Scientific Contributions of LAGEOS Data

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The LAGEOS Mission

- LAGEOS was designed and launched with geodynamics as the primary objective:
  - *"A satellite which looks like a giant golf ball will be launched by NASA next month into a 5,900-kilometer (3,600-mile) high orbit to serve as a tool for obtaining information on Earth's crustal movements, polar motion, solid Earth tides and precise locations of various spots on Earth. "* [NASA Press Kit, RELEASE NO: 76-67]
- Space Geodesy had just completed a successful 10-yr global program, the "National Geodetic Satellite Program (NGSP) 1964-1974", and everyone wanted a lot more of what had been accomplished through that and at **higher accuracy**:
  - Global station coordinates at ±10 m, gravity models to (15,15), most national datums linked to a geocentric frame, etc.

Mission Objectives

- LAGEOS is the first NASA satellite dedicated exclusively to laser ranging;
- The LAGEOS orbit was intended to be the stable reference to monitor :
  - *the motion of tectonic plates,*
  - *the time-varying behavior of the Earth's polar positions,*
  - *the maintenance of geodetic reference systems,*
  - *the more accurate determination of universal time*
- Ultimately, the intension was *"to contribute to development of an understanding of earthquakes, their origin and the ability to forecast their occurrence."*

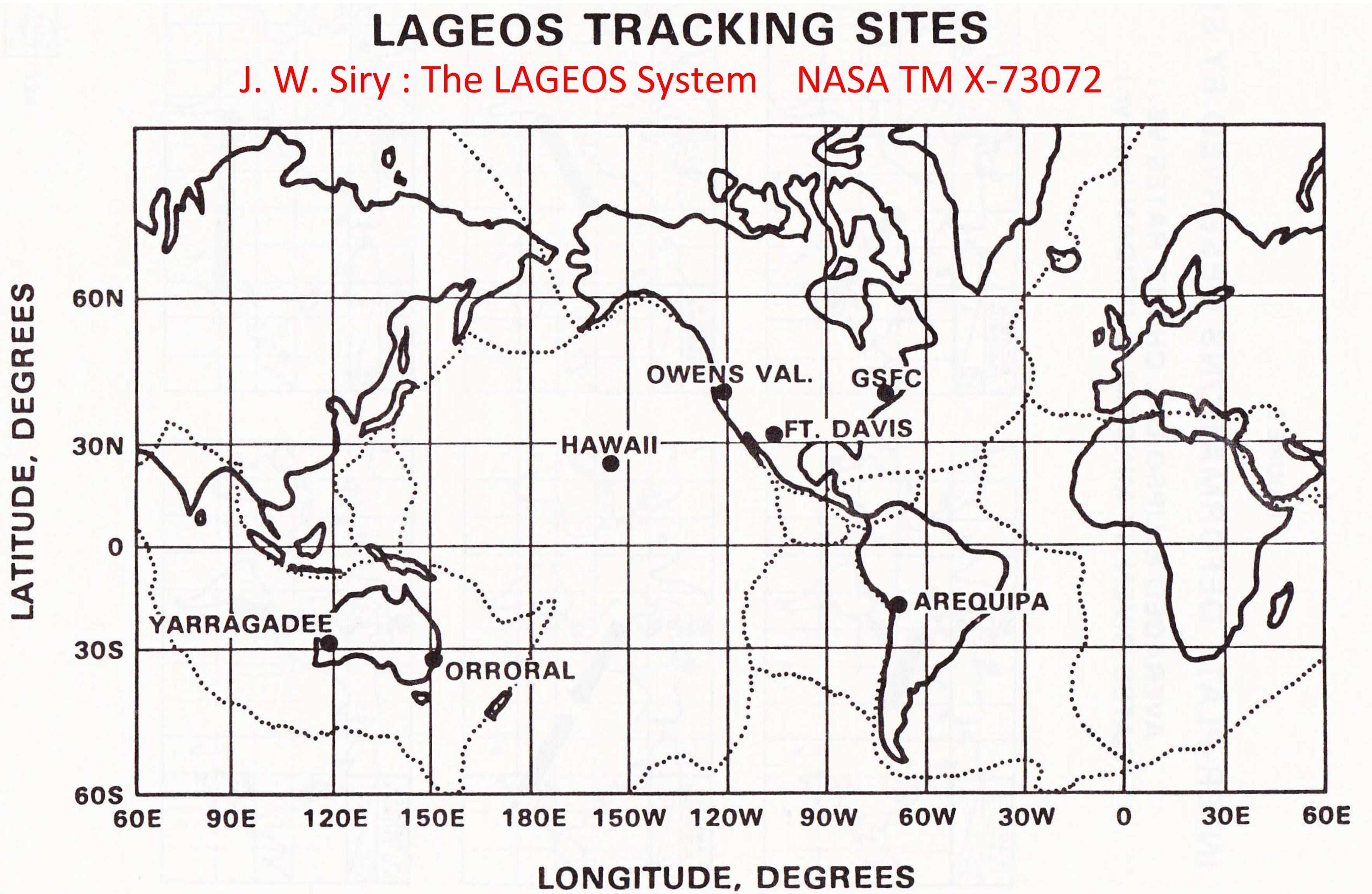
Pre-launch LAGEOS Requirements

