Laser Ranging:
Scientific Accomplishments of the Past
and
Requirements for the Future

Erricos C. Pavlis
GEST/UMBC, Baltimore, MD, USA

ILRS Technical Laser Workshop
"Satellite, Lunar and Planetary Laser Ranging: Characterizing the Space Segment",
INFN-LNF, Frascati, Italy,
November 5-9, 2012

The Early Years

- First light in 1964, ranging to Beacon-B
- First “global network” was established with SAO’s participation and contribution in the International Geophysical Year (IGY), (Whipple and Hynek, 1958)
- The goals were:
  - “to tie together the observing stations and the center of the geoid to a precision of the order of 10 m
  - to add appreciably to our knowledge of the density distribution of the earth, particularly in crustal volumes
  - to provide the value of the atmospheric density a few kilometers above the initial perigee distance, and periodic effects or predictable cyclic effects that may occur in the earth’s high atmosphere” (Whipple and Hynek, 1958)

SAO Global Network

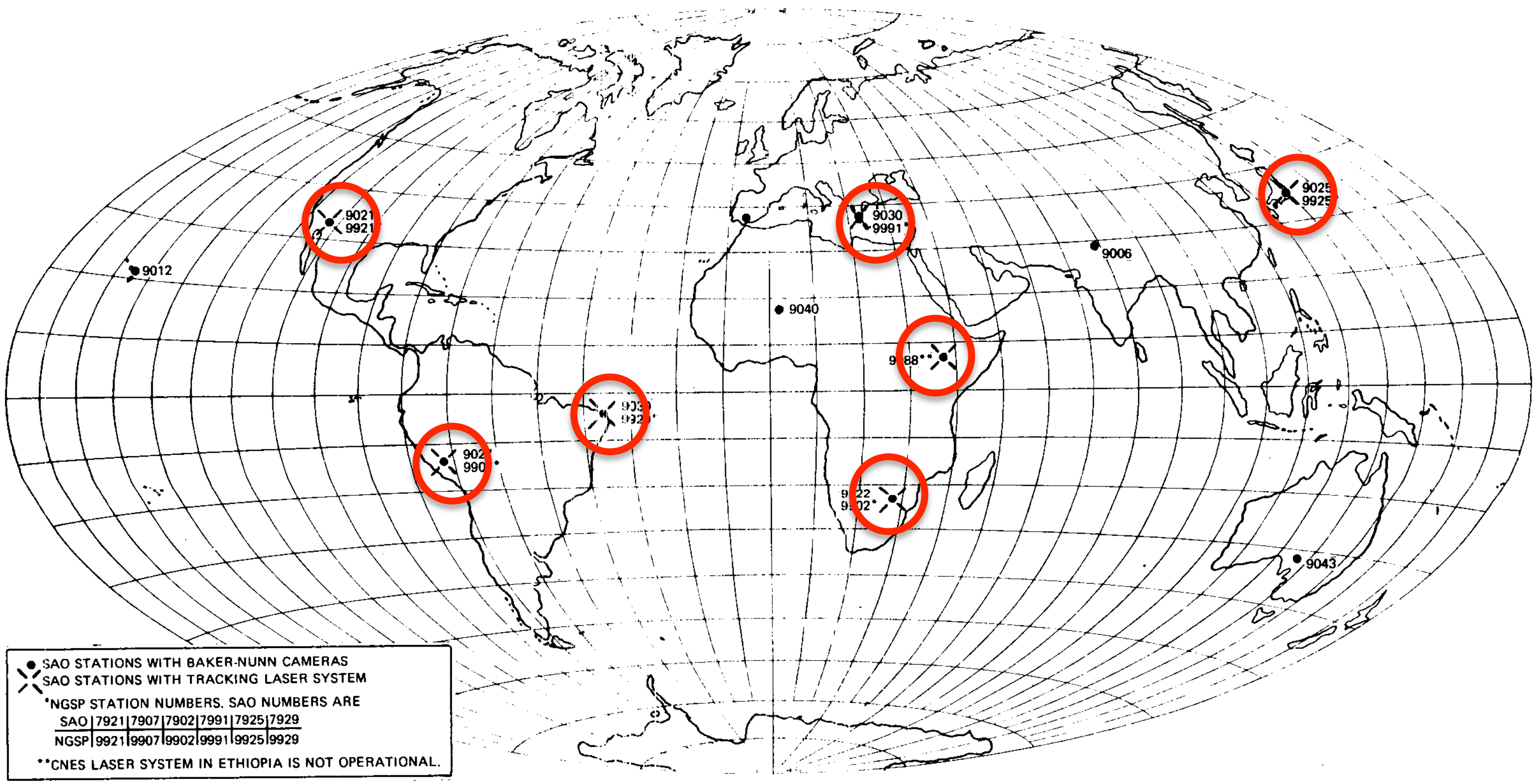
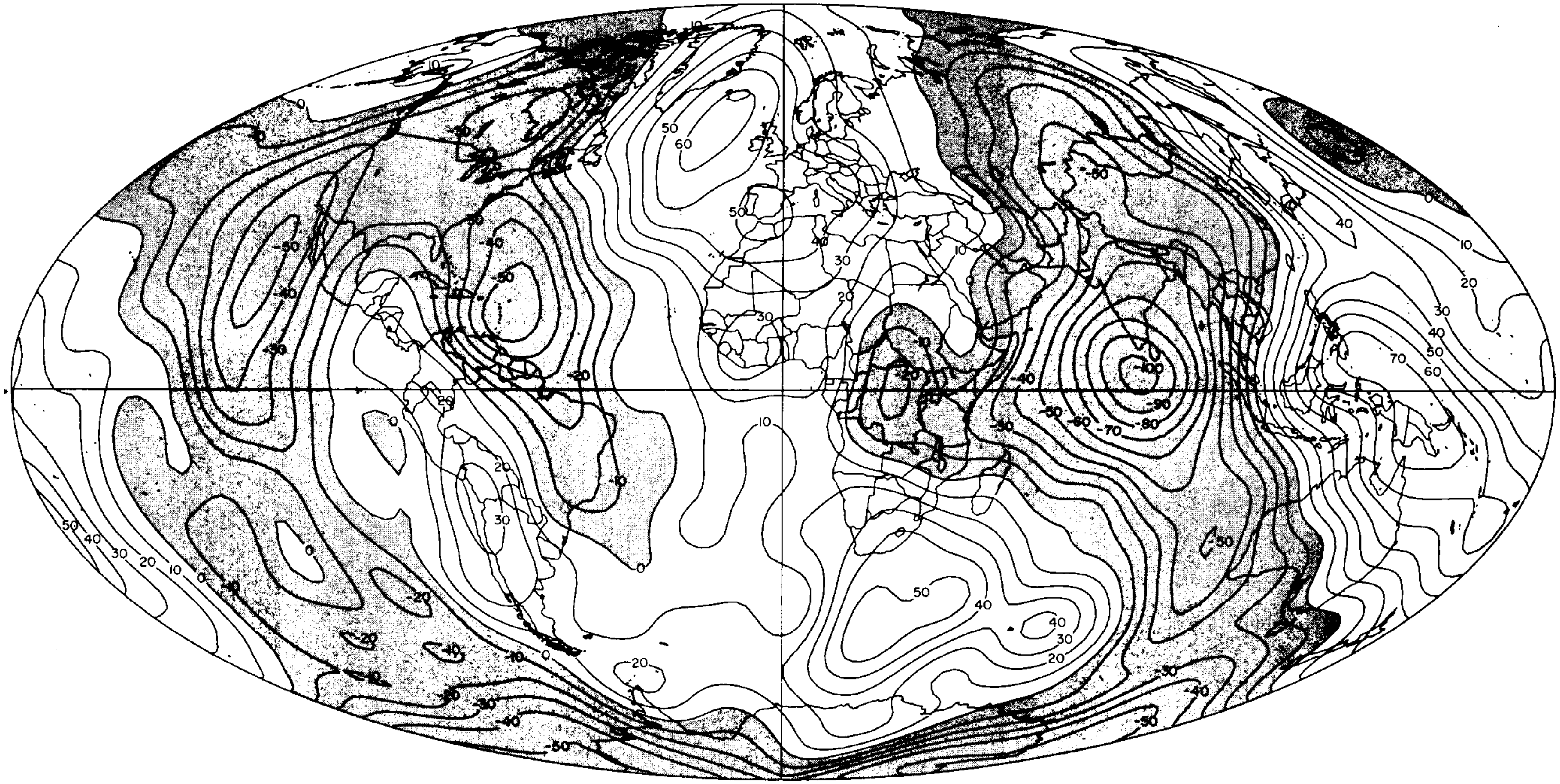


FIGURE 9.6.—SAO field stations.

SMITHSONIAN ASTROPHYSICAL OBSERVATORY

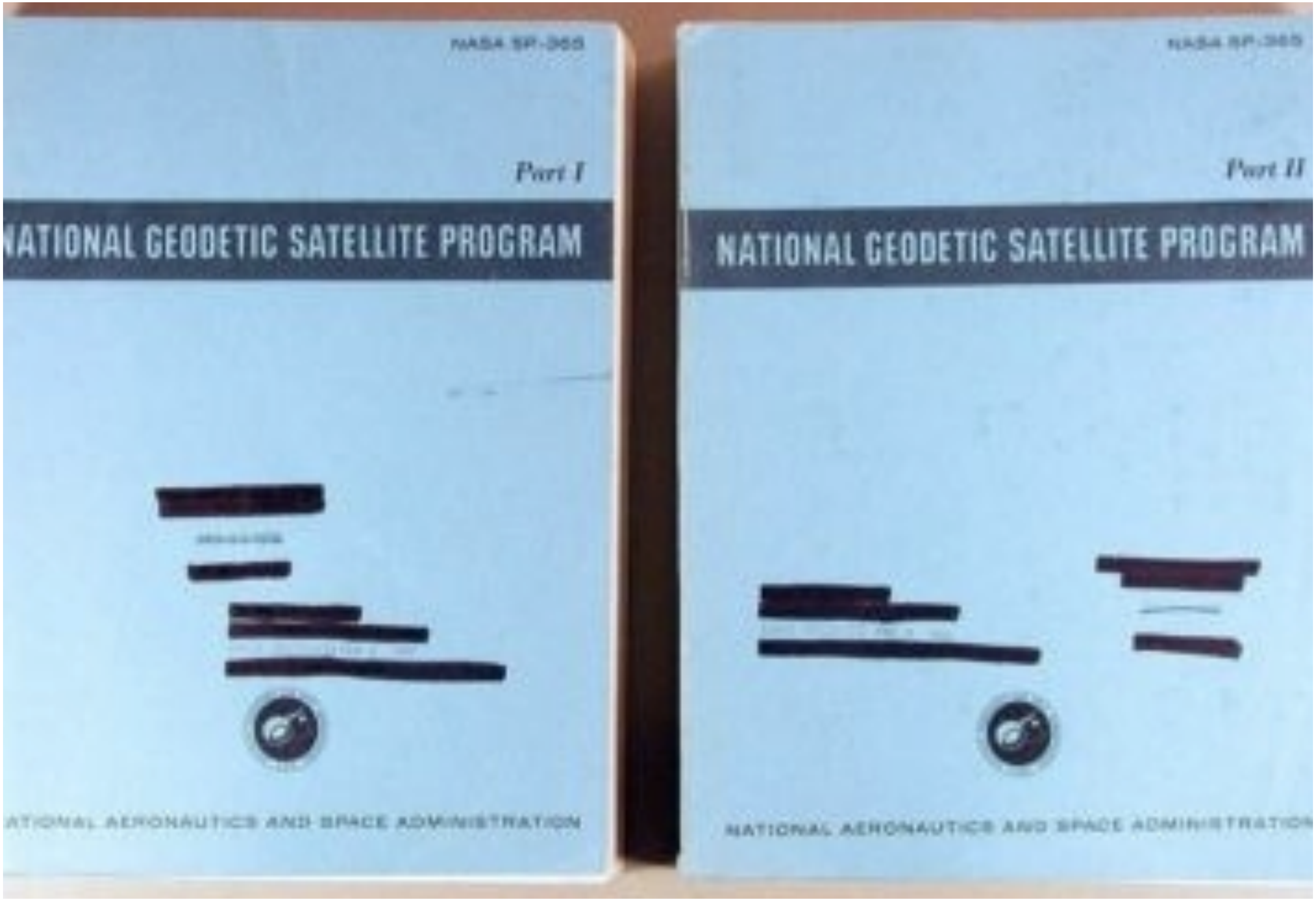
Major Global Geophysical Results: SE III



NATIONAL GEODETIC SATELLITE PROGRAM

FIGURE 9.21a.—Standard Earth III, geoid heights in meters with respect to the best fitting ellipsoid, $f = 1/298.256$.

