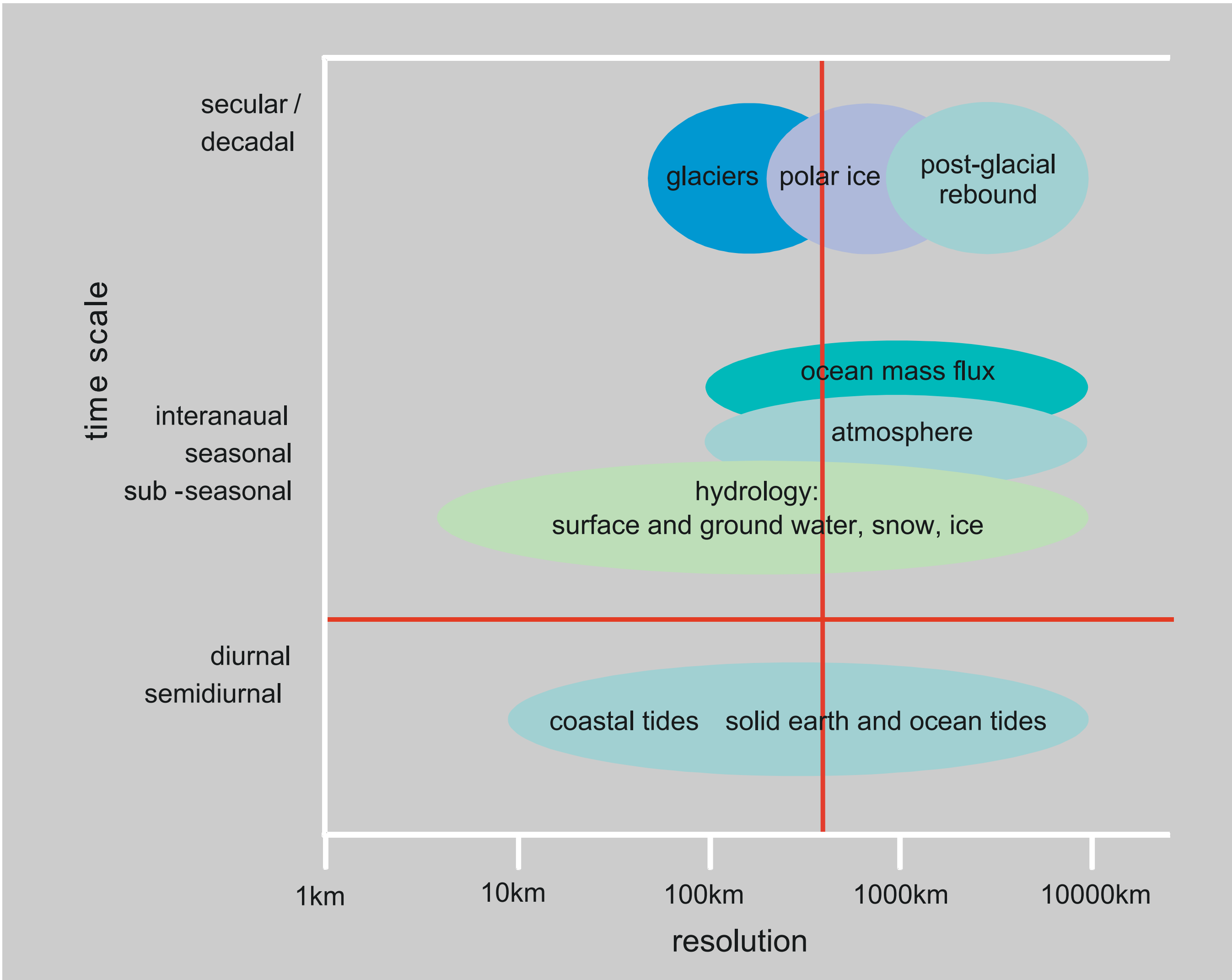
Mass transport phenomena in the upper layers of the Earth



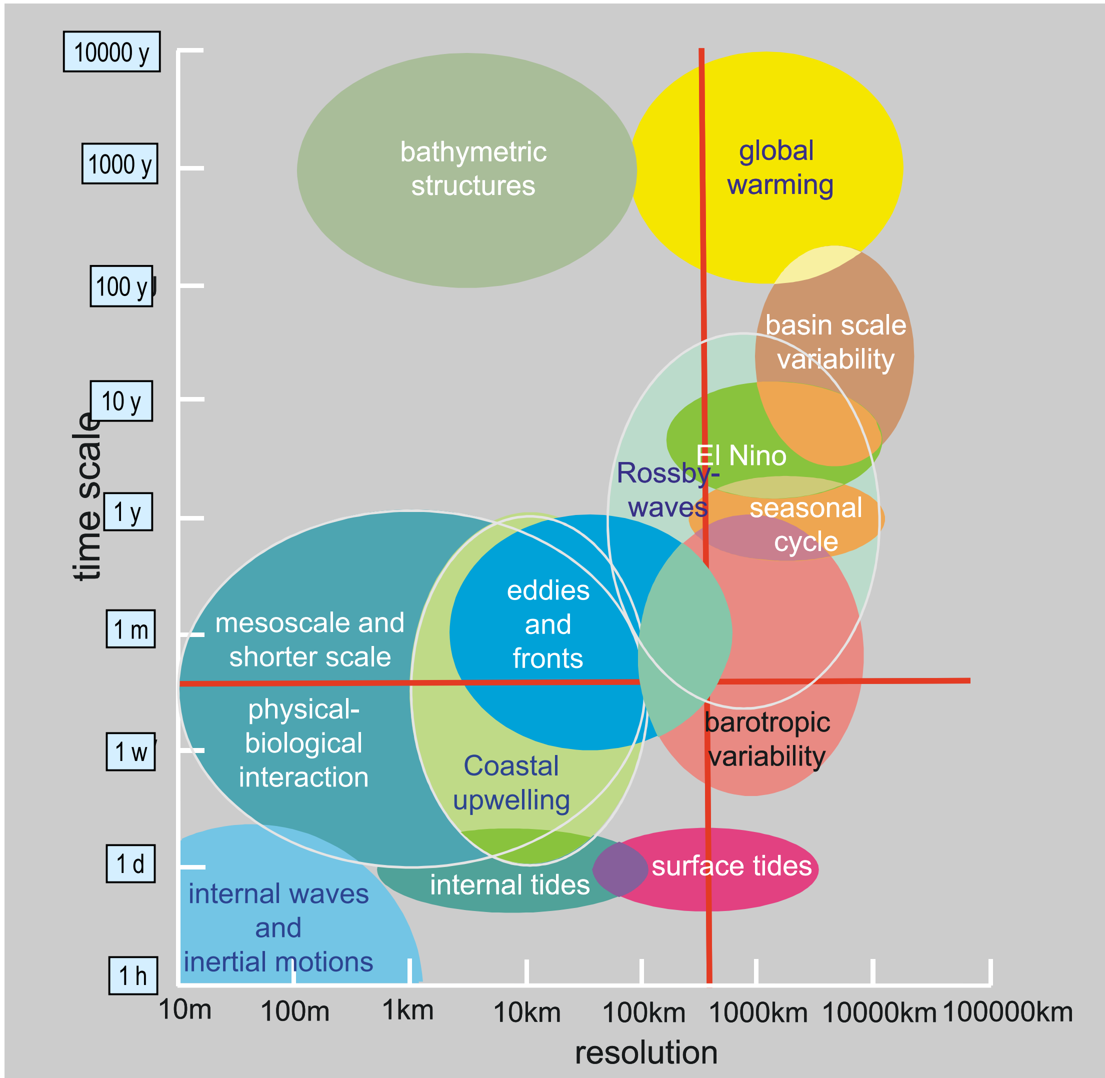
Mass transport phenomena:

- Hydrological cycle of the continents and in the ice regions,
- Ice mass balance and as a consequence the variation of sea level,
- Mass transport in the oceans, ocean currents transport heat and represent therefore an important factor of climatological development,
- The melting of the large ice covers cause isostatic adjustment,
- Mass changes within the Earth, caused by various forces within the Earth