MEASUREMENT REQUIREMENTS SUMMARY*

*J. W. Siry : The LAGEOS System NASA TM X-73072

MEASUREMENT	ACCURACY
• CRUSTAL MOTION	1 cm / year
• POLAR MOTION, EARTH ROTATION	2 cm / 0.5 day
• SATELLITE ORBITS	10 cm
• GRAVITY FIELD / GEOID	10 cm
• SEA SURFACE TOPOGRAPHY	10 cm
• SEA STATE / WAVE HEIGHT	1–3 m
• SURFACE WINDS	2–5 m/s
• MAGNETIC FIELD	2 gamma, 0.5 arc min

NASA SLR Network



IAU/IUGG Project MERIT

INTERNATIONAL ASTRONOMICAL UNION

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

Joint Working Group on the Rotation of the Earth

PROJECT MERIT

OBSERVATIONS AND RESULTS OF THE SHORT CAMPAIGN

1980 AUGUST 1 TO OCTOBER 31

August 1 to October 31, 1980

CONTENTS

DRAFT SUBMITTED TO THE 1981 MERIT WORKSHOP

NASA Goddard Laser Network

NASA GODDARD SPACE FLIGHT CENTER LASER NETWORK

LASER LOCATION	SYSTEM NAME	SITE ID	LAT (DEG)	LONG (DEG)	COMMENTS
GREENBELT, MD.	STALAS	7063	39.02	283.17	
PATRICK AFB, FL.	RAMLAS	7069	28.23	279.39	THROUGH SEP
MCDONALD OBS, TX.	TLRS-1	7086	30.68	255.98	TO 80AUG08
YARAGADEE, AUS.	MOBLAS-5	7090	-29.05	115.35	
HAYSTACK, MASS.	MOBLAS-7	7091	42.62	288.51	
KWAJALEIN ATOLL	MOBLAS-8	7092	9.39	167.48	
AMERICAN SAMOA	MOBLAS-6	7096	-14.34	189.28	
GREENBELT, MD.	MOBLAS-4	7102	39.02	283.17	
OWENS VALLEY, CA.	MOBLAS-2	7114	37.23	241.71	
GOLDSTONE, CA.	MOBLAS-3	7115	35.25	243.21	
MAUI, HAWAII	MOBLAS-1	7120	20.71	203.74	
PASADENA, CA.	TLRS-1	7896	34.21	241.83	FROM 80OCT27
GREENBELT, MD.	TLRS-1	7899	39.02	283.18	80AUG22-80OCT08