NGSP: Nat. Geodetic Satellite Program



The SAO Network @ NGSP

TABLE 9.2.—*Laser Sites*

Station number NGSP	SAO	Station location	Period of operation
9901	7901	Organ Pass, New Mexico	March 1966 to July 1967
9912	7912	Maui, Hawaii	May 24, 1968 to March 27, 1969
9902	7902	Olifantsfontein, South Africa	February 1971 to present
9907	7907	Arequipa, Peru	December 1970 to present
9921	7921	Mt. Hopkins, Arizona (prototype)	December 1967 to June 20, 1972
9921	7921	Mt. Hopkins, Arizona (rebuilt system)	November 1972 to present
9929	7929	Natal, Brazil	November 1970 to present
9991	7991	Athens, Greece	September 1968 to June 1969
9930	7930	Dionysos, Greece	July 1969 to present
9925	7925	Tokyo, Japan	November 1972 to present

Satellites Contributing to NGSP

TABLE 9.7.—*Dynamical Data Used in SE III*

Satellite Number	Satellite Name	Inclination	Eccentricity	a (km)	Perigee (km)	Laser observations	Station coordinates	Zonal harmonics	Tesseral harmonics	Number of files
7001701	DIAL	5°	0.088	7344	301			x		
7010901	PEOLE	15	0.017	7070	635	x		x	x	4
6001301	COURIER 1B 1970ν1	28	0.016	7465	965		x	x	x	7
5900101	VANGUARD 2 1959 α1	33	0.165	8300	557		x	x	x	7
5900701	1959 η1	33	0.188	8483	515		x			18
6100401	1961 δ1	39	0.119	7960	700				x	4
6701401	D1D	39	0.053	7337	569	x	x		x	10
6701101	D1C	40	0.052	7336	579	x	x		x	9
6503201	Explorer 24 BE-C	41	0.026	7311	941	x	x		x	13
6202901	TELSTAR 1 1962 $\alpha\epsilon$1	44	0.241	9672	962			x		4
6000902	1960 ι2	47	0.011	7971	1512		x	x	x	10
6206001	ANNA-1B 1962 $\beta\mu$1	50	0.007	7508	1077		x	x	x	12
6302601	Geophysical Research	50	0.062	7237	424			x		6
6508901	Explorer 29 GEOS-1	59	0.073	8074	1121	x	x	x	x	56
6101501	TRANSIT 4A 6101	67	0.008	7318	885			x	x	10
6101502	INJUN-1 6102	67	0.008	7316	896				x	9
6506301	SECOR-5	69	0.079	8159	1137		x		x	2
6400101		70	0.002	7301	921			x	x	4
6406401	Explorer 22 BE-B	80	0.012	7362	912	x	x	x	x	6
6508101	OGO-2	87	0.075	7344	420			x	x	5
6600501	OSCAR-07	89	0.023	7417	868		x		x	1
6304902	5BN-2	90	0.005	7473	1070		x		x	5
6102801	MIDAS-4 1961 $\alpha\delta$1	96	0.013	10005	3503		x	x	x	6
6800201	Explorer 36 GEOS-2	106	0.031	7709	1101	x	x		x	13
6507801	OV1-2	144	0.182	8306	416		x		x	4

Laser Data Accuracy

SMITHSONIAN ASTROPHYSICAL OBSERVATORY

TABLE 9.8.—*Assumed Accuracy for Data Used in SE III*

Data	Weight	Remarks
Baker-Nunn	4″	
Smoothed Baker-Nunn	2″	
SAO laser	5 m	Observed before 1970
CNES laser	10 m	Observed before 1970
GSFC laser	5 m	Observed before 1970
ISAGEX laser	5 m	1971 International Campaign

TABLE 9.9.—*Satellite Center of Mass*[a]

BE–B and BE–C	$\Delta = 0.3493 - 1.09183 \times 10^{-3} \times \phi + 2.9222 \times 10^{-6} \times \phi^2 - 1.5338 \times 10^{-7} \times \phi^3$ $(\Delta = 0 \text{ for } \phi > 120°)$
D1C and D1D	$\Delta = 0.164612 - 2.824 \times 10^{-3} \times \phi + 2.0639 \times 10^{-5} \times \phi^2 + 8.1214 \times 10^{-7} \times \phi^3 - 5.81302 \times 10^{-9} \times \phi^4$ $(\Delta = 0 \text{ for } \phi > 120°)$
GEOS–1	$\Delta = 0.3972 \cos \phi$
GEOS–2	$\Delta = 0.4298 \cos \phi$
PEOLE	$\Delta = 0.48 - 1.108 \times 10^{-2} \times \phi + 4.19267 \times 10^{-4} \times \phi^2 - 3.619 \times 10^{-6} \times \phi^3 + 8.12555 \times 10^{-9} \times \phi^4$ $(\Delta = 0.768 \text{ for } \phi > 96°)$

[a] From D. Arnold and J. Latimer.

NASA Geodynamics Program

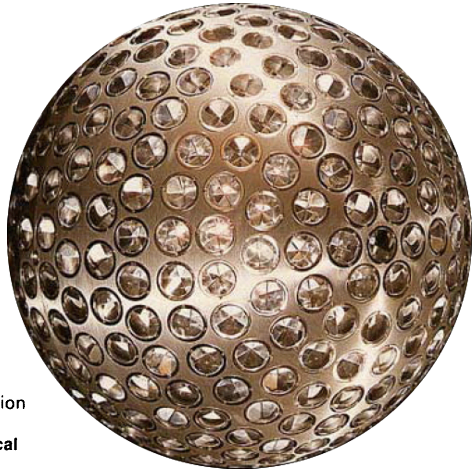
- The launch of LAGEOS in 1976 was catalytic for the evolution of the NASA programs
- NASA network modernized and expanded
  - MOBLAS systems deployed but rarely moved
- Launch of the Crustal Dynamics Project
- Major international expansion with several new stations (14 countries participated)
  - WEGENER
  - MERIT
- Transportable systems introduced in US and Europe, and major international campaigns executed
  - e.g. MEDLAS

NASA Technical Memorandum 4065

NASA Geodynamics Program
Summary Report: 1979–1987

Progress and Future Outlook

NASA Office of Space Science and Applications
Washington, D.C.



NASA
National Aeronautics and Space Administration

Scientific and Technical Information Division

1988

Tectonic Motion First Observed

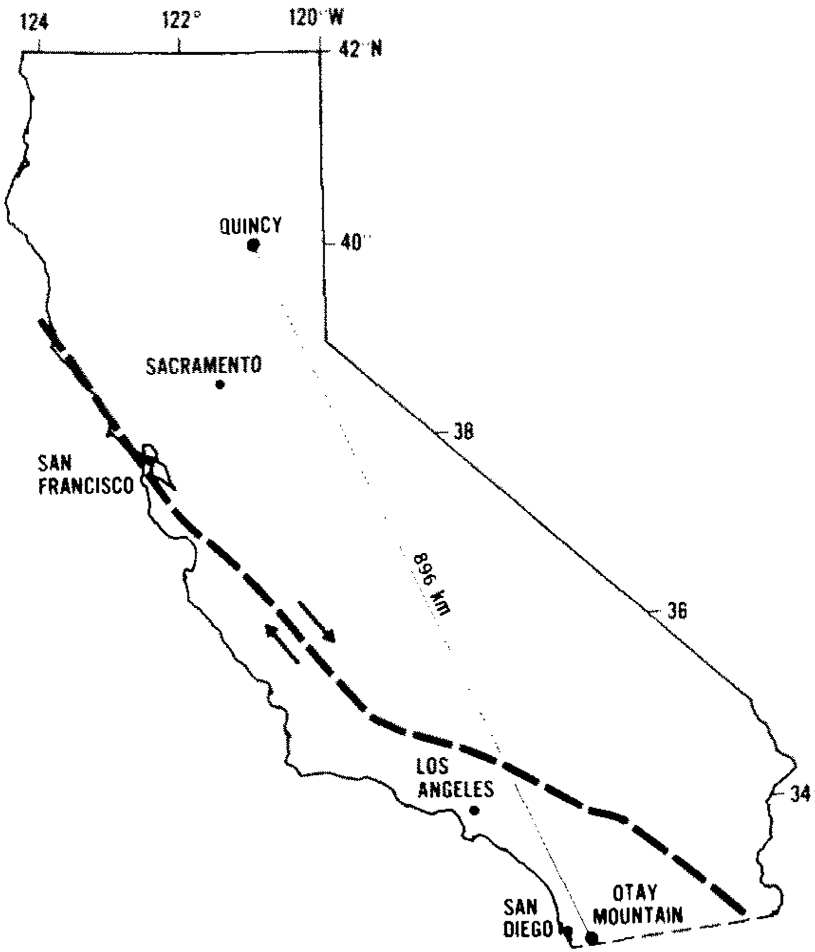


Fig. 1. Laser tracking sites were established at Otay M
the falls of 1972, 1974 and 1976.

Tectonophysics, 52 (1979) 59—67 59

THE MEASUREMENT OF FAULT MOTION BY SATELLITE LASER RANGING

D.E. SMITH [1], R. KOLENKIEWICZ [1], P.J. DUNN [2] and M.H. TORRENCE [2]

[1] *Goddard Space Flight Center, Greenbelt, Md. 20771 (U.S.A.)*
[2] *EG&G, Washington Analytical Services Center, Inc., Riverdale, Md. 20840 (U.S.A.)*

(Revised version accepted for publication March 24, 1978)

ABSTRACT

Smith, D.E., Kolenkiewicz, R., Dunn, P.J. and Torrence, M.H., 1979. The measurement of fault motion by satellite laser ranging. In: C.A. Whitten, R. Green and B.K. Meade (Editors), Recent Crustal Movements, 1977. Tectonophysics, 52: 59—67.

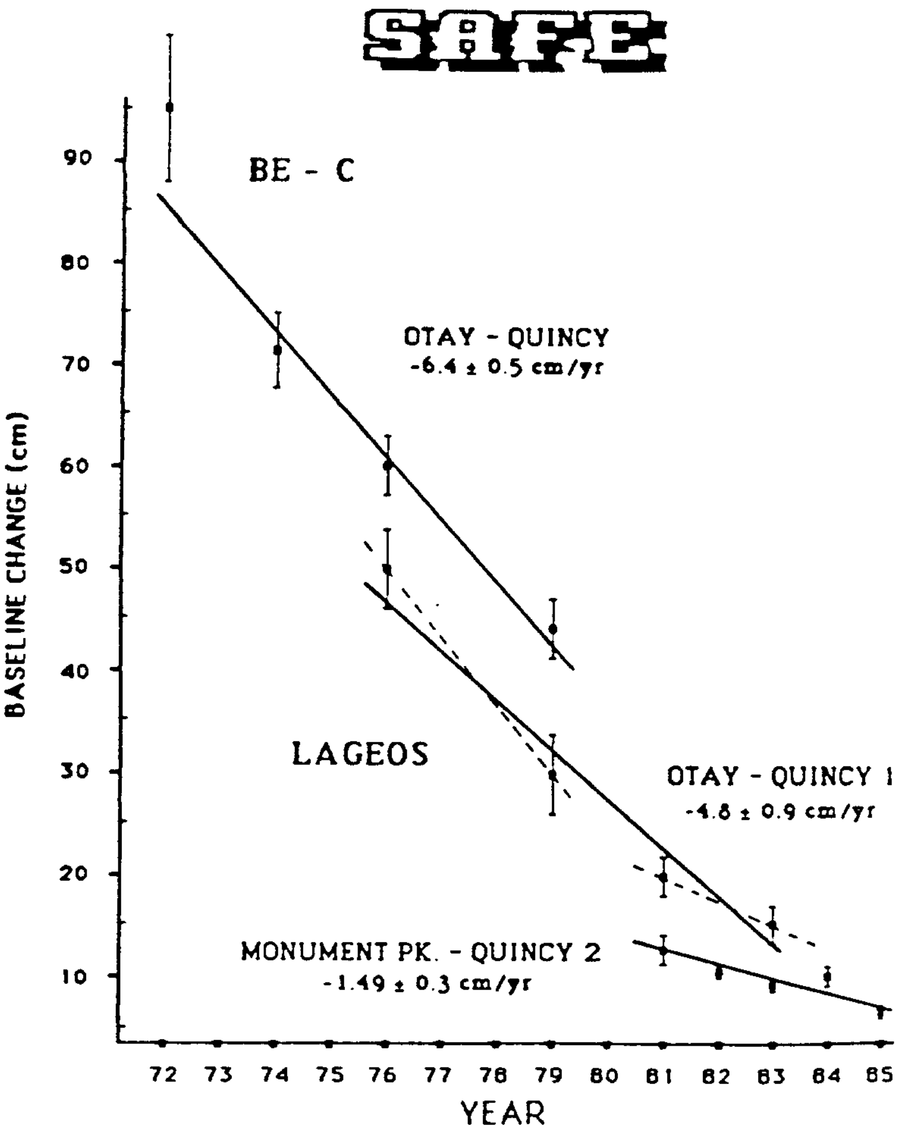
The distance between two points on opposite sides of the San Andreas Fault is being derived from laser tracking of near-earth satellites as part of an experiment to estimate the motion along the plate boundary. The two sites, at Otay Mountain near San Diego and at Quincy in northern California, are nearly 900 km apart and approximately 150 and 270 km, respectively, away from the main strike of the San Andreas Fault. The angle between the fault and the intersite vector is approximately 25°. In the fall of 1972 satellite laser tracking systems occupied these two sites, and from the data collected the relative location of the two sites was determined. The two sites were reoccupied in the fall of 1974 and again in the fall of 1976, and provided two further estimates of the relative positions of the two sites.

The results of these first three measurements indicate a shortening of the intersite baseline between San Diego and Quincy at an average rate of 9 ± 3 cm/year, suggesting a much larger possible present-day motion across the fault system than expected. The main source of error in this analysis is the motion of the spacecraft which is significantly affected by unmodeled anomalies in the earth's gravity field. However, major advances in our knowledge of the gravity field are expected over the next few years and as these occur the accuracy of the present results will improve.

INTRODUCTION

In order to estimate the gross plate motion across the San Andreas Fault in California an experiment was conceived in 1972 to repeatedly measure the intersite distances between several points along, but back from, the fault over an extended period of time. The technique proposed was laser ranging to near-earth satellites. Three sites were selected in the United States: one

Improved LAGEOS Results



Adv. Space Res. Vol. 6, No. 9, pp. 41–51, 1986
Printed in Great Britain.

0273–1177/86 $0.00 + .50

CONTEMPORARY PLATE MOTIONS FROM LAGEOS: A DECADE LATER

D. C. Christodoulidis,* D. E. Smith,*
S. M. Klosko,** P. J. Dunn,** J. W. Robbins** and
M. H. Torrence**

**NASA/Goddard Space Flight Center, Geodynamics Branch/Code 621, Greenbelt, MD 20771, U.S.A.*
***EG&G Washington Analytical Services Center, Incorporated, Lanham, MD 20706, U.S.A.*

Reduction of a decade's worth of Lageos Satellite Laser Ranging (SLR) is providing new insights into contemporary plate kinematics. Globally, the SLR results have largely confirmed the plate motion models developed from geologic evidence. Analysis of the data from 12 base stations finds all interstation SLR rates having a linear cross correlation of .91 with the Minster and Jordan geologic model. To within their uncertainties, the time scales of the geologic and SLR models are found to be in agreement indicating that globally, the tectonic rates are linear over time scales of 1 to 10 million years. Regionally, SLR data exclusively has been used to develop a model of the absolute station motions for observing sites within the Western United States. The observed intersite motion of the two stations comprising the San Andreas Fault Experiment appears to be non-linear over the last decade, with the relative motion between these sites changing from -6 to -2 cm/year during the last four years. The results achieved with SLR are complemented and largely confirmed by those achieved with other space technologies. It is clear that Satellite Laser Ranging has reached a new level of maturity. After passing through the threshold of confirming the global nature of plate kinematics, research is now focusing on the development of models for the effective utilization of the constraints provided by space geodesy. These constraints will assist in our understanding of the mechanisms which drive tectonic motions and cause a complex picture of strain accumulation at the plate boundaries.

INTRODUCTION

The use of satellite laser ranging for accurate earth-fixed positioning has been advanced since the early 1970's. In light of the promising early results from the San Andreas Fault Experiment where tectonic motion was observed using laser tracking of the BE-C spacecraft (Smith et al, 1977), a satellite mission capable of providing a picture of geodynamics on a global basis was proposed. It was hoped that a dedicated laser satellite would further our understanding of the earthquake hazard over many of the world's most active tectonic regions and stimulate international cooperation in global laser system development. As a result, the Lageos (LAser GEOdynamics Satellite) Mission was initiated to enhance the capabilities of satellite based station- positioning. Lageos would provide a target in near-earth orbit whose dynamics were more readily modeled and which would yield better tracking geometry with frequent instances of simultaneous tracking even for sites separated by continental distances. After careful study, the Lageos orbit was selected to minimize less well understood short wavelength gravity and non-conservative force model effects. The orbit chosen was at about an earth's radius in altitude, nearly circular, and with an inclination of 109.8 degrees (a=122750 km, e=.003).