Temporal and spatial resolution of mass transport phenomena

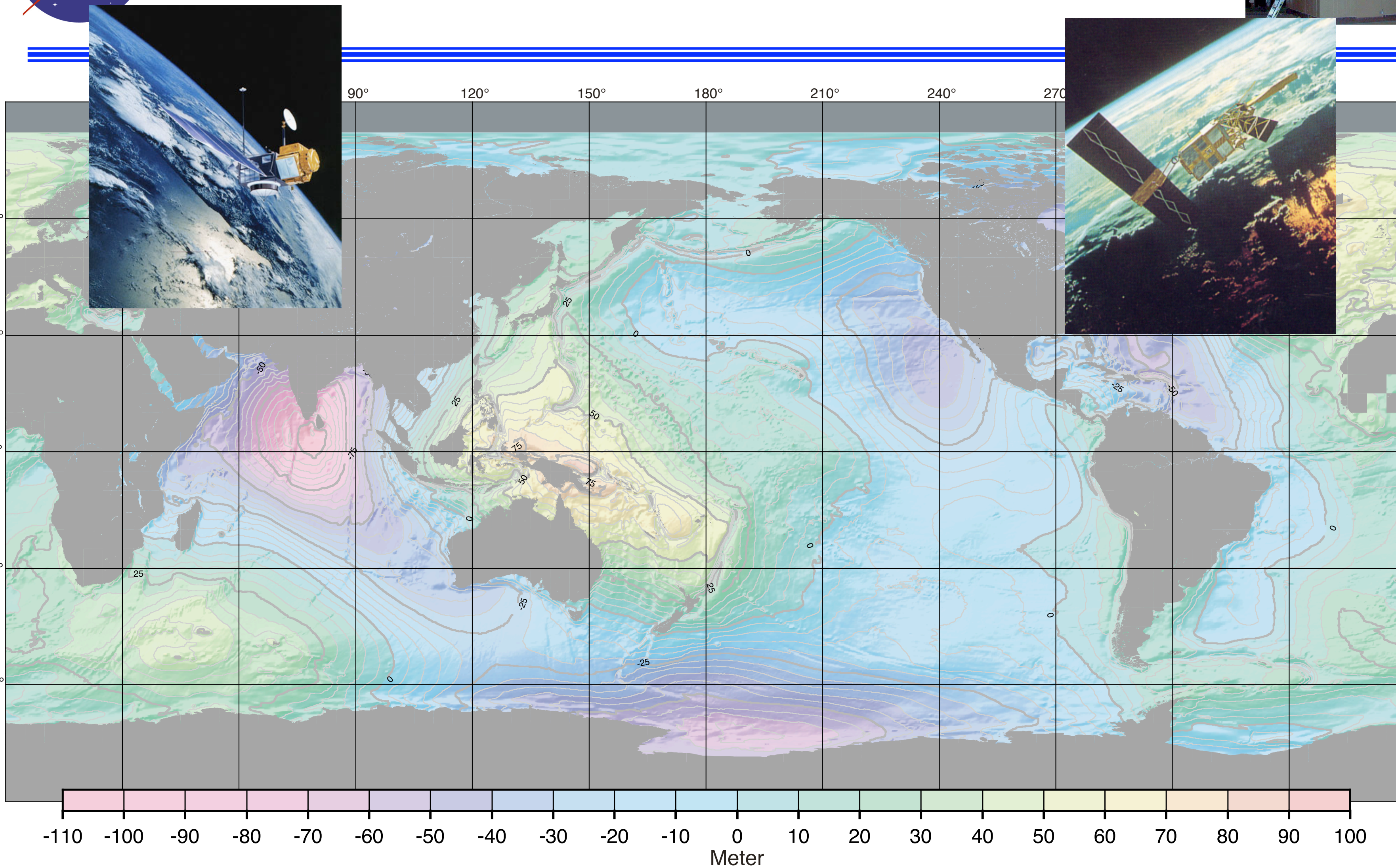


Temporal and spatial resolution of oceanographic features

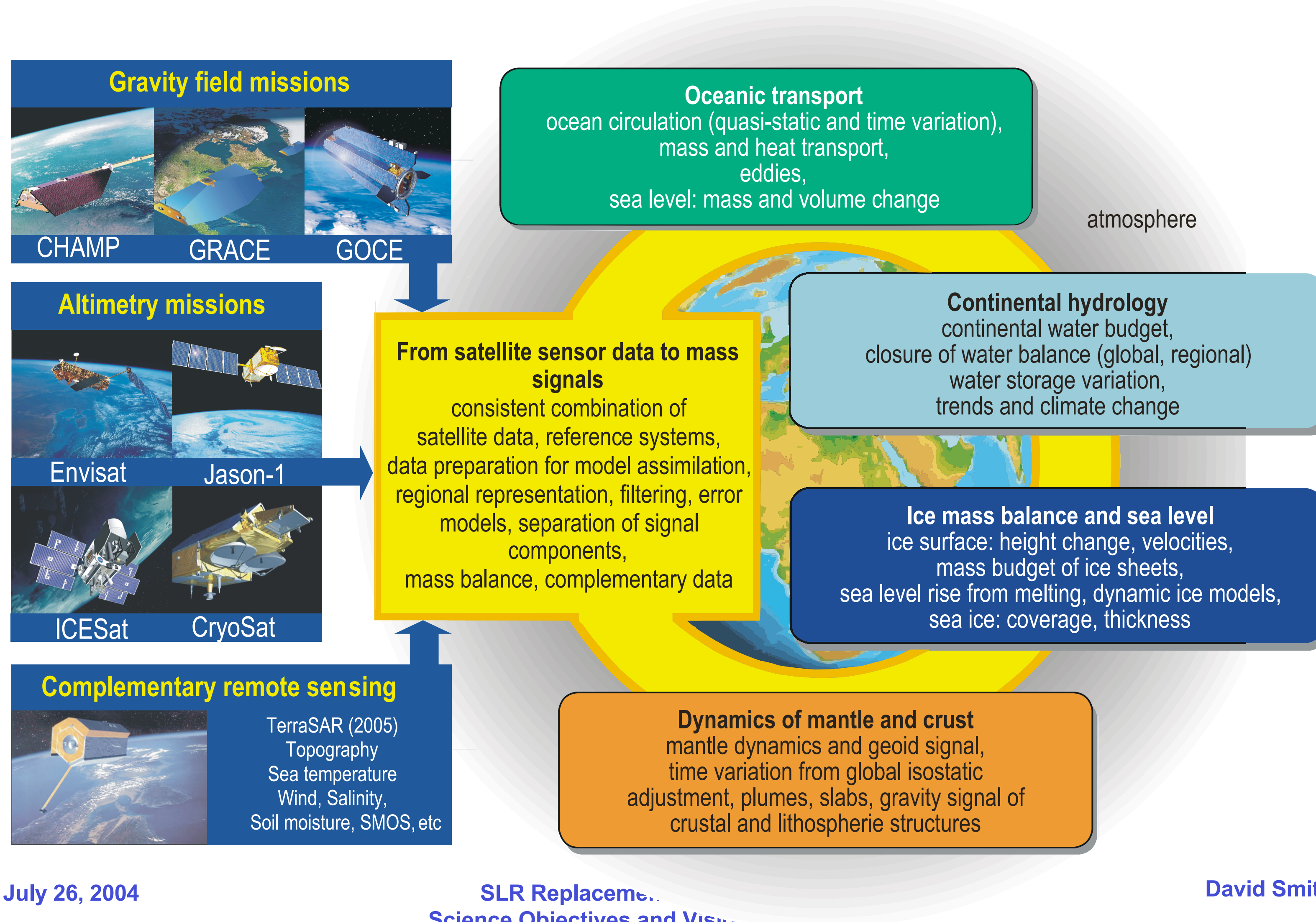


Mean Sea Surface

from an Integrated and Calibrated Suite of Satellite Altimeters

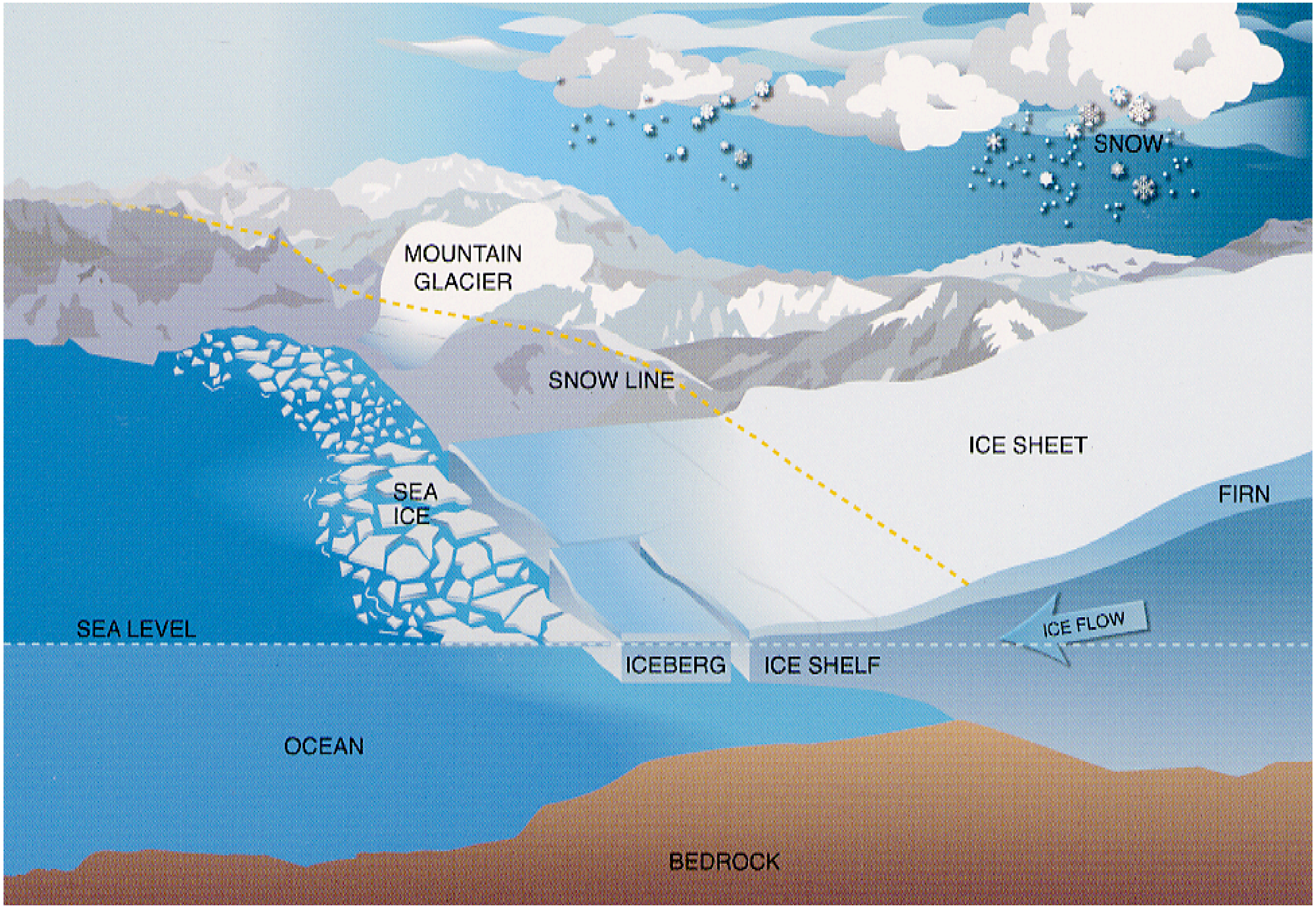


Satellite gravity and altimeter mission products to determine mass transport and mass distribution in a multi-disciplinary environment