SAO Laser Network

SMITHSONIAN ASTROPHYSICAL OBSERVATORY LASER SYSTEMS

AREQUIPA, PERU	7907	-16.47	288.51
JRRORAL, AUS.	7943	-35.62	148.95
NATAL, BRAZIL	7929	-5.93	324.84

Other Laser Systems

OTHER OBSERVATORIES

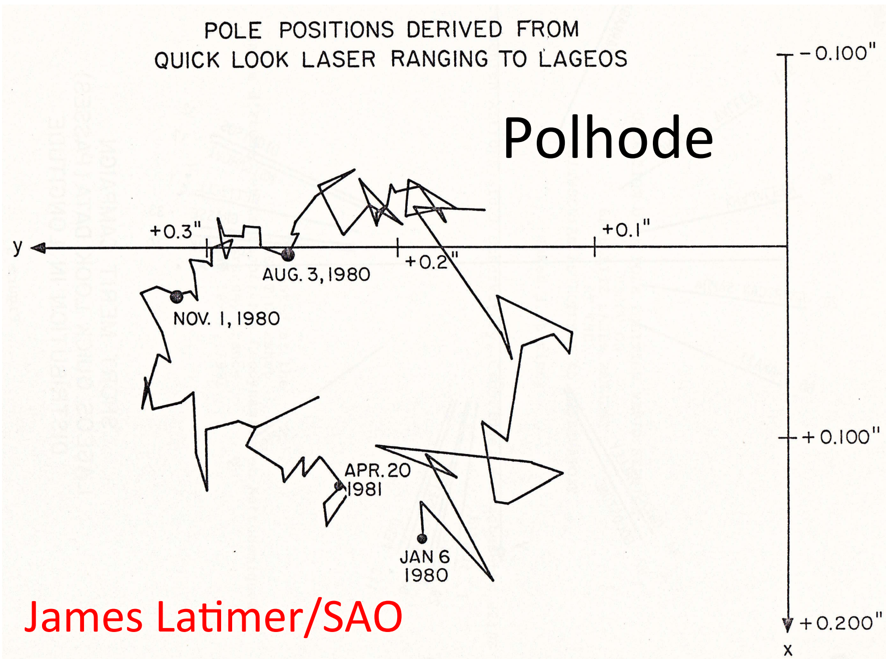
METASAHOVI, FINLAND	7805	60.22	24.39
KOOTWIJK, THE NETHERLANDS	7833	52.18	5.81
GRASSE, FRANCE	7835	43.75	6.92
WETTZELL, WEST GERMANY	7834	49.14	12.88
SHANGHAI, CHINA	7837	31.10	121.19
DIONYSOS, GREECE	7940	38.08	23.93
HELWAN, EGYPT	7801	29.86	31.34

INTERCOSMOS Network

INTERCOSMOS LASER STATIONS

KAVALUR, INDIA	1892
PENC, HUNGARY	1815
POTSDAM, GDR	1181
RIGA, USSR	1884
SIMEIZ, USSR	1873
ZVENIGOROD, USSR	1872

Polar Motion & LOD from LAGEOS



James Latimer/SAO

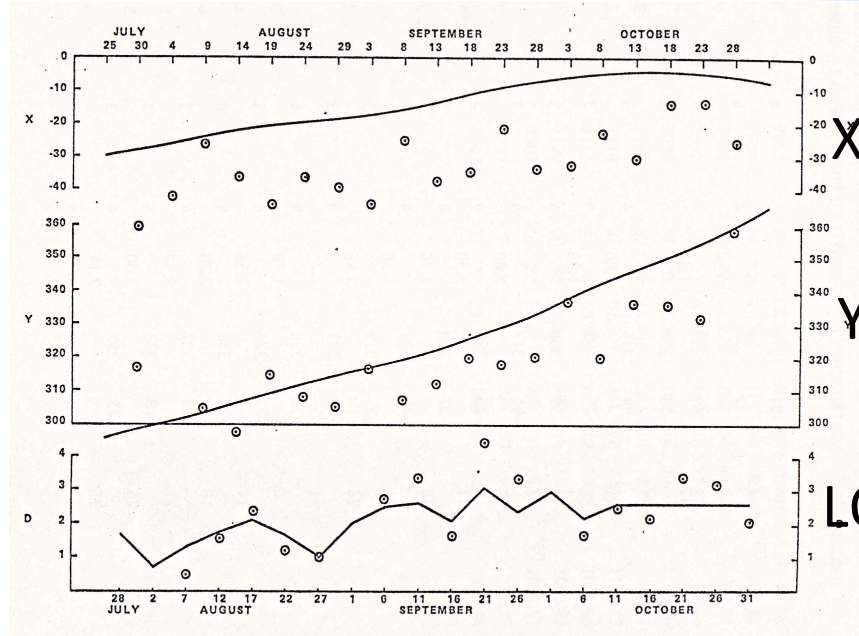