Lageos was launched in May of 1976. Table 1 gives the published mission objectives with regard to geodynamics and station positioning found within the Lageos Project Plan of 1975. We can now look back at a decade's worth of extraordinary progress which has been achieved due to Lageos tracking and the active participation of over twenty countries in the acquisition and analysis of precise range measurements. This paper will provide a review of NASA/Goddard Space Flight Center's analysis of these observations and provide an overview of our current assessment of contemporary plate tectonics which have been detected in our latest solutions. Currently, we have analyzed nine years of Lageos data spanning meaurements obtained from launch through the end of 1985. Results of both the observed global and regional plate kinematics are presented.

If the success of a mission is gauged by its fulfillment of its planned objectives, Lageos must be viewed as a great success. International cooperation has been strong; laser technology has advanced more than an order of magnitude in single point range precision (Figure 1) over the last ten years; station positioning at the few centimeter accuracy level for annual solutions has been achieved; and a global picture of plate kinematics has emerged. There have been other timely developments which were made possible through the

41

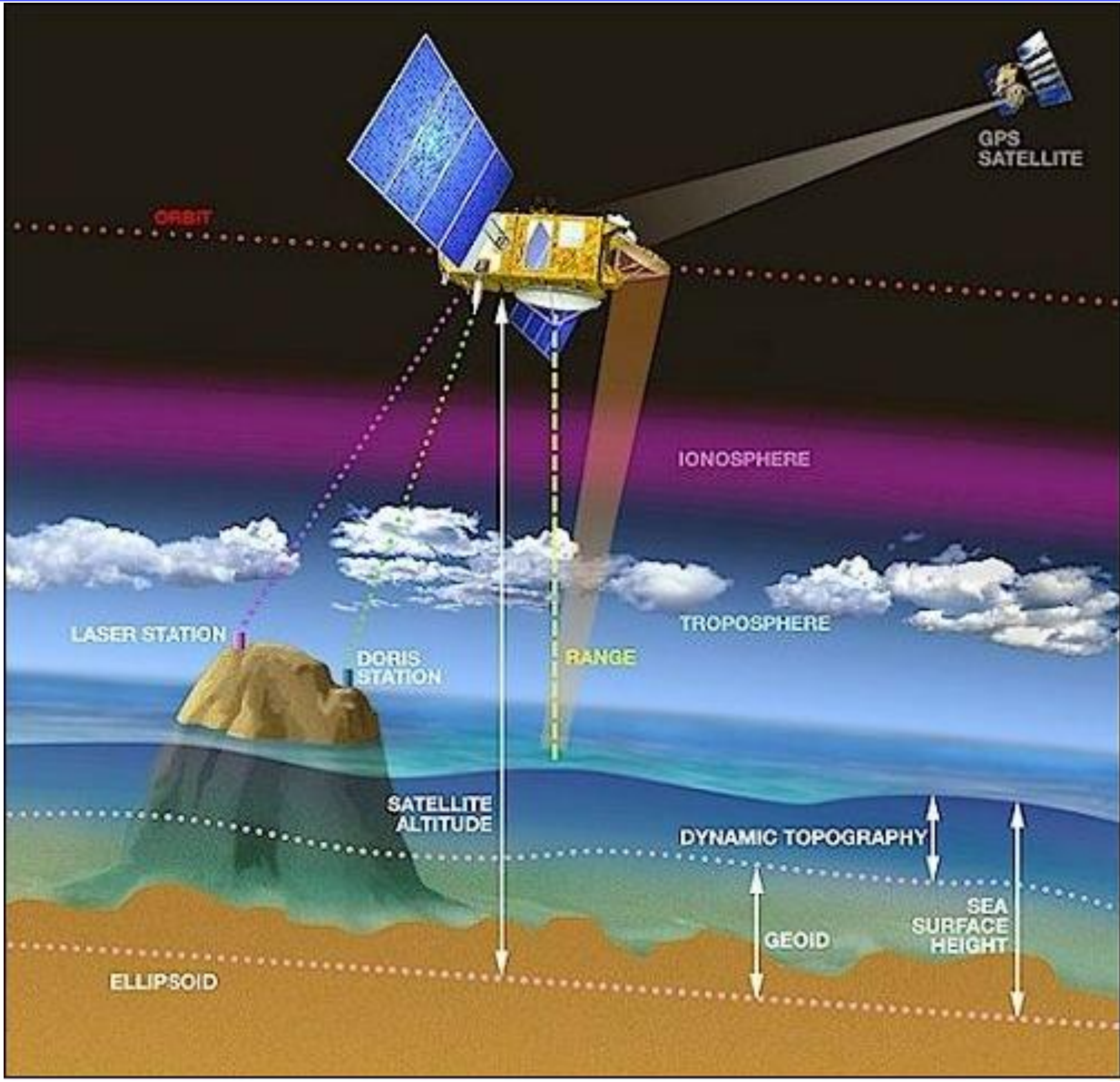
Gravity Model Improvements

- LAGEOS makes strong contributions to the accurate modeling of low degree terms of the model
- Tidal models are improved with the use of SLR data to Starlette (designed to be sensitive to most of the significant tidal lines) and to LAGEOS
- Planned oceanographic missions impose stringent requirements for geoid accuracy, reference frame quality and dedicated tracking for POD and validation of the orbits used in the calibration of altimeter radars
- The Topex/Poseidon mission benefits the most from accurate LAGEOS data used in the development of the pre-launch gravity model and the subsequent ones

Altimetry Mission Requirements

- POD for accurate satellite orbit
  - Radial accuracy at ≤1 cm level

- Reference frame with comparable accuracy to position tide gauges used for the calibration of the radar and the seamless observation of MSL rates from multiple and non-overlapping missions



The Gravity Mapping Missions

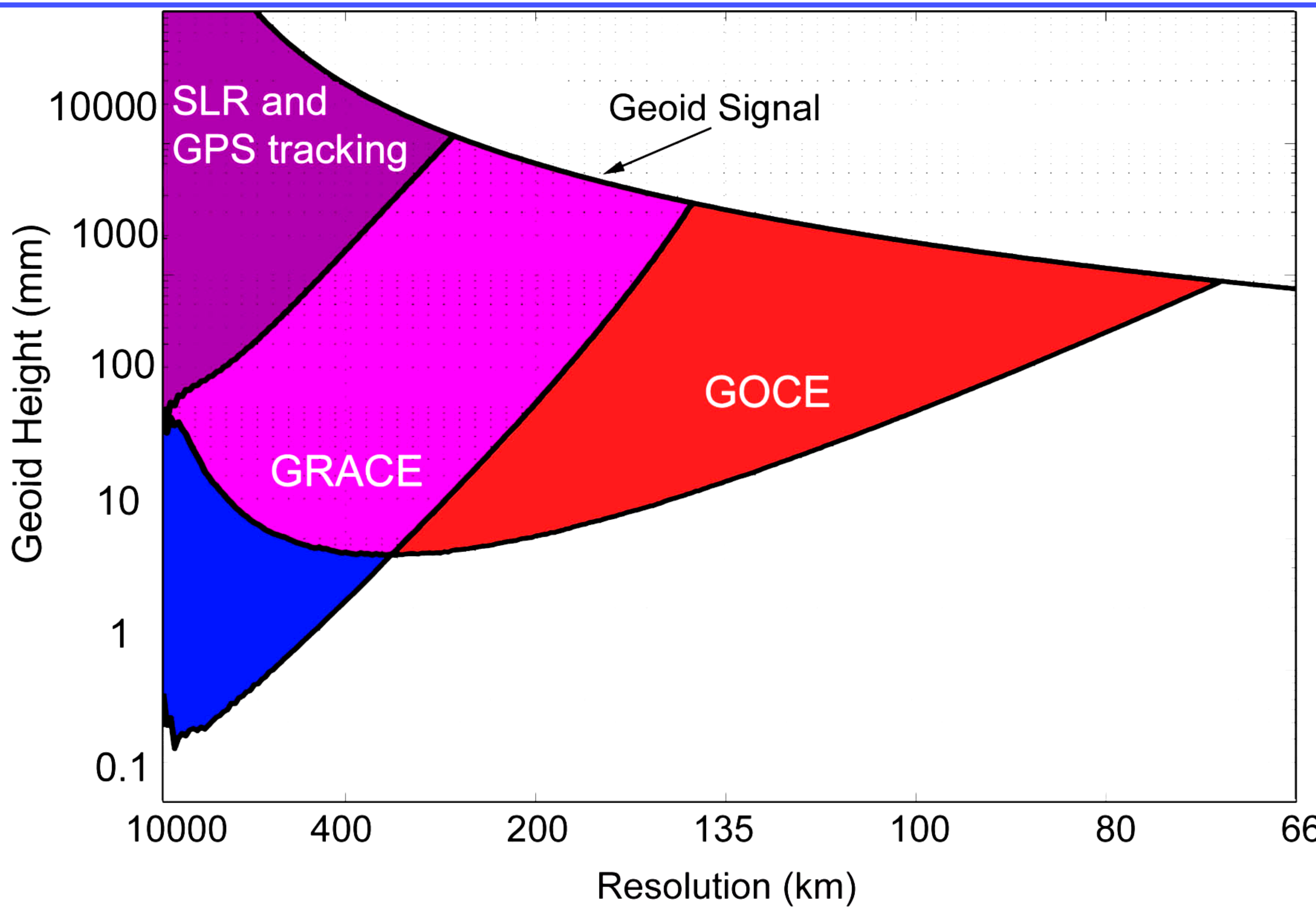
- The planning of geopotential mapping missions raises the need for a high degree and order *a priori* model

- Starting with the highly successful models for T/P, a new effort is launched by a group of agencies to develop the most accurate and detailed model for terrestrial gravity and the geoid

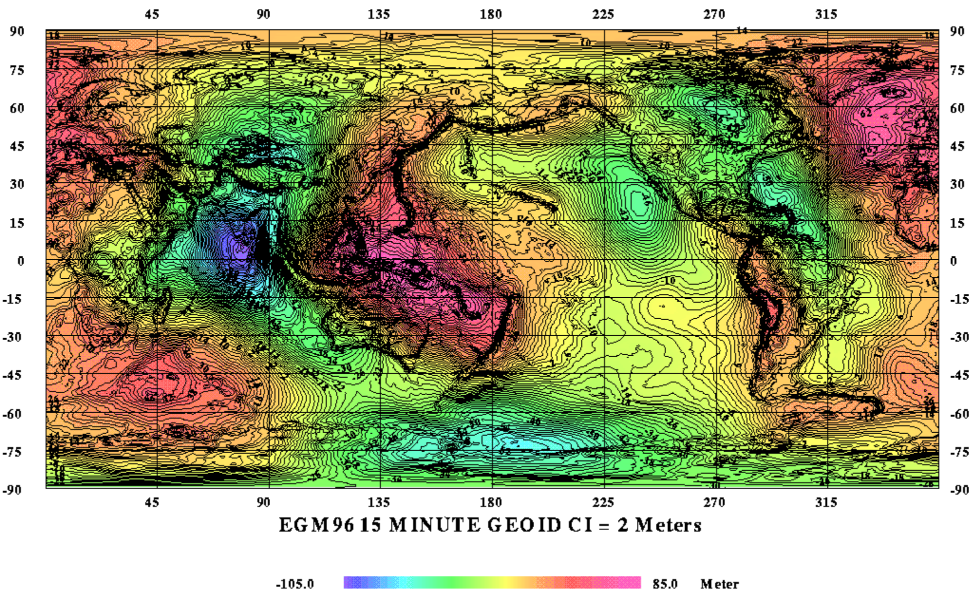
- SLR data play a major role and contribute the most accurate space geodetic data in large amounts covering a very long period of time and many orbital configurations

- The result was EGM96, twenty years after the launch of LAGEOS and soon after the sister s/c LAGEOS-2 was successfully launched through a collaboration of NASA and the Italian Space Agency (ASI)

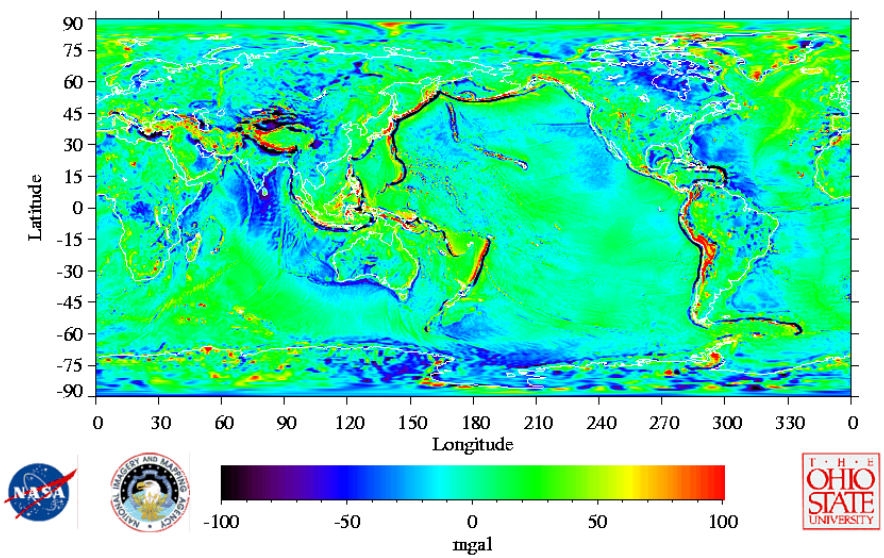
SLR: Still Important in the era of GRACE, GOCE, etc.