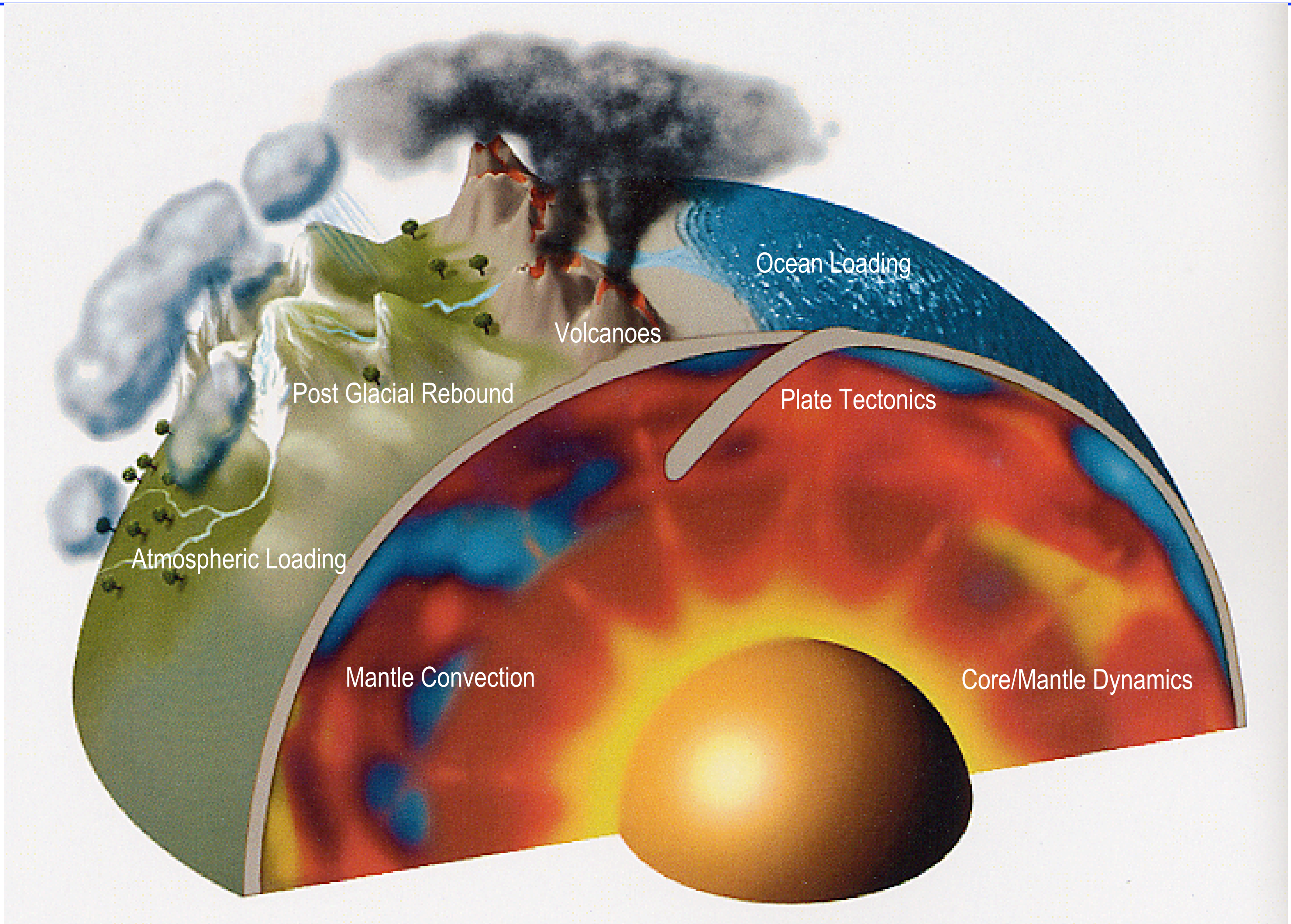


Continental hydrology

Ice mass balance and sea level



Dynamics of crust and mantle



Time Varying Gravity:
A Unique Form of Remote Sensing

29. D. R. Jennison, A. Bogicevic, *Surf. Sci. Lett.* **464**, 108 (2000).
30. A. E. Mattsson, D. R. Jennison, in preparation.
31. L. A. Curtiss, K. Raghavachari, G. W. Trucks, J. A. Pople, *J. Chem. Phys.* **94**, 7221 (1991).
32. The endothermic reaction $2OH^- + Co^0 \rightarrow O^{2-}Co^0 + H_2O$ does not produce Co(II).
33. G. Mills, H. Jonsson, G. K. Schenter, *Surf. Sci.* **324**, 305 (1995).
34. The LDA binding energy (1.08 eV) is likely below the real value (*28*). Estimating the surface self-energy correction (*30*) produces this estimate. In addition, the thermal energy of the source contributes 0.11 eV.
35. J. Strömquist *et al.*, *Surface Science*, **397**, 382 (1998).
36. M. Persson *et al.*, *J. Chem. Phys.* **110**, 2240 (1999).
37. K. C. Hass, W. F. Schneider, A. Curioni, W. Andreoni, *J. Phys. Chem. B* **104**, 5527 (2000).
38. We thank R. R. Stumpf for critical comments and J. Strömquist for useful discussions. Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratory (SNL) are multiprogram laboratories operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830 (PNNL), and by Sandia Corporation, a Lockheed Martin Company, under Contract DE-AC04-94AL85000 (SNL). The experimental work was conducted in the Environmental Molecular Sciences Laboratory, a national scientific user facility sponsored by the Department of Energy's Office of Biological and Environmental Research and located at PNNL. T.R.M. acknowledges the Motorola/SNL computational materials Cooperative Research and Development Agreement. S.A.C. and T.D. were supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, Division of Materials Science at PNNL.

30 April 2002; accepted 14 June 2002

Detection of a Large-Scale Mass Redistribution in the Terrestrial System Since 1998

Christopher M. Cox[1]* and Benjamin F. Chao[2]

Earth's dynamic oblateness (J_2) had been undergoing a decrease, according to space geodetic observations over the past 25 years, until around 1998, when it switched quite suddenly to an increasing trend that has continued to the present. The secular decrease in J_2 resulted primarily from the postglacial rebound in the mantle. The present increase, whose geophysical cause(s) are uncertain, thus signifies a large change in global mass distribution with a J_2 effect that considerably overshadows that of mantle rebound.

Earth's mean tide-free dynamic oblateness $(J_2) \equiv [C - (A + B)/2]/MR^2 = 1.082627 \times 10^{-3}$, where $C > B \geq A$ are Earth's mean principal moments of inertia and M and R are the mean mass and radius, respectively. Satellite laser ranging (SLR) has yielded precise determination of the temporal variation in the low-degree spherical harmonic components of Earth's gravity field, beginning with the initial observations of J_2 change made by observing Lagoes-1 satellite orbital node accelerations (*1*, *2*). More recent studies have extended the knowledge to higher degree zonals and examined the annual signals in the low-degree geopotential (*3–5*). The estimated values of the J_2 rate have ranged from -2.5×10^{-11} year^{-1} to -3×10^{-11} year^{-1}.

The extension of comprehensive solutions for low-degree geopotential zonal, static, annual, and rate terms and the 9.3- and 18.6-year ocean tide amplitudes to include data since 1997 has resulted in increasingly significant changes in the estimated J_2 rate and 18.6-year tide amplitude (*4*). These changes implied that the models for these terms were not accommodating the observed signal. Consequently, we estimated a time series of low-degree (maximum degree of 4) static geopotential solutions using SLR observations of 10 satellites over the period from 1979 to 2002. The inclusion of multiple orbital inclinations improves separation of the higher degree zonal components and allows recovery of the gravity coefficients over shorter time periods. All processing used the same algorithms used to develop the EGM96S satellite–only gravity model and to calibrate that model's covariance (*5*). The 18.6-year and much smaller 9.3-year tide amplitudes were set to the values estimated in the comprehensive solution with data from 1979 through 1997 (*4*). The applied 18.6-year tide amplitude of 1.41 cm has the equivalent J_2 amplitude of 1.67×10^{-10}. The 18.6-year tide–J_2 effect is minimized (that is, the geopotential is less oblate) when the lunar node is 0 degrees, which occurred in mid-October 1987.

Shown in Fig. 1 is the estimated J_2 as a function of time, $J_2(t)$. Lageos-1 data are present throughout, and Starlette data are present from January 1980 onward. Data completeness issues precluded the use of the earlier Starlette and Lageos-1 data. Other satellites were added when launched: Ajisai from August 1986 and Lageos-2 and several other satellites from 1992 onward. TOPEX/POSEIDON (T/P), which is also tracked by the Détermination d'Orbite et Radiopositionnement Intégrés par Satellite system, was added in January 1993. The formal uncertainties shown reflect the SLR data weights derived from the calibration of the comprehensive 19-year solution and should be realistic (*6*).

Dominant in $J_2(t)$ is a seasonal signal of amplitude 3.2×10^{-10}, which is driven by meteorologic mass redistribution in the atmosphere-hydrosphere-cryosphere system (*7–10*). Also plotted in Fig. 1 is the atmospheric contribution calculated according to the National Center for Environmental Prediction (NCEP) reanalysis data (*11*), including the inverted-barometer (IB) correction (*12*). Subtraction of this signal and further empirical removal of the residual seasonal signals (which are attributable to the poorly known seasonal mass redistribution in the oceans and land hydrology) result in a nonatmospheric and nonseasonal $J_2(t)$ (Fig. 2).

A linear fit to the observed J_2 through 1996 shows a decrease in J_2 of -2.8×10^{-11} year^{-1} (Fig. 2). For this period, the uncertainty for the J_2 rate in the comprehensive solution (which considers the correlation with the 18.6-year tide) is 0.4×10^{-11} year^{-1}. Despite the lack of data before 1979, the results are in excellent agreement with estimates of the J_2 rate that included those data (*2*). The secular drift results primarily from postglacial rebound (PGR) (*2*, *13*, *14*) in the mantle, plus various secondary contributions of climatic and anthropogenic origin (for example, reservoirs, which are an order of magnitude too small to explain the recent observations) (*4*, *15*, *16*). At some time during 1997 or 1998, the trend reversed. The post-1996 points have deviated from the pre-1997 slope by about six times the uncertainties, on average, over that period. A linear fit from 1997 onward yields a rate of $+2.2 \times 10^{-11}$ year^{-1}. On the basis of the comprehensive solutions, the uncertainty for this rate is $\sim 0.7 \times 10^{-11}$ year^{-1}; however, because of the nonlinearity in $J_2(t)$, the slope can vary by more than the uncertainty value, depending on the period fitted. Another departure may exist around 1980, but excepting a few data points the deviation is only one to two times the uncertainties, making the importance unclear.

An increase in J_2 means a net transport of mass from high to low latitude (the nodal lines of J_2 are $\pm$ 35.3° latitude). Transport of terrestrial water and/or ice mass to the oceans is one likely cause, because most of the ice mass resides in high-latitude polar caps and glaciers. As an example of the mass flux involved, imagine one fictitious scenario that

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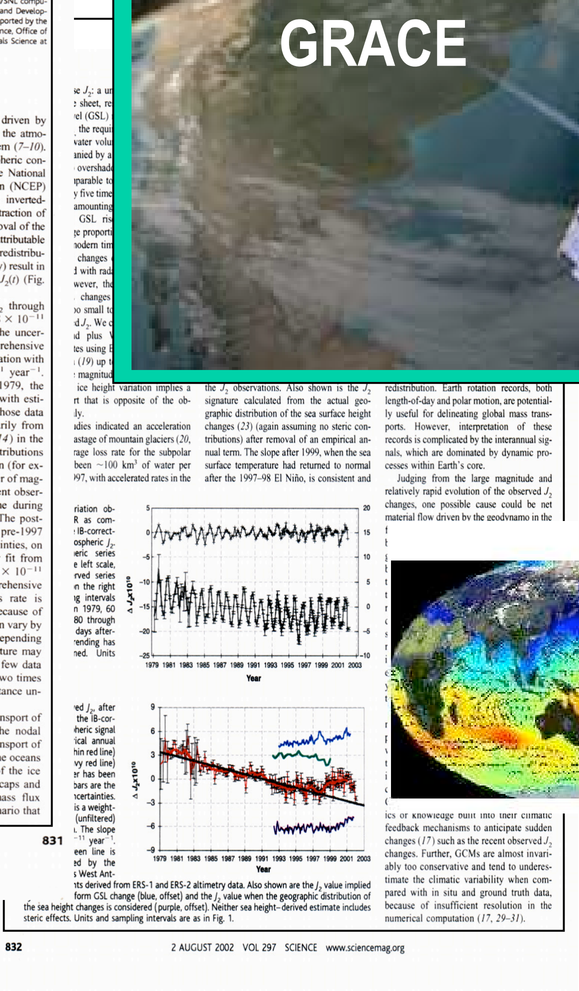
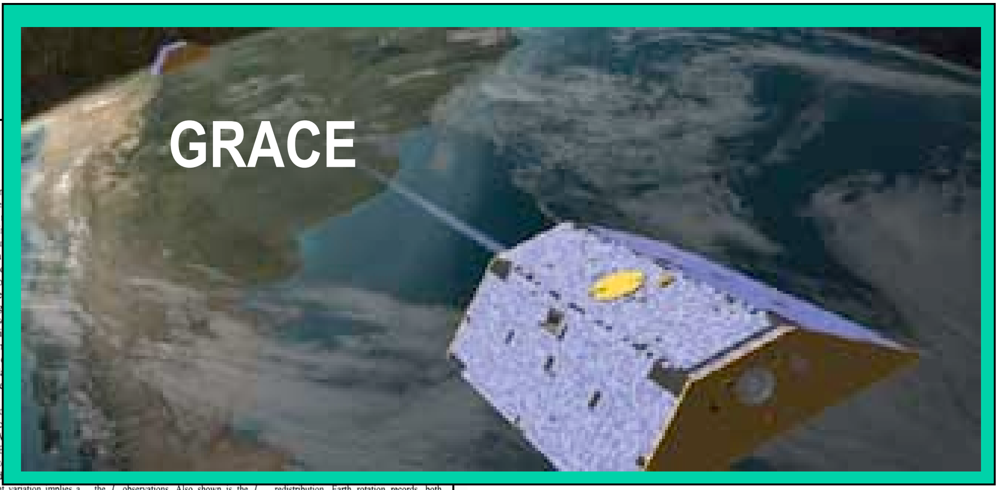
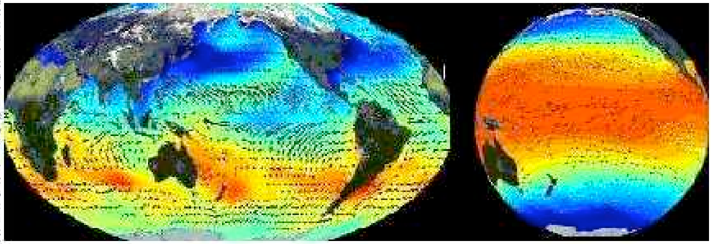
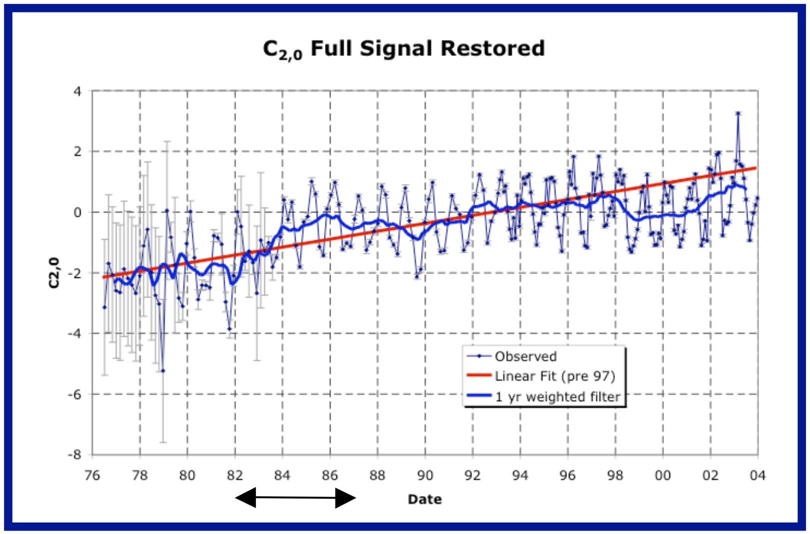
*To whom correspondence should be addressed. E-mail: ccox@stokes.gsfc.nasa.gov





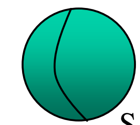


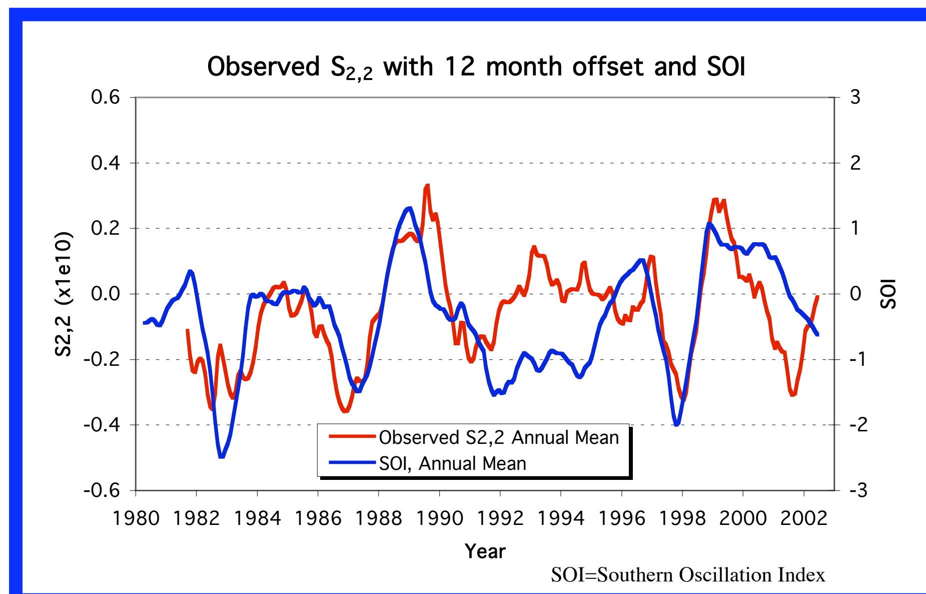
Geodetic Networks:
Monitoring Temporal Gravity Changes Using SLR



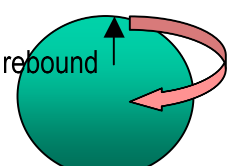
Duration of GRACE

- +0.6 correlation between $S_{2,2}$ time series and the SOI when $S_{2,2}$ is shifted forward in time by 12 months.
- Evidence of El Nino prediction?
- Reported by Cox, Chao et al. (AGU, 2003)