Gravity Modeling: EGM96



30’ Mean Gravity Anomalies: EGM96 (Nmax=360)



NASA/TP—1998–206861

The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96

F.G. Lemoine, Laboratory for Terrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD

S.C. Kenyon, J.K. Factor, and R.G. Trimmer, National Imagery and Mapping Agency, St. Louis, MO

N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S.B. Luthcke, M.H. Torrence, Y.M. Wang, and R.G. Williamson, Raytheon STX Corporation, Lanham, MD

E.C. Pavlis, Joint Center for Earth Systems Technology, University of Maryland, Baltimore County, and NASA Goddard Space Flight Center, Greenbelt, MD

R.H. Rapp, Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, Columbus, OH

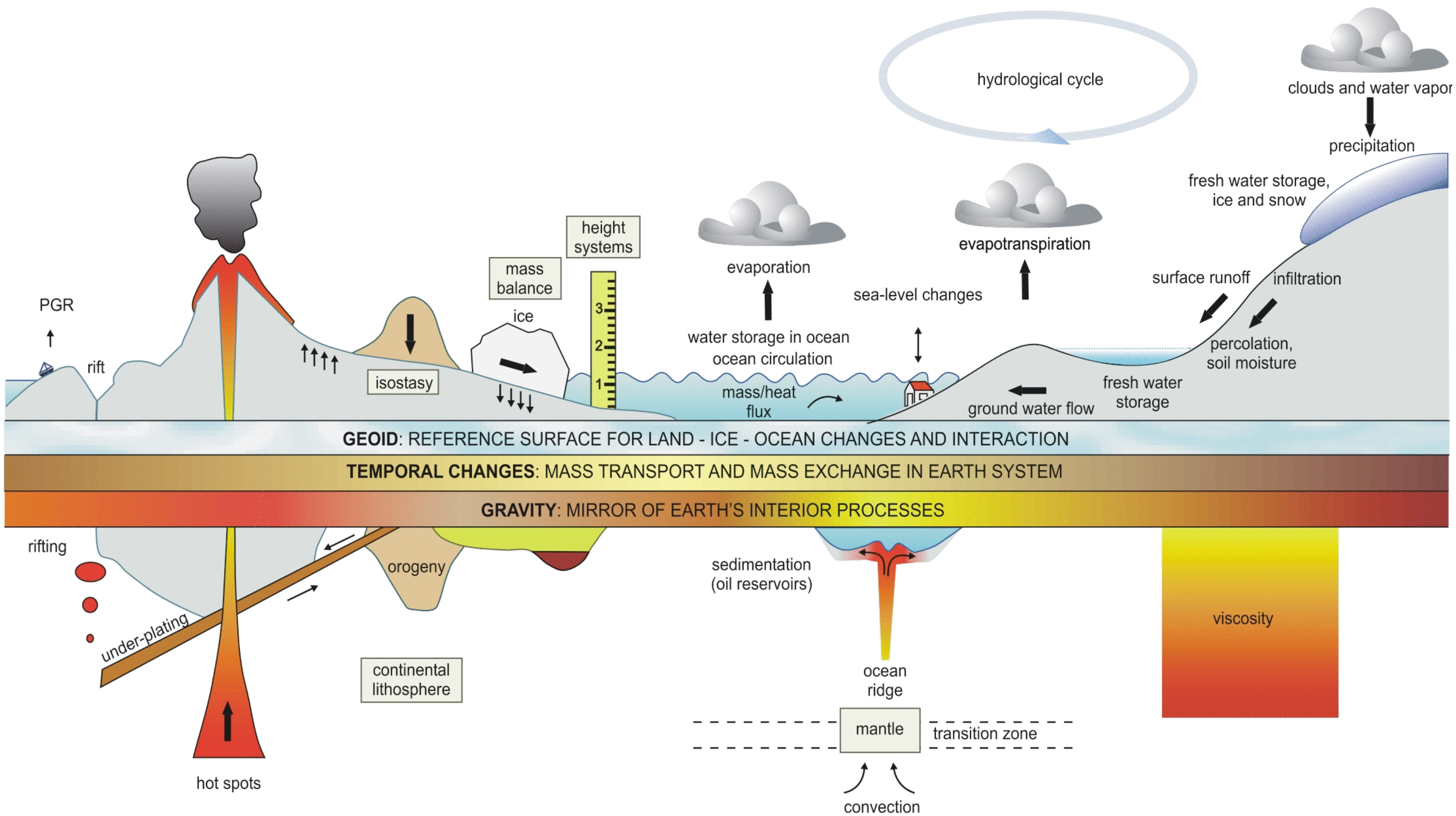
T.R. Olson, Colorado Center for Astrodynamics Research, University of Colorado, Boulder, CO

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

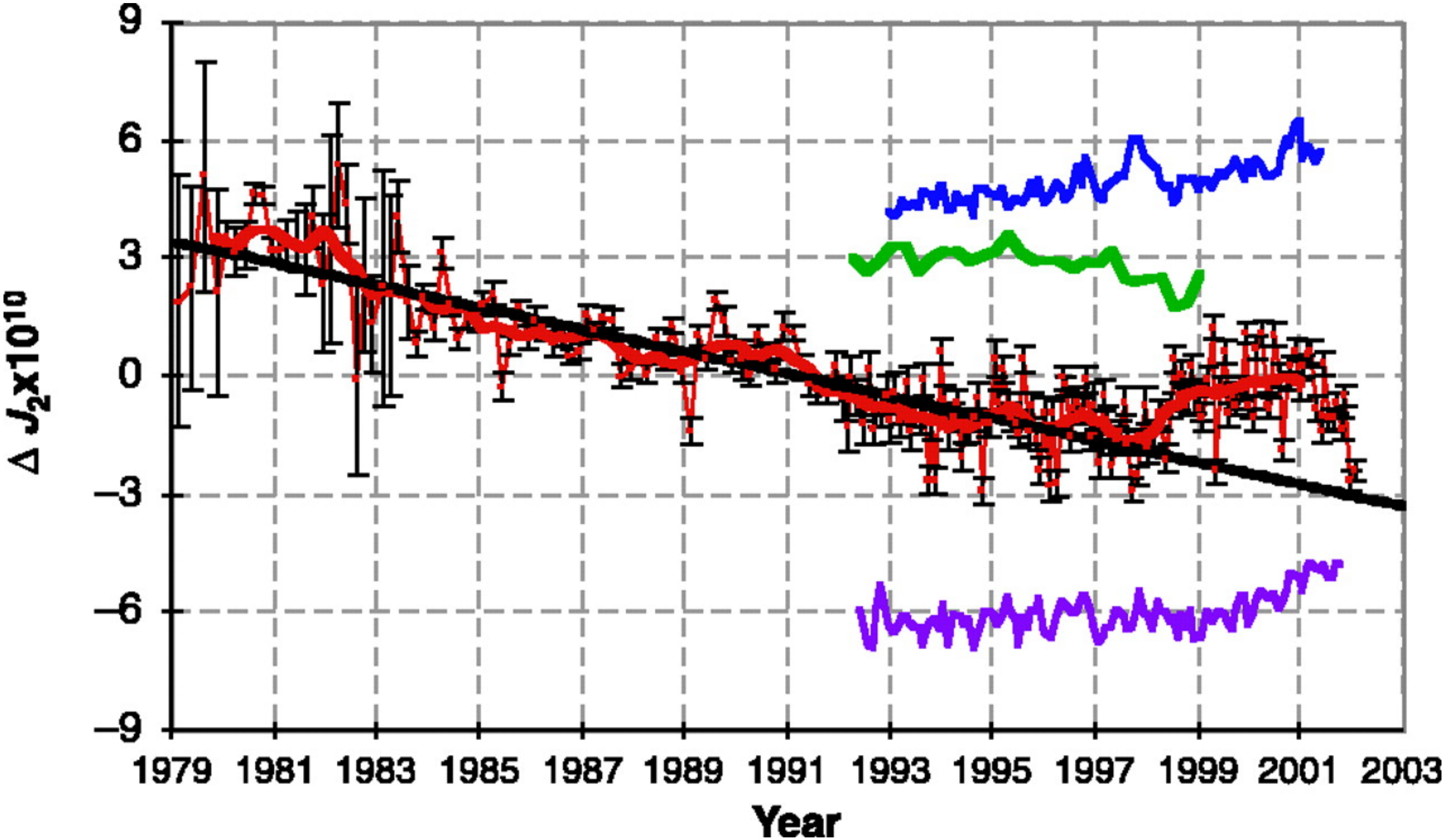
July 1998

Mass Transport in the Earth System



Ilk et al. (2005)

J_2 Variations from SLR (Cox & Chao 2002)



C M Cox, B F Chao Science 2002;297:831-833

Figure 2 Observed J 2, after subtraction of the IB-corrected atmospheric signal and an empirical annual term before (thin red line) and after (heavy red line) an annual filter has been applied.

Laser Ranging Contributions Today

- **International Terrestrial Reference Frame:**
  - Defines the origin of the ITRF
  - Contributes to determining scale of TRF
- **Global Gravity Modeling:**
  - SLR first determined the existence of temporal gravity variations
  - SLR provides the longest series of temporal variations in terrestrial gravity from space-geodetic techniques
  - Despite several geopotential mapping missions, SLR today provides the most accurate series of *2nd* degree variations
- **Earth Rotation:**
  - SLR/LLR EOP series are the longest from space-geodetic techniques
  - SLR/LLR provide the most accurate series available for studying decadal variations
  - Due to being the longest, SLR/LLR series form the basis for EOP series combination from multiple techniques
- **POD:**
  - Large number of missions, growing with exponential rate (GNSS !!!)

International Terrestrial Reference Frame

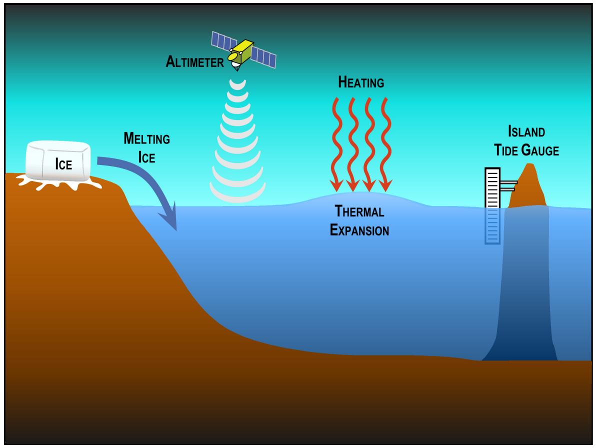
GGOS Goal:

<1 mm reference frame accuracy

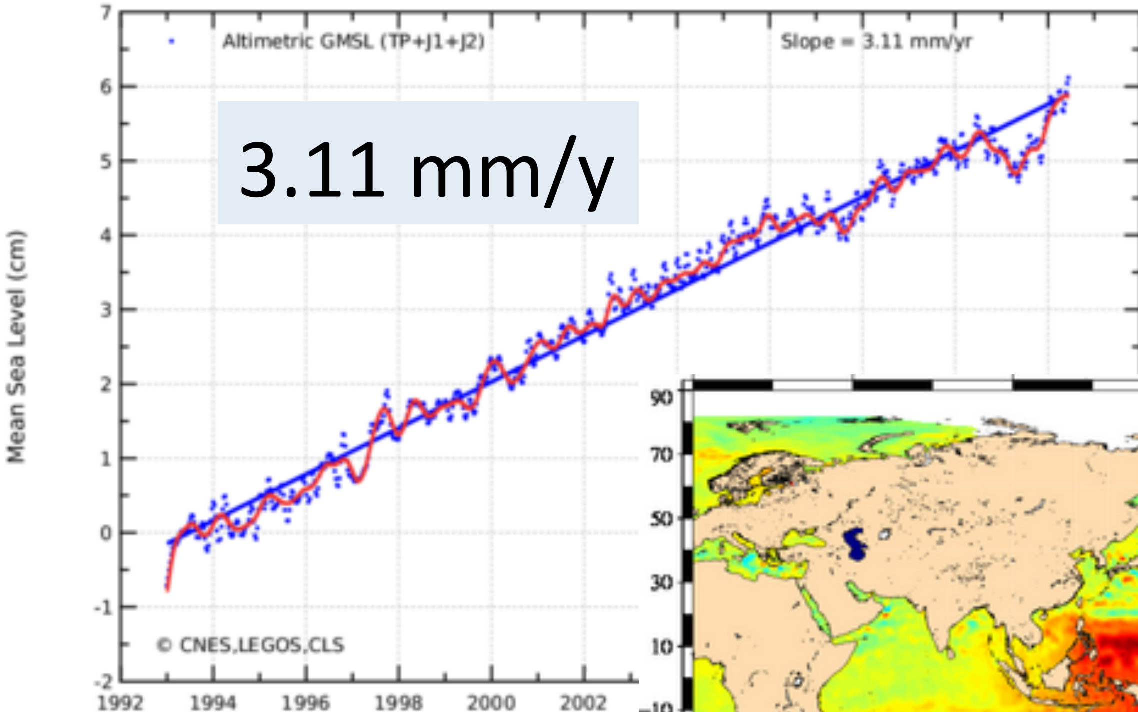
< 0.1 mm/y stability

Improvement over current ITRF performance by a factor of 10-20!