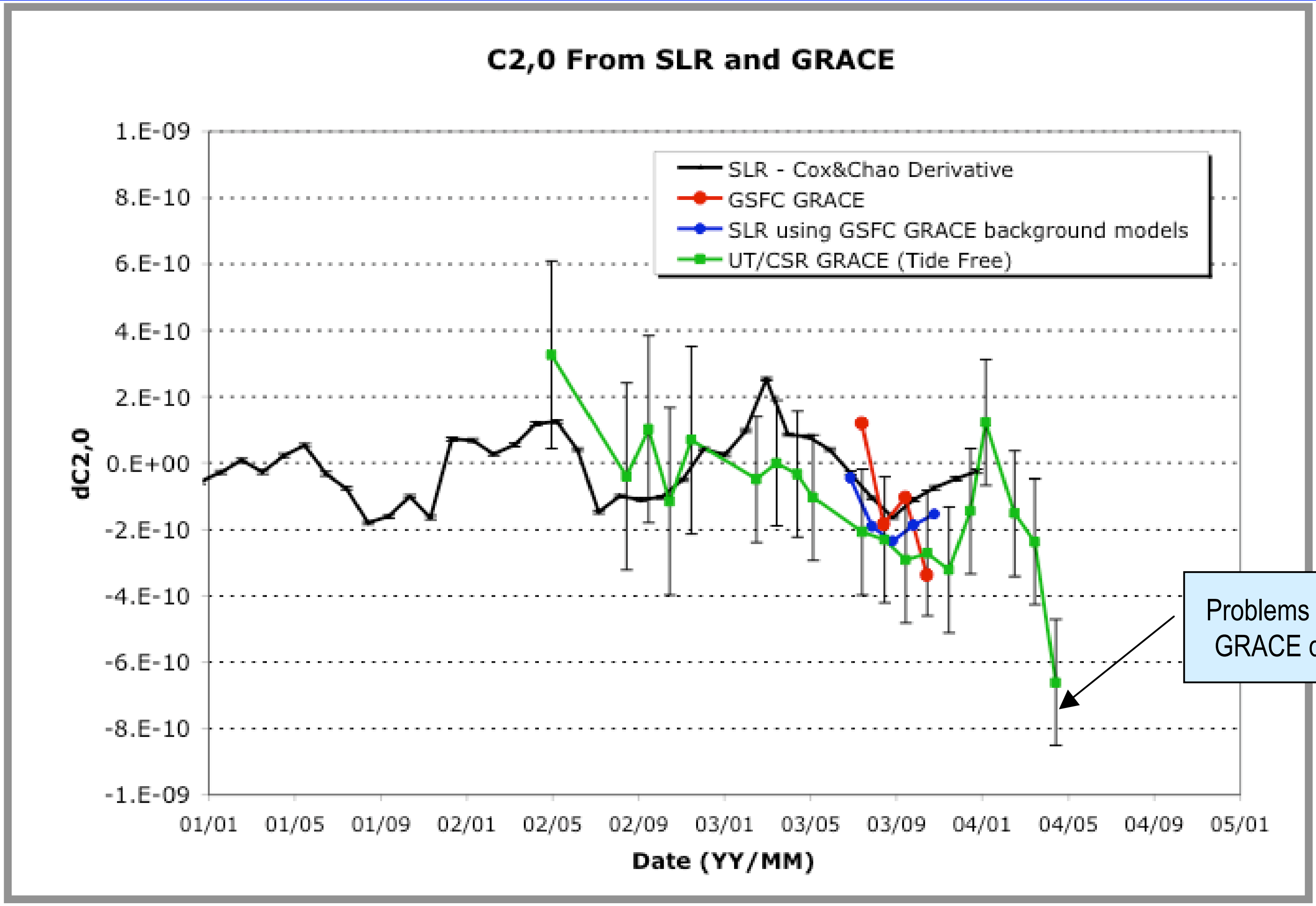




- Anomalistic behavior of J_2 time series
- First detection of large-scale unanticipated mass redistribution
- Reported by Cox and Chao, (SCIENCE, 2002)

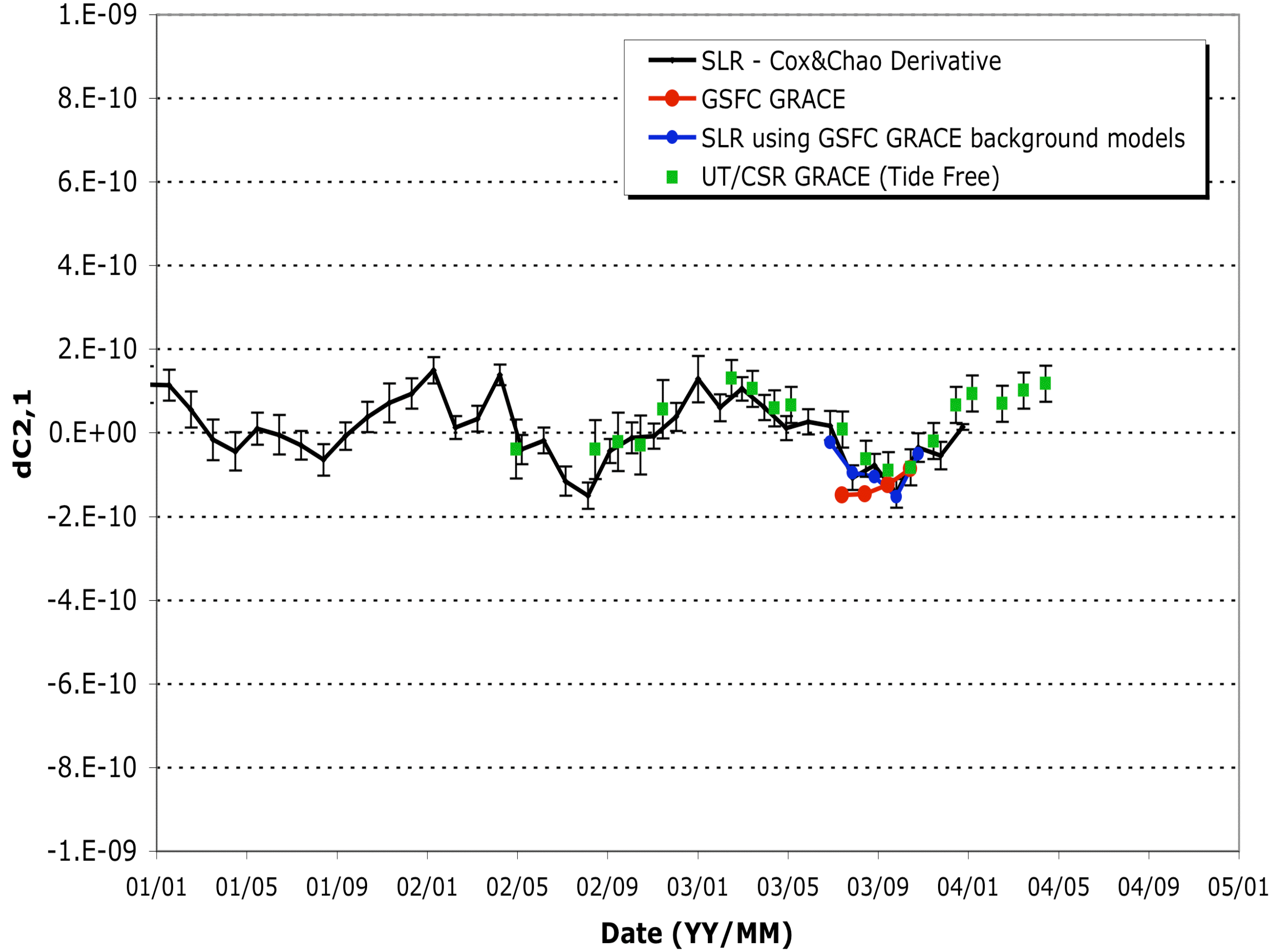


$C_{2,0}$: SLR vs GRACE monthly

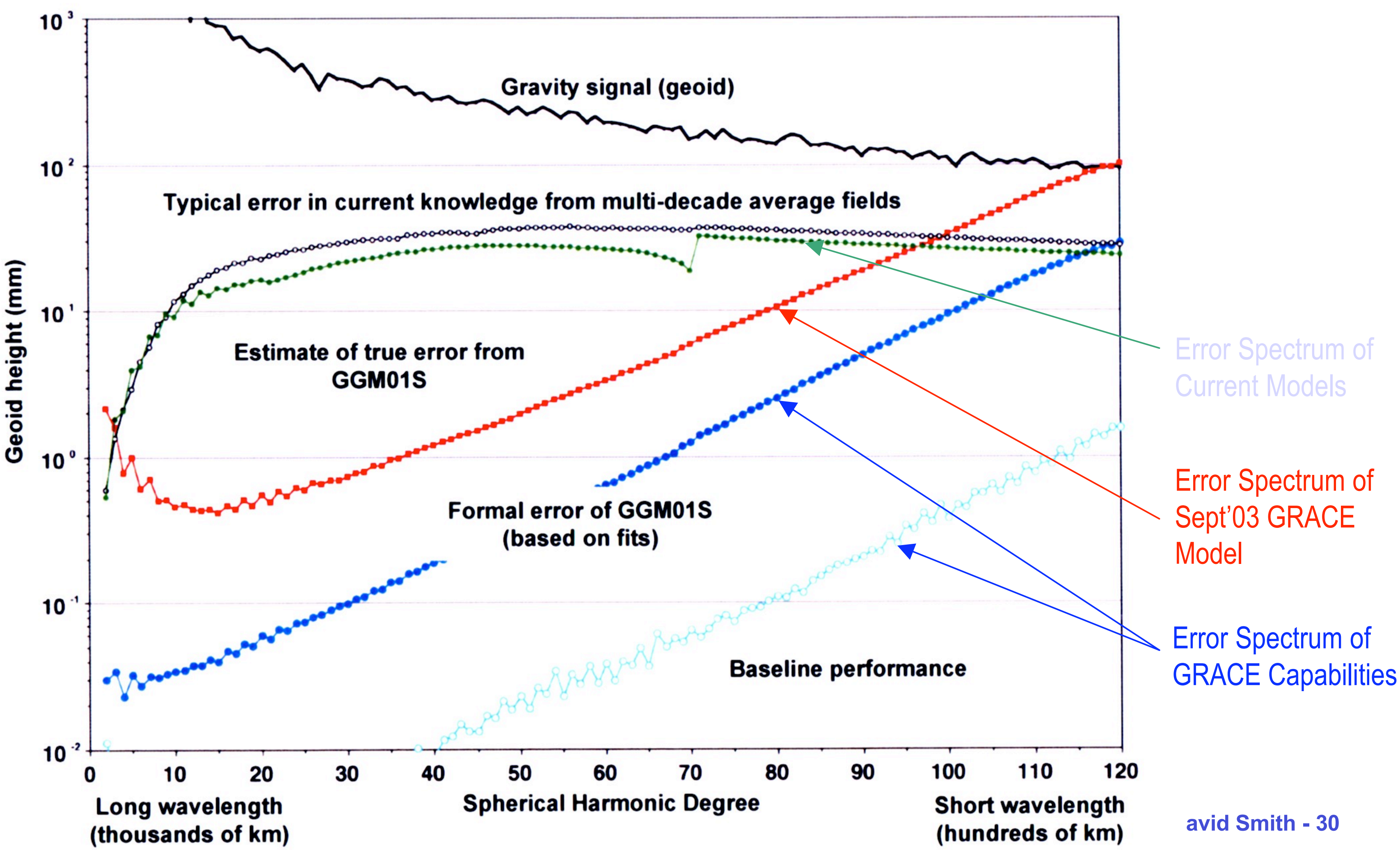


Formal Errors shown for SLR **Calibrated Errors shown for GRACE**

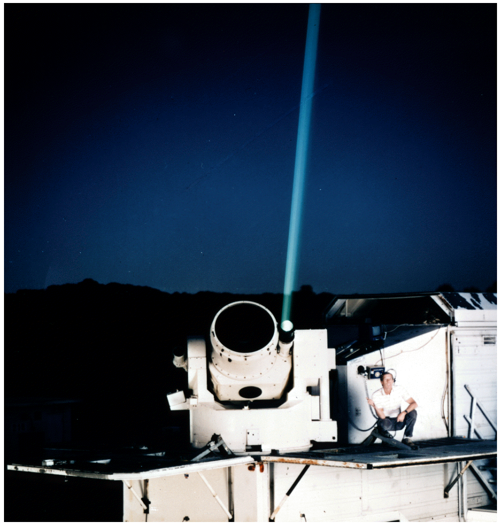
$C_{2,1}$: SLR vs GRACE monthly



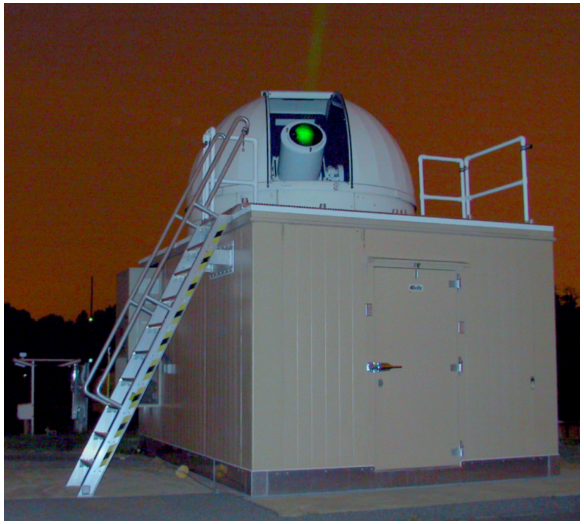
Reduction in Major SLR Error Source: GRACE Gravity Field Modeling



SLR2000, the Future of SLR



NASA MOBLAS System



NASA SLR2000 System

- Fully automated
- Continuous operation
- Increased reliability
- Lower replication and operating costs
- Self monitoring, low maintenance
- Remote locations
- Improved geographic distribution
- Possible use of SLR2000 as ground link in laser communications and transponder experiments

SLR2000: Planetary Applications

- SLR2000 has been designed to work over lunar and planetary distances:
  - passive tracking of satellites at lunar distances with a large retro-reflector (r^4 law)