Measurement of sea level change is the primary science driver

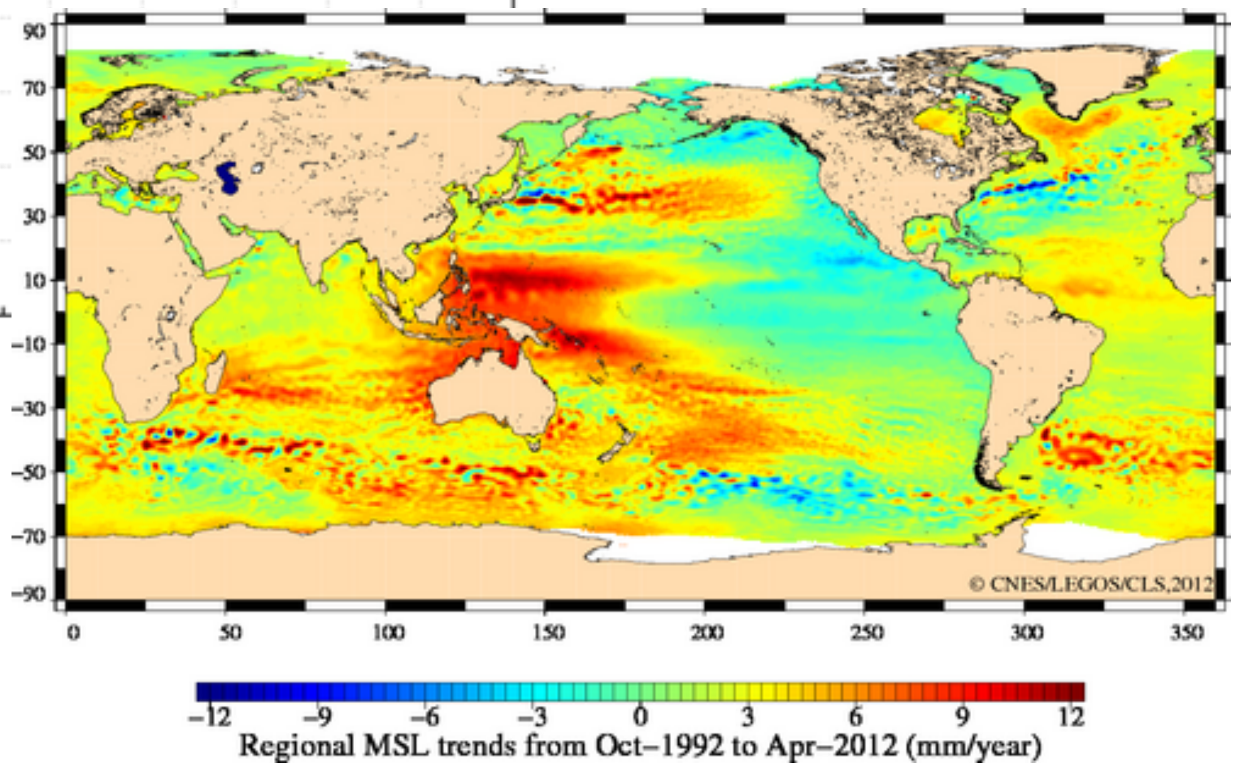


Global MSL Change – The driver



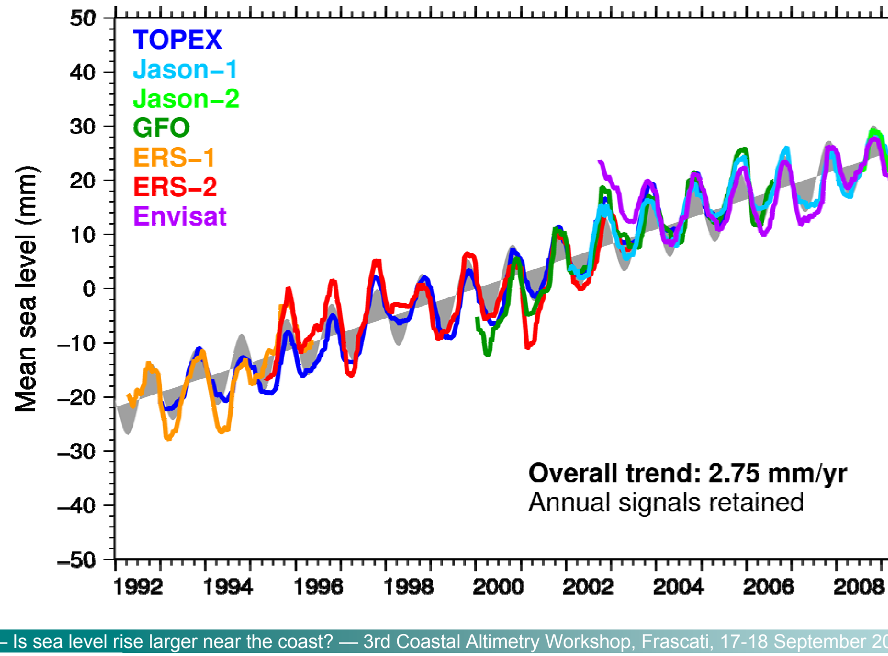
3.11 mm/y

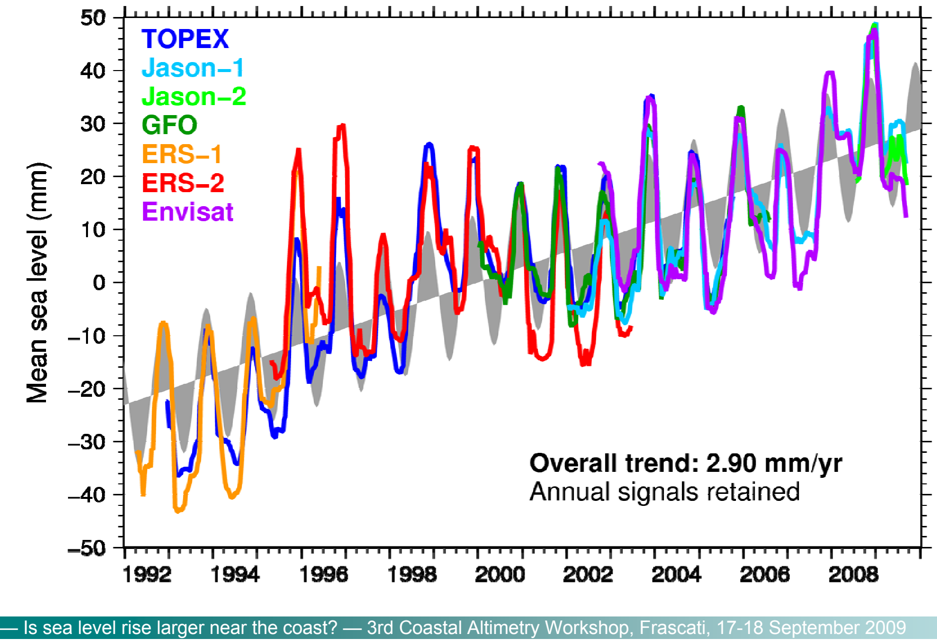
Regional rates: ± 12 mm/y



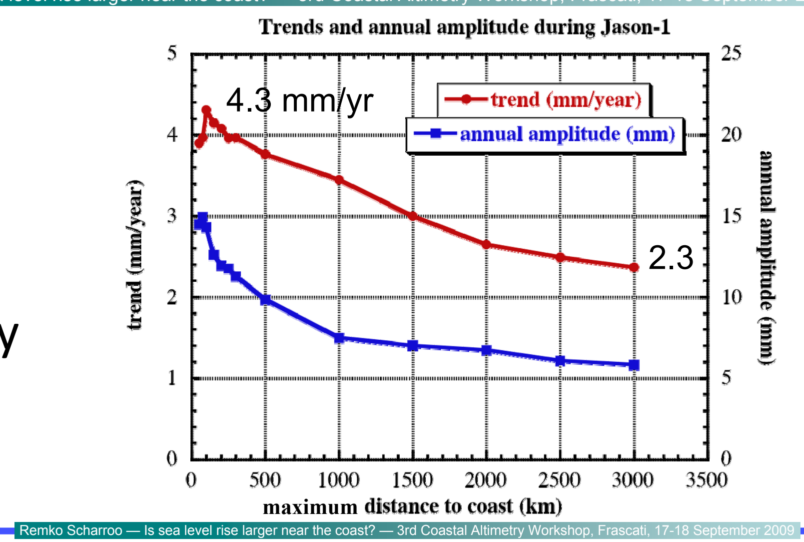
Globally averaged rate: ~3 mm/y

Coastal Effects: Huge Societal Impact



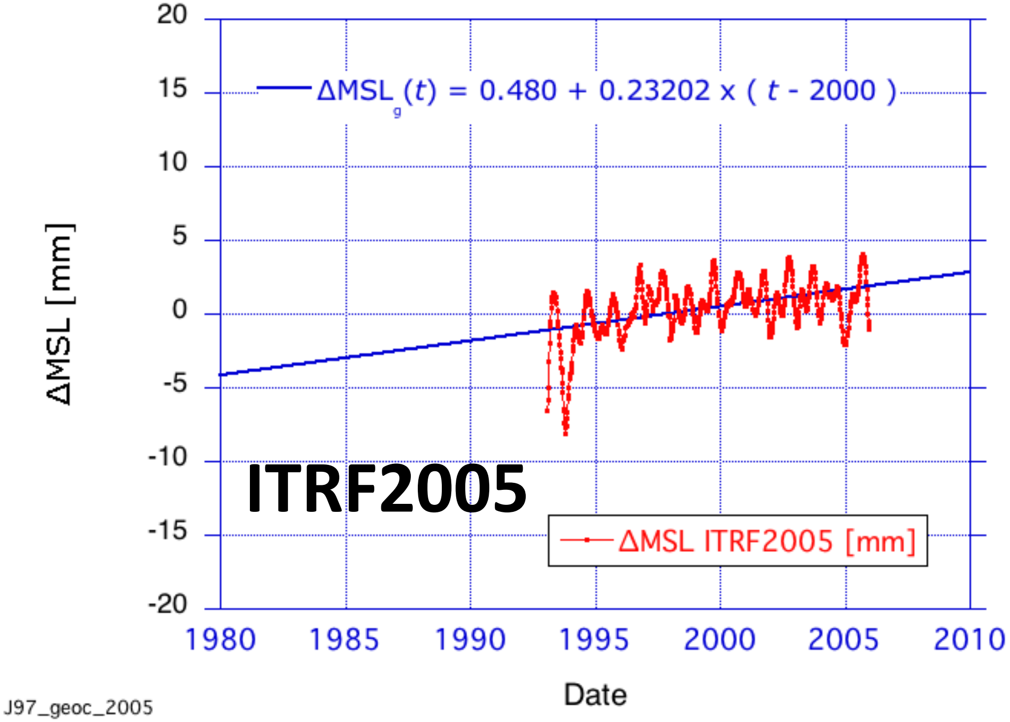


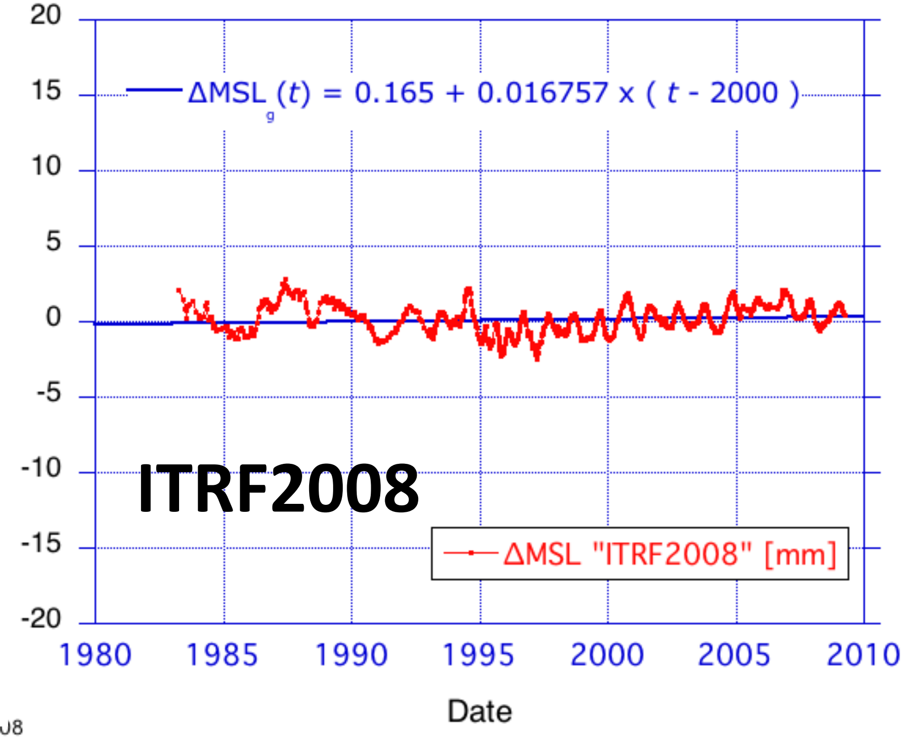
- MSL linear rate not much different near coastal areas: 2.75 mm/y vs. 2.90 mm/y
- Annual variations though are significantly enhanced near the coasts (<200 km), as much as 2 mm/y !!!