  - active tracking of satellites, probes and landers over planetary distances (100's of millions of kilometers) in concert with an onboard laser transponder (r^2 law)

- The inner solar system is open for tracking with SLR2000 and transponders.

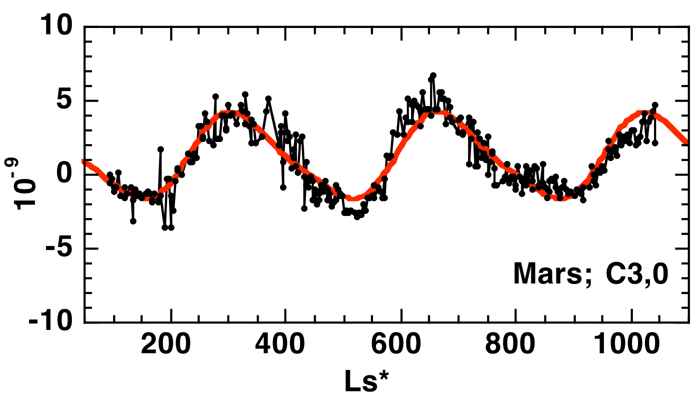
- Soon, laser transponders will be as reliable as microwave systems (remember your CD system)

SLR2000: Planetary Applications - 2

Optical Tracking of Lunar and Planetary Spacecraft

- Lunar Orbiters - precision orbit determination (Lageos quality)
  - support of altimetry missions
  - science (static and time dep. gravity; hi - resolution imagery)

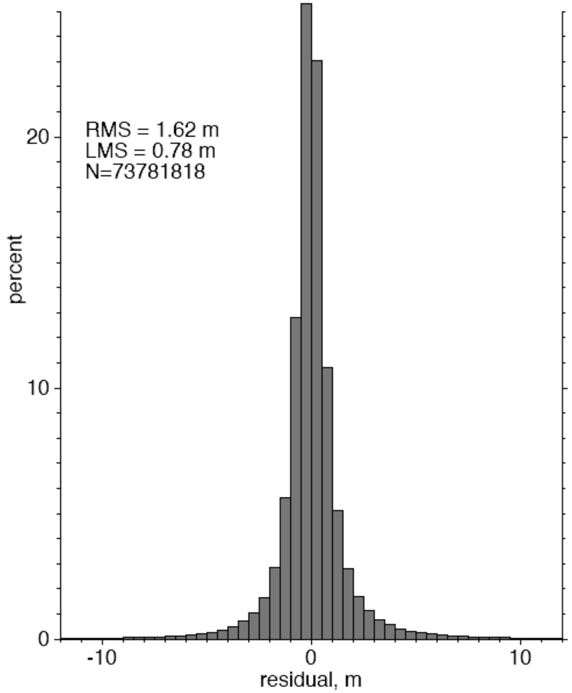
- Planetary Orbiters/Landers
  - cm orbit determination
  - gravity (seasonal time dependence), etc
  - planetary rotation variations
  - timing at GPS accuracies



The State of the Art: Planetary Spacecraft Orbit Determination

- The most precise planetary orbit determination is for Mars Global Surveyor (MGS) operating in orbit at Mars since Sept. 1997.