MSL Rate Differences Due to TRF Error

Mapping the Error in the Z-axis Rate of the ITRF onto the MSL Rate





ITRF2005 used SLR data over 1993 - 2004

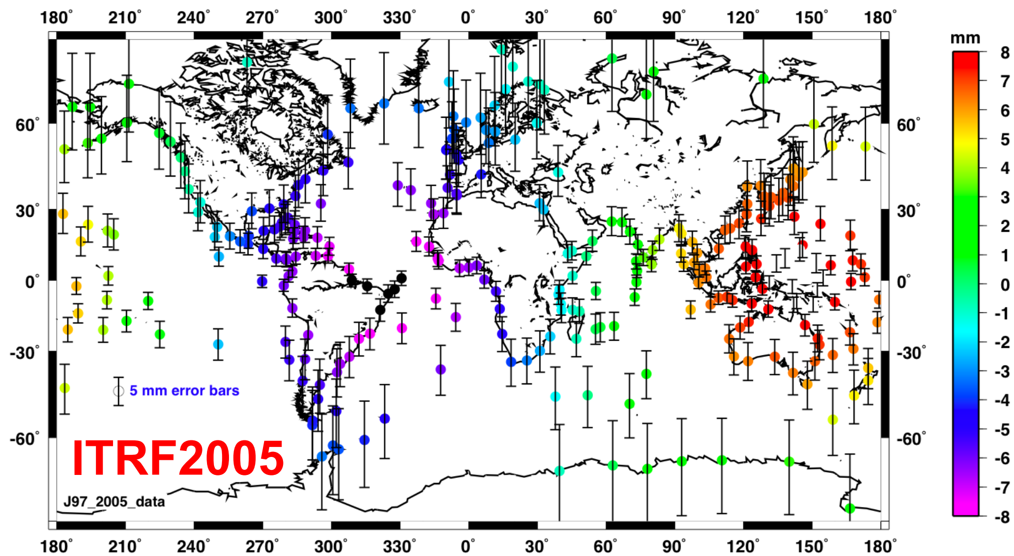
Rate bias: **0.232 mm/y**

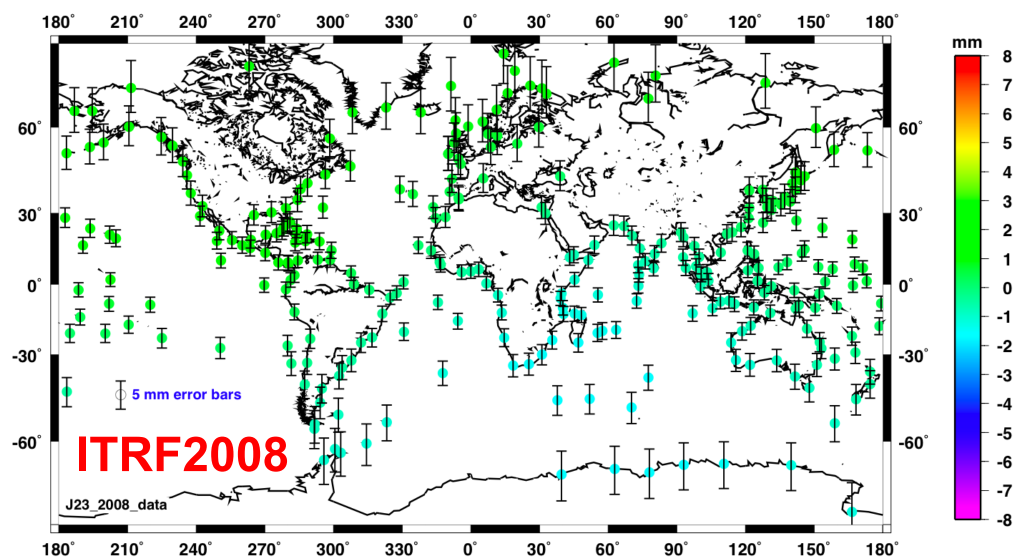
ITRF2008 used SLR data over 1983 - 2008

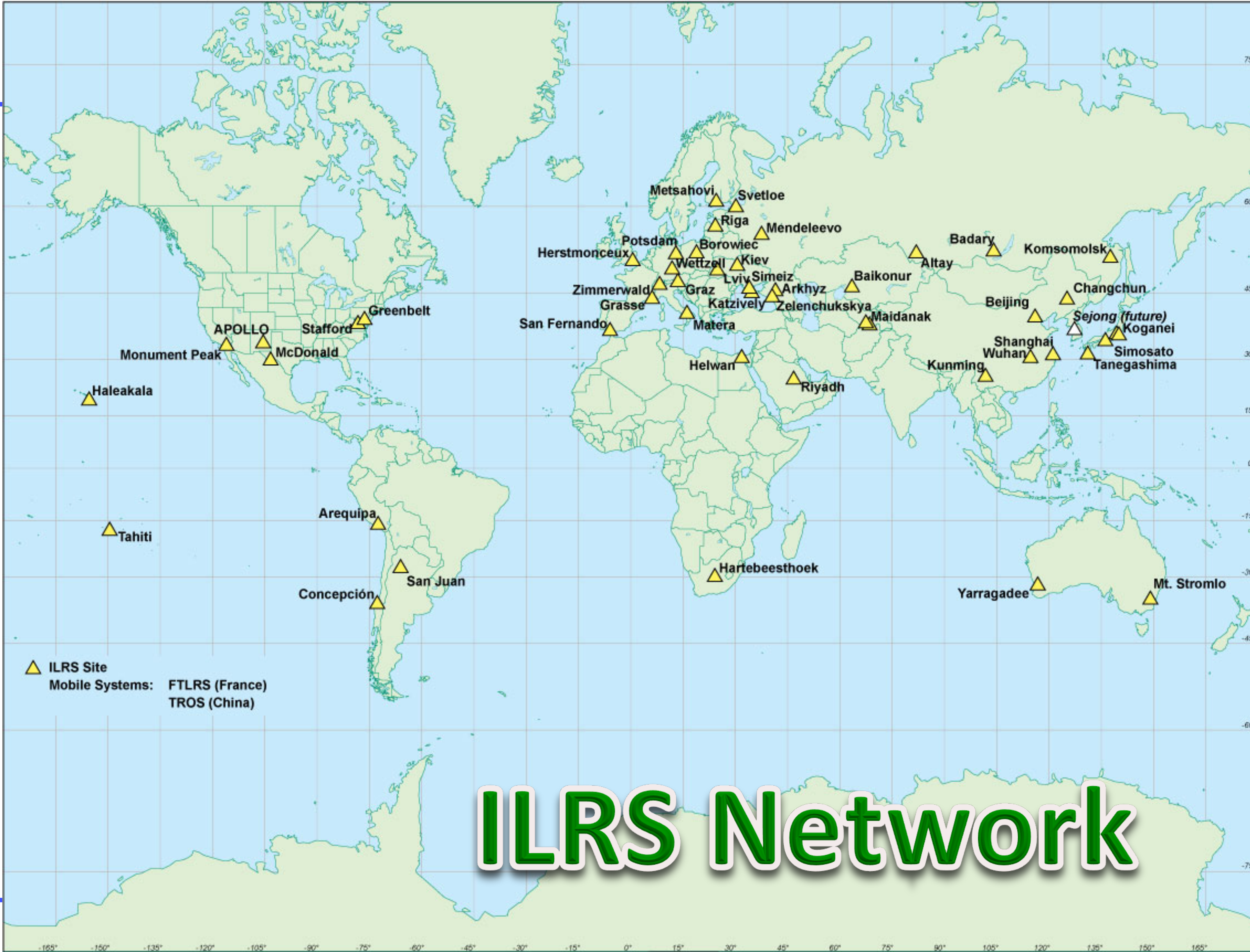
Rate bias: **0.017 mm/y**

Geocenter Error on GLOSS TG Network

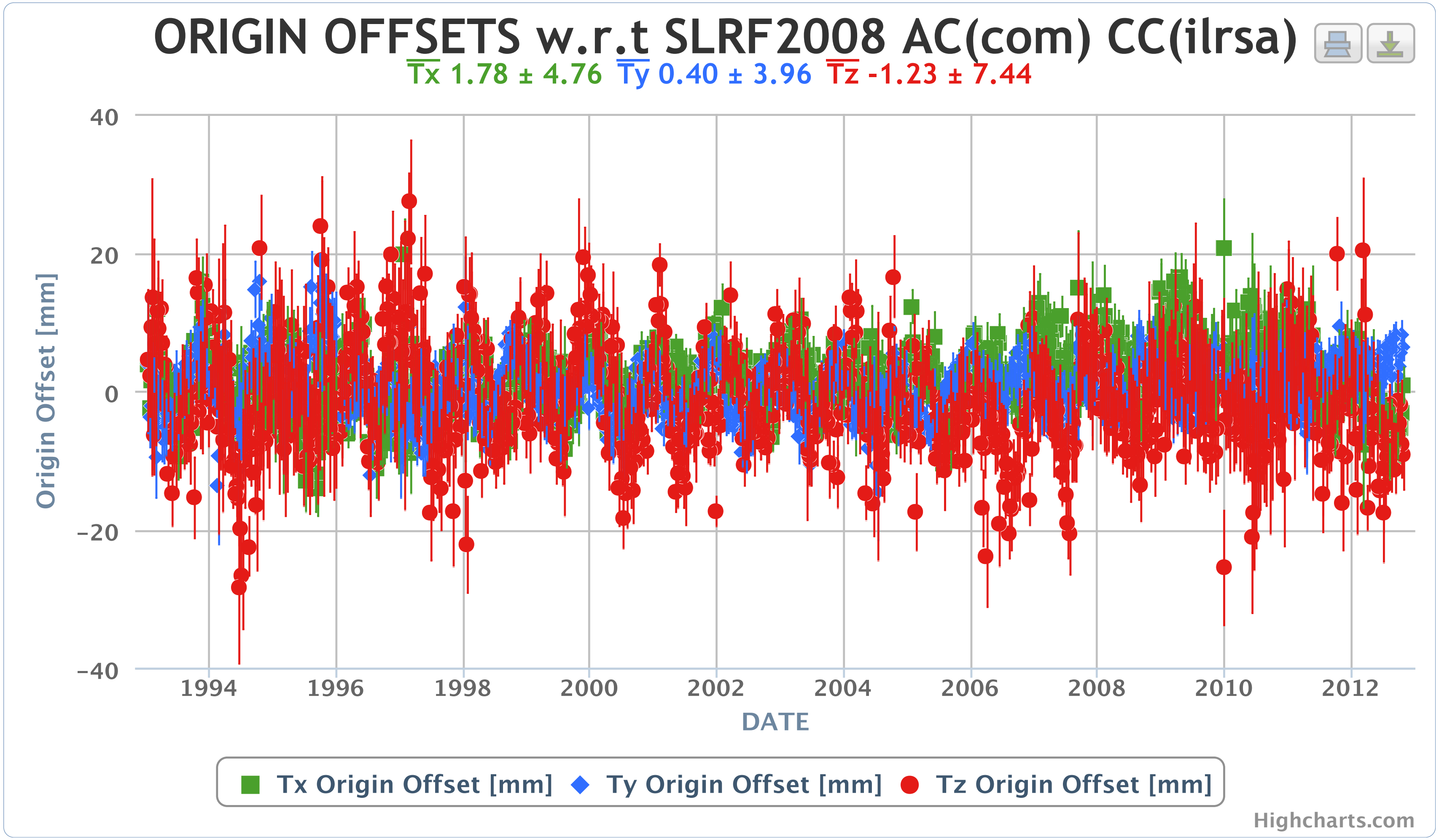
- MSL rate bias noted by color of site marker
- Noise increase shown by error bars
- Top figure is for ITRF2005, bottom is for ITRF2008



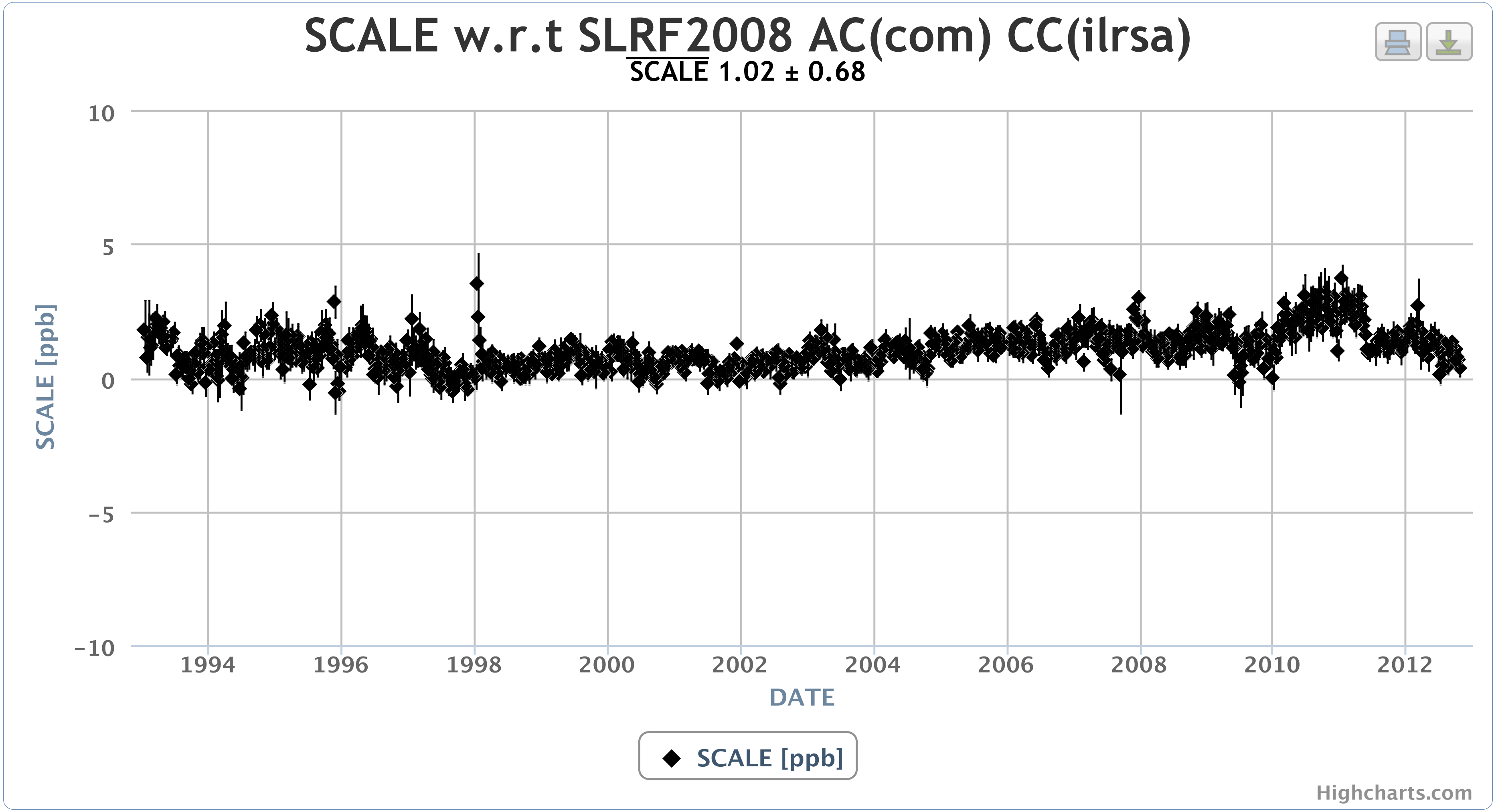



ILRS Network
Metsahovi
Svetloe
Riga
Mendeleevo
Potsdam
Borowiec
Herstmonceux
Wettzell
Kiev
Lviv
Simeiz
Zimmerwald
Graz
Arkhyz
Grasse
Katzively
Zelenchukskya
San Fernando
Matera
Baikonur
Maidanak
Altay
Badary
Komsomolsk
Changchun
Beijing
Sejong (future)
Koganei
Shanghai
Wuhan
Simosato
Tanegashima
Kunming
Helwan
Riyadh
Greenbelt
Stafford
APOLLO
Monument Peak
McDonald
Haleakala
Tahiti
Arequipa
San Juan
Concepción
Hartebeesthoek
Yarragadee
Mt. Stromlo
ILRS Site
Mobile Systems: FTLRS (France)
TROS (China)