- The orbital "accuracy" evaluated by laser altimeter cross-overs is ~ 1 meter rms radially and 100 meters horizontally.



- The tracking of MGS is X-band doppler with precision ~ 50 microns/s every 10 seconds.

- <u>How much better could we do if we tracked planetary orbiters using laser transponders?</u>

Typical Tracking Requirements for a Lunar Orbiter or Lander

- The tracking requirements of a lunar satellite tracking system are similar to those for geodetic Earth satellites:

  - sub-centimeter ranging;
  - 10 mm/sec velocity (derivable for the range?)
  - 5-second normal points (~ 8km along track)

[*Mircowave tracking at X-band provides 2 meter ranges, ~50 mm/sec velocity at 10-second intervals; Ka-band tracking "can" provide ~40 cm ranges, ~20 mm/sec at 10 second intervals. Weather limitations at Ka-band*]

- Provide the timing system for the spacecraft instrumentation at the 0.1 millisecond level (the transfer of GPS timing to the Moon.

Possibilities for LRO and the New Vision

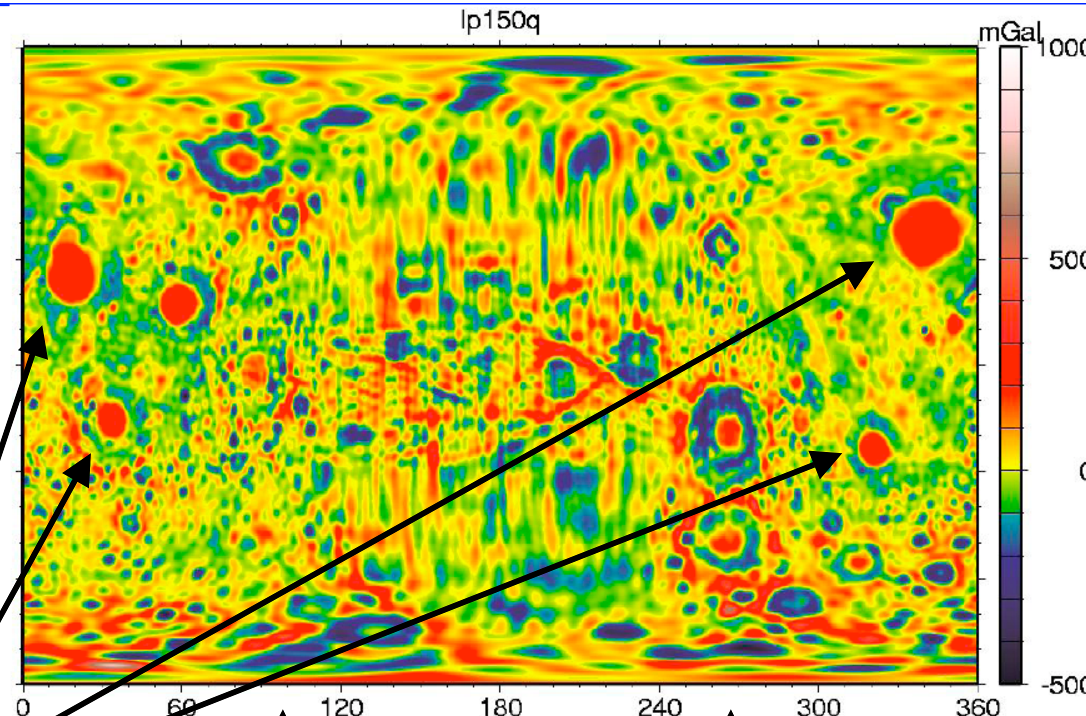
- The objectives for LRO could benefit substantially if improved orbit determination were possible (~ 10 ~~meters~~ → ~ 1 meter) radially
  - better topography
  - better positioning of surface features
  - better gravity field
  - ……..

- If LRO carried a simple retro-reflector it could be tracked by SLR2000 (not the Moblas's) to about 10 cm precision. This alone could probably make a 5 fold improvement in nearside radial orbit quality

- If LRO carried a laser transponder then SLR2000's could track LRO to <1 cm, potentially moving the orbital quality of LRO from 10 m to a few tens of centimeters, radially.

The Lunar Gravity Field
- not to be improved by LRO

- Present knowledge based upon Clementine and Lunar Prospector S-band tracking:
  - ± 20 mGal near-side
  - ± 100 mGal far-side
- Science needs ± 1 mGal



"Mascons"

Lunar Far-side

Striping indicates unresolved gravity signal

1 mGal = 10^{-5} meters/sec^2

SLR2000 and Lunar Discovery Missions

- Several (3?) Discovery proposals for science at the Moon were submitted to NASA last week (7/15/04).
- At least one of those missions, *Moonlight*, needs high precision tracking to support an imaging lidar and to improve the model for the lunar gravity field.
- This mission proposes to carry a laser transponder and plans to support the operation of 2 SLR2000 type stations; one at GSFC, one at JPL. It has requested and received the endorsement of the ILRS laser tracking network.
- *Moonlight* also needs ~ 0.1 ms timing for the payload which it will achieve by the transfer of GPS time via SLR2000 stations

SLR2000 and Lunar Discovery Missions

- *Moonlight* put out an RFI to industry for a network of SLR2000's capable of precision tracking of the s/c and communicating 60Mb/s from the lunar orbit to Earth continuously (24/7) for 2 years.

- The response proposed was for 9 stations globally distributed and included all operations and delivery of the tracking data and science data to JPL.

The Synergism of SLR2000 and Lasercom

- Shelter and azimuth tracking dome has internet connections for high speed ground data transfer and internal instrument health and security monitors
- "Smart" Meteorological Station provides protection against local weather conditions (wind, precipitation, etc) and monitors ground visibility and cloud cover for efficient lasercom operations
- GPS-disciplined Rubidium Time and Frequency Reference provides accurate epoch times for reliable satellite acquisition as well as a stable clock reference for optical communications
- Modest 40 cm off-axis telescope provides sufficient aperture to handle high bandwidth optical com from Earth orbiting satellites using modest spaceborne laser powers and is less sensitive to atmospheric perturbations than meter-class telescopes. No adaptive optics needed.
- Arcsecond precision tracking mount plus mount model provides high accuracy open loop pointing (~2 arcsec) to satellites
- Quadrant detector is expected to provide sub-arcsecond pointing corrections and closed loop tracking for optimizing both the ranging and optical com signals
- Ground-based ranging beam serves as a powerful beacon for the spaceborne lasercom system to lock onto and the returns from onboard reflectors provide accurate orbit information and independent verification of satellite "lock".
- Communication satellites can be included in SLR constellation for automatic updating of orbit predictions by the central processor to expedite target acquisition

The Long-Range Vision for SLR
(I have a dream?……)

- Understanding the dynamics of the solar system on present-day time scales is one of the basic challenges of understanding the evolution of all the bodies in the solar system and how these changes affect life on Earth and elsewhere.

- Monitoring the dynamical and rotational motions of the bodies comprising the solar system is now possible if optical transponders are placed on bodies of interest - planets, moon, asteroids, comets, etc, etc

- SLR can be the solar system’s measuring tool with accuracies at the centimeter level - almost nothing else can do this.

- For exploration of the solar system:
  - we can know where we are
  - we can return to the same position should we choose to do so
  - we can do it at the decimeter level, and
  - we can communicate home at the same time.