TRF Origin from Official ILRS Series



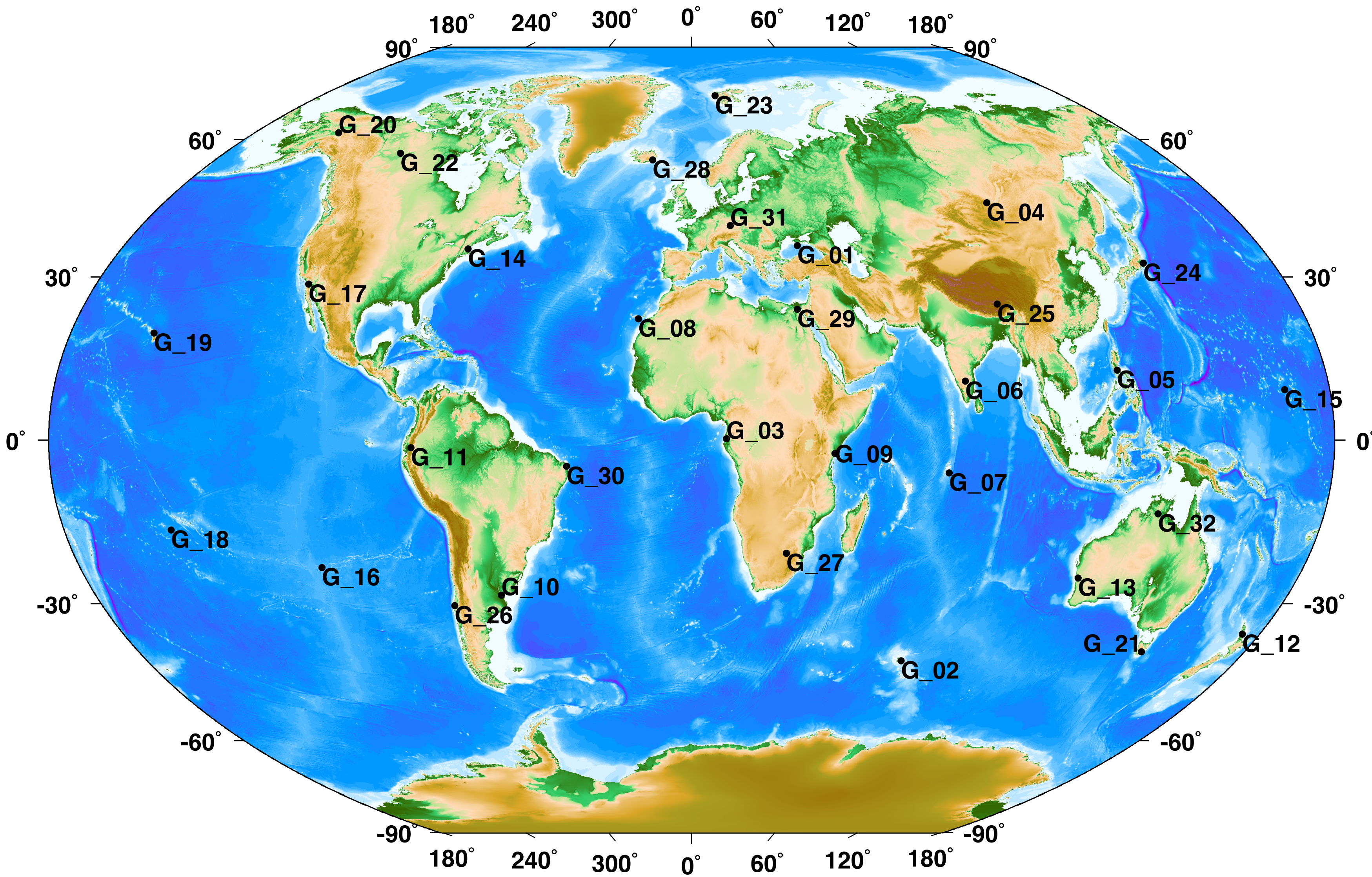
TRF Scale from Official ILRS Series



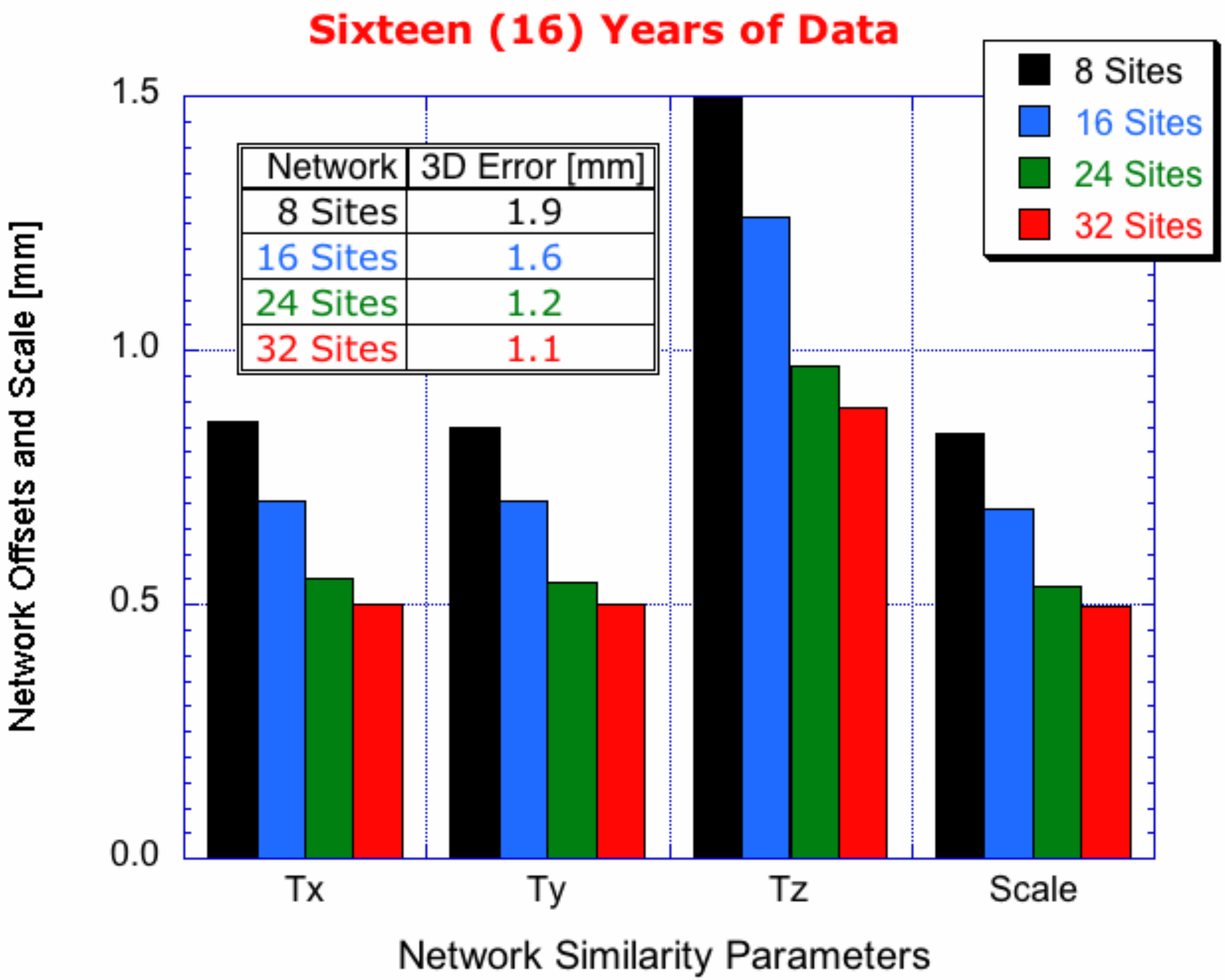
Future TRF Requirements

- SLR uniquely defines the origin of the TRF and in part its scale, with a required accuracy of 1 mm and a stability of 0.1 mm/y in case of the GGOS network
  - For a GGOS-class network with a reasonably global and uniform distribution of stations, we can achieve this if we assume that:
    - All 24-32 sites are equipped with SLR systems that can track 24/7 with efficient target interleaving capability, NP precision of 1 mm and systematic errors limited to a few mm, stable over time intervals on the order of weeks
    - The targets we used were LAGEOS-1 and LAGEOS-2, with the assumption that the CoM offset error is negligible (single photon systems)

Simulations Network (32 sites)



GGOS Network Simulation Results

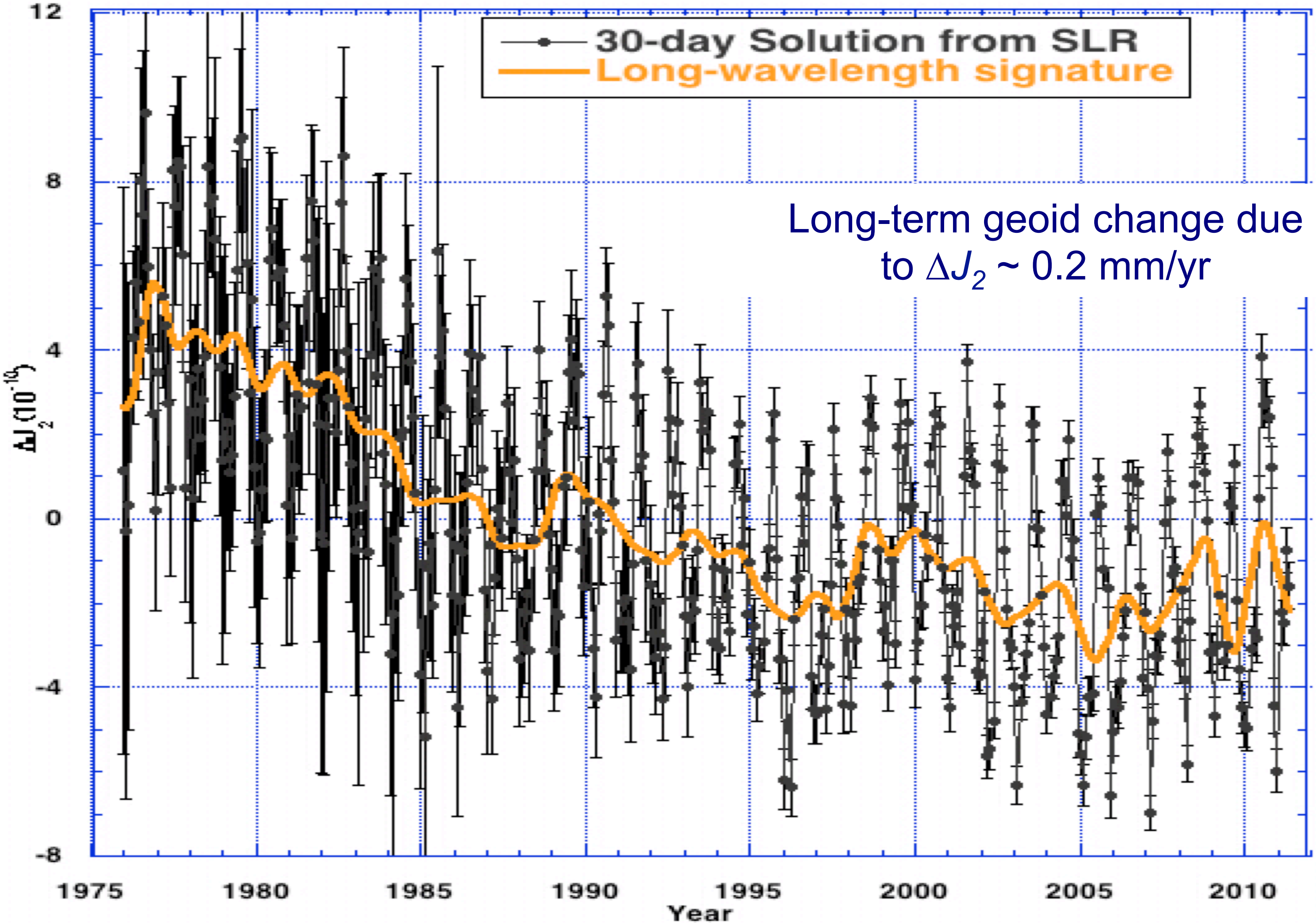


Global Gravity Modeling

Temporal Gravity Variations

- Despite the exceptional results from GRACE and recently from GOCE, SLR plays still an important role in this area, especially in monitoring temporal variations for the very low degree (long wavelength) part of the model
- Temporal variations have a rich spectrum from secular down to few hours or even less, so missions like GRACE with a limited history (2002 to present) are not sufficient to provide such observations
- Furthermore, in case of a mission failure, SLR will be able to fill the gap until a new mission is launched at least for the most significant part of the spectrum
- Even today, the GRACE project provides SLR-derived J_2 values in place of what GRACE observes since they are far more accurate

J_2 Variations from SLR (Cheng, 2012)



Observed **J_2 variations from SLR data analysis to multiple geodetic satellites [M. Cheng, 2012]**.

Static Gravity Contribution

- Missions like GOCE, have even less sensitivity at the longest wavelengths, it is thus absolutely necessary to have other techniques provide that information
- Possible providers of such information are SLR and GNSS receivers onboard LEO s/c with well-defined dynamical models or instrumented with accurate accelerometers
- SLR will remain the optimal technique for improving GM and terrestrial scale
- Continue observations of tidal dissipation

International Laser Ranging Service

Fundamental Physics Tests

IAG GGOS

» Look Inside   » Get Access

The European Physical Journal Plus
November 2012, 127:133

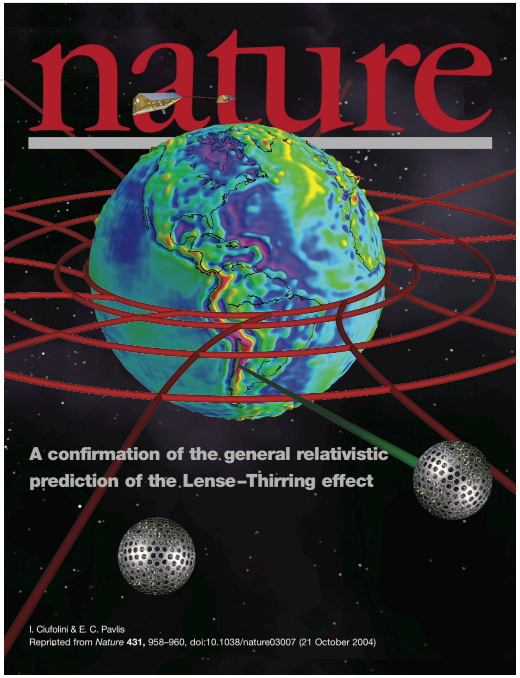
Testing General Relativity and gravitational physics using the LARES satellite

Ignazio Ciufolini, Antonio Paolozzi, Erricos Pavlis, John Ries, Vahe Gurzadyan, Rolf Koenig, Richard Matzner, Roger Penrose, Giampiero Sindoni

» Look Inside   » Get Access

Abstract

The discovery of the accelerating expansion of the Universe, thought to be driven by a mysterious form of "dark energy" constituting most of the Universe, has further revived the interest in testing Einstein's theory of General Relativity. At the very foundation of Einstein's theory is the geodesic motion of a small, structureless test-particle. Depending on the physical context, a star, planet or satellite can behave very nearly like a test-particle, so geodesic motion is used to calculate the advance of the perihelion of a planet's orbit, the dynamics of a binary pulsar system and of an Earth-orbiting satellite. Verifying geodesic motion is then a test of paramount importance to General Relativity and other theories of fundamental physics. On the basis of the first few months of observations of the recently launched satellite LARES, its orbit shows the best agreement of any satellite with the test-particle motion predicted by General Relativity. That is, after modelling its known non-gravitational perturbations, the LARES orbit shows the smallest deviations from geodesic motion of any artificial satellite: its residual mean acceleration away from geodesic motion is less than \ensuremath$0.5 \times 10^{-12}$ m/s^2. LARES-type satellites can thus be used for accurate measurements and for tests of gravitational and fundamental physics. Already with only a few months of observation, LARES provides smaller scatter in the determination of several low-degree geopotential coefficients (Earth gravitational deviations from sphericity) than available from observations of any other satellite or combination of satellites.



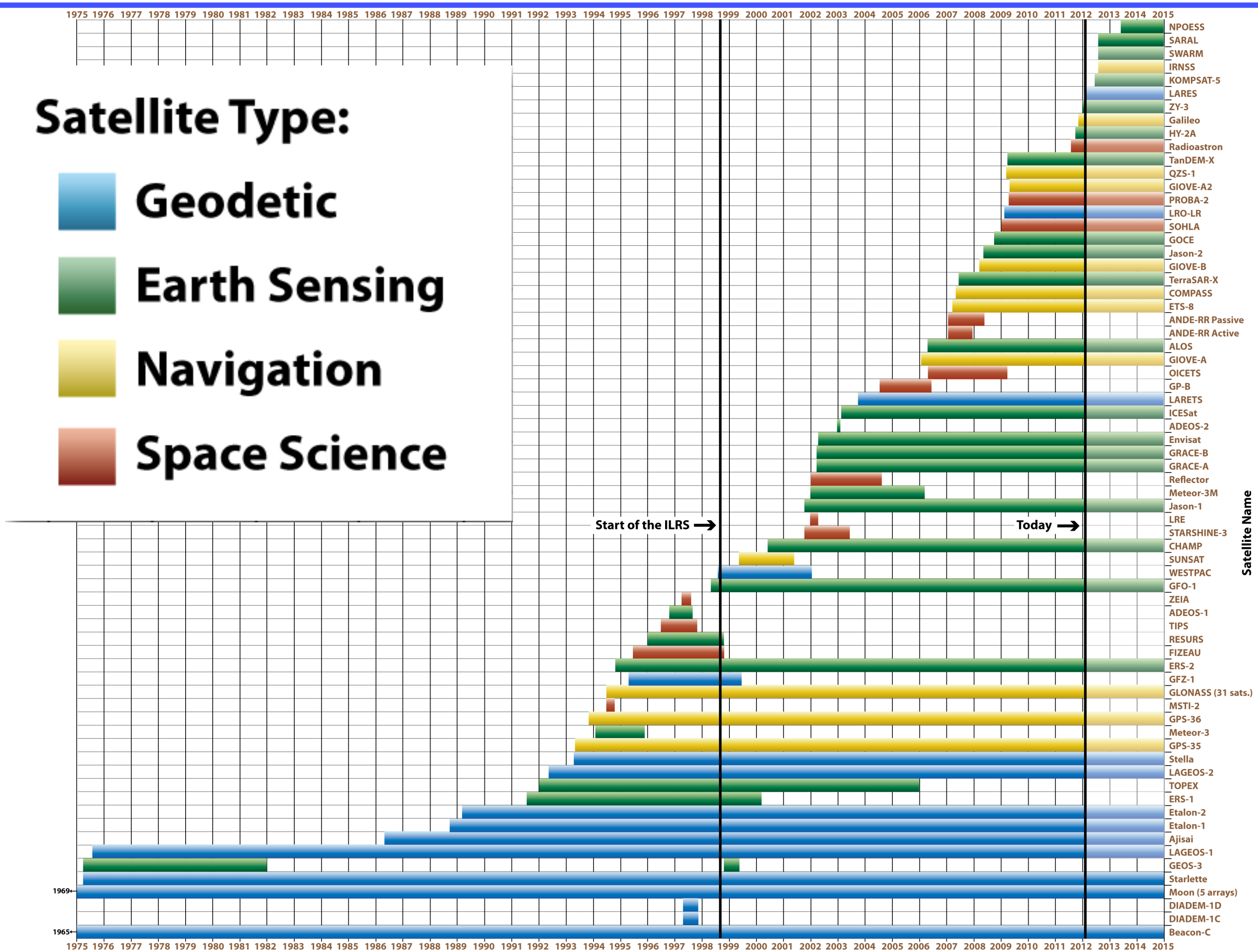
Earth Rotation

Earth Rotation Observations

- SLR should continue to provide EOP observations since there is a need for accurate observations with minimal latency for prompt forecast development by USNO and other users
- As the "SLR Constellation" of geodetic satellites grows, we will soon be able to benefit from improved geometry and averaging of modeling errors so that the SLR EOP product improves in accuracy as well
- The future need to track GNSS for POD and calibration purposes, will have as side benefit the dramatic increase of observed orbits, with further benefits as mentioned above
- The improved network geometry and tracking HEO targets results also in similar benefits

Precision Orbit Determination

Missions Supported by SLR POD



POD

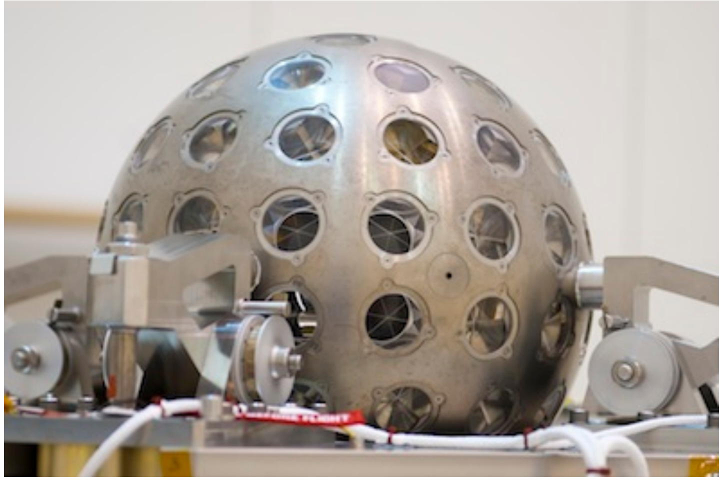
- The low cost, size, mass and passive nature of LRAs makes them very attractive means for Precision Orbit Determination for many missions, either as the primary or the backup one
- SLR has "saved" missions where the primary (and only other) POD system failed, saving both the cost of replacing the s/c and the loss of the science to be generated from the mission
- The future need to track GNSS for POD and calibration purposes, will place tremendous pressure on the network and operations, although at the same time will provide significant returns in scientific products
- SLR tracking of s/c equipped with other positioning techniques will help realize the "ties in space" between the reference frames defined by each of these techniques separately
- Stations with dual capability of SLR and LLR will contribute to the tie of the ITRF with the dynamical realization of the ICRF

The Future LR Ground Network

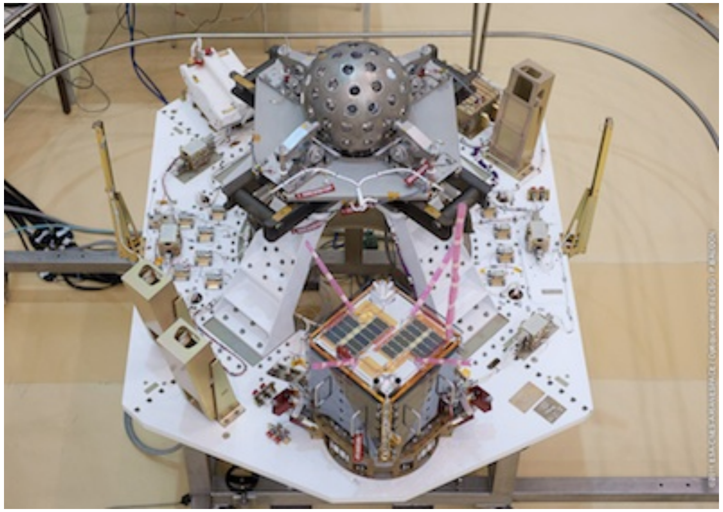
- The future network should seriously address the shortcomings of the current one, especially the poor spatial distribution and the lack of co-locations with the other space geodetic techniques
  - At a minimum 24-32 (CORE) sites with global distribution
- The systems should be designed to be as uniform as possible, recognizing that very few will be replicas of a single design, and fulfill the operational and accuracy specifications that were assumed for GGOS-class systems
- Recognizing that the future list of client missions will be much longer than the one we have today, it is certain that there will be need for more than the CORE sites, and these should be by design co-located with GNSS
- We will need additional sites with lunar capability in order to realize a stronger tie between the ITRF and D-ICRF as an independent check (from VLBI)

The Future Space Segment for LR

- There are already several space geodetic targets in orbit that due to the low altitude of their orbits are not used in Reference Frame work (although they contribute immensely in gravity modeling)
  - Improved modeling with the help of timely and high resolution information on global geophysical fluids mass transport will help in making these targets useful for TRF work as well

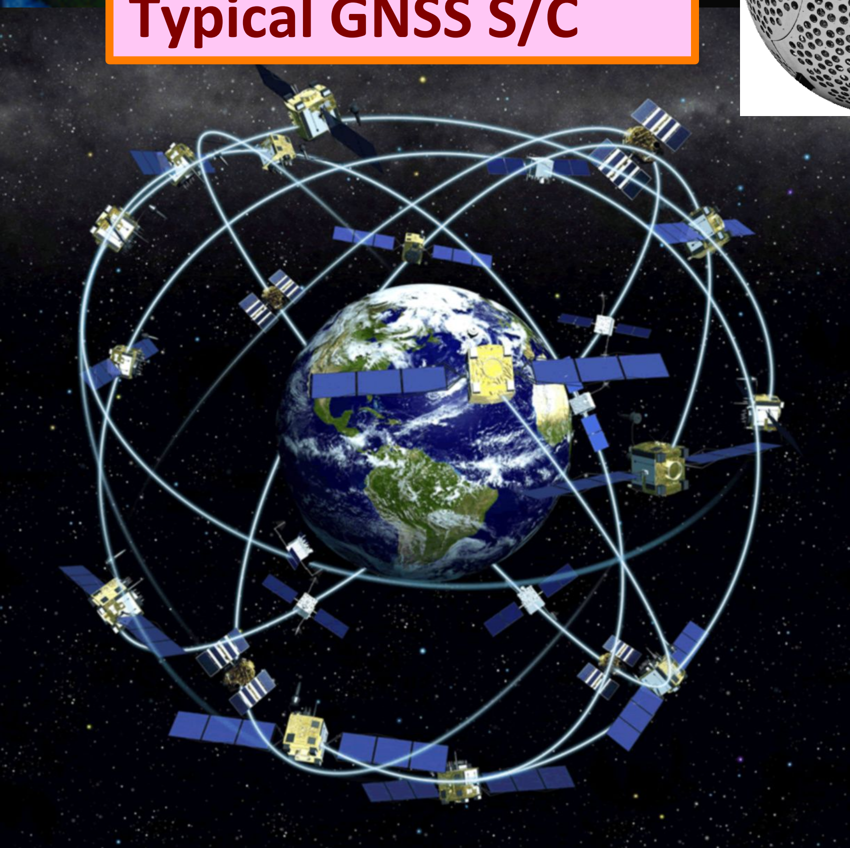


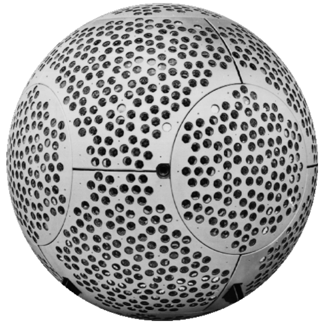
- Launching additional satellites with improved design, such as the recently launched Italian satellite LARES would also help strengthen the geodetic (cannonball) SLR Constellation and provide orbits in additional inclinations to help with gravitational monitoring

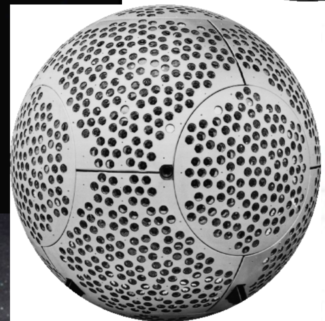


- Any improvement of the present knowledge for s/c already in orbit will be extremely helpful and improve the results from historic as well as future data

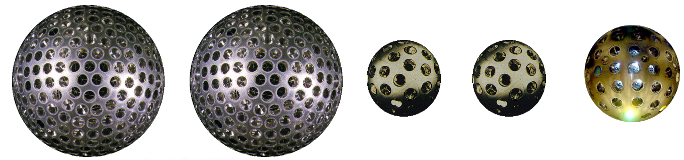
Typical GNSS S/C

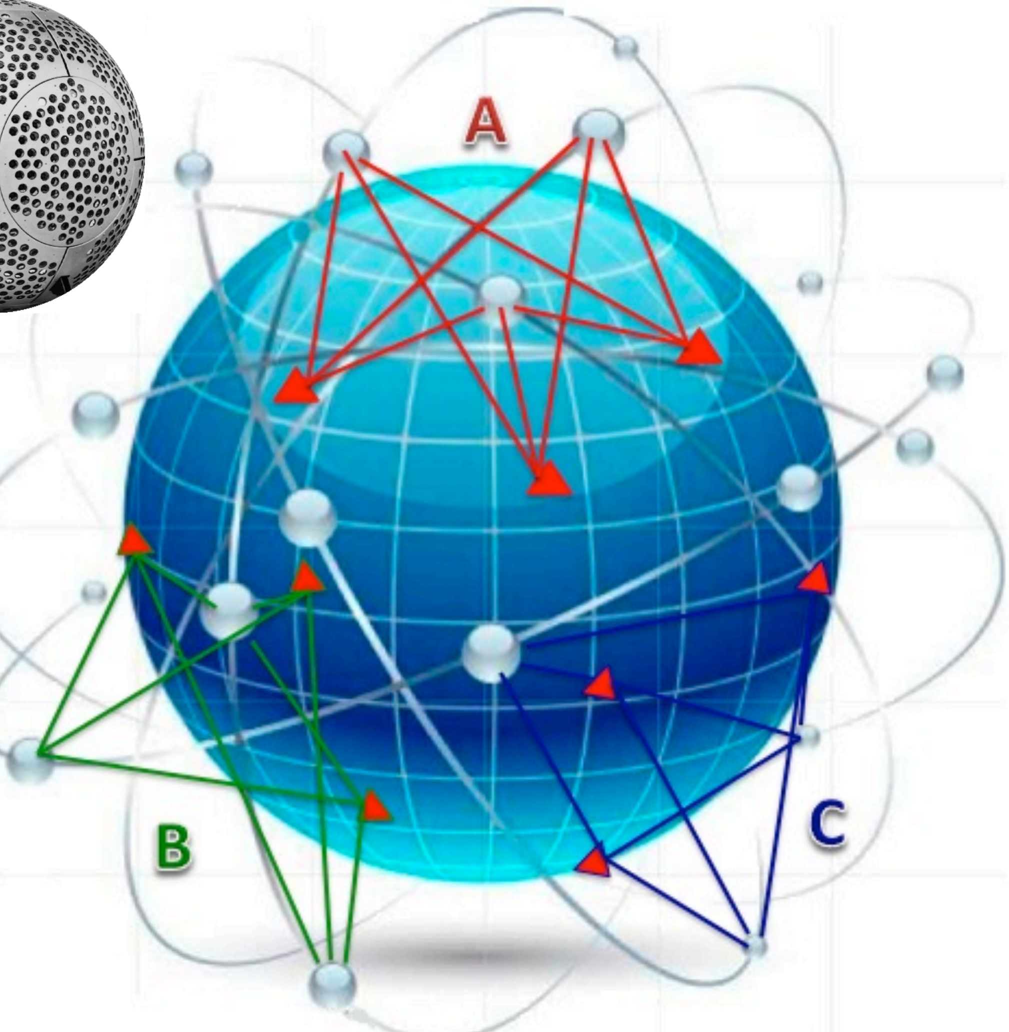






SLR Cannonball S/C





ILRS Network

International Laser Ranging Service

Thank you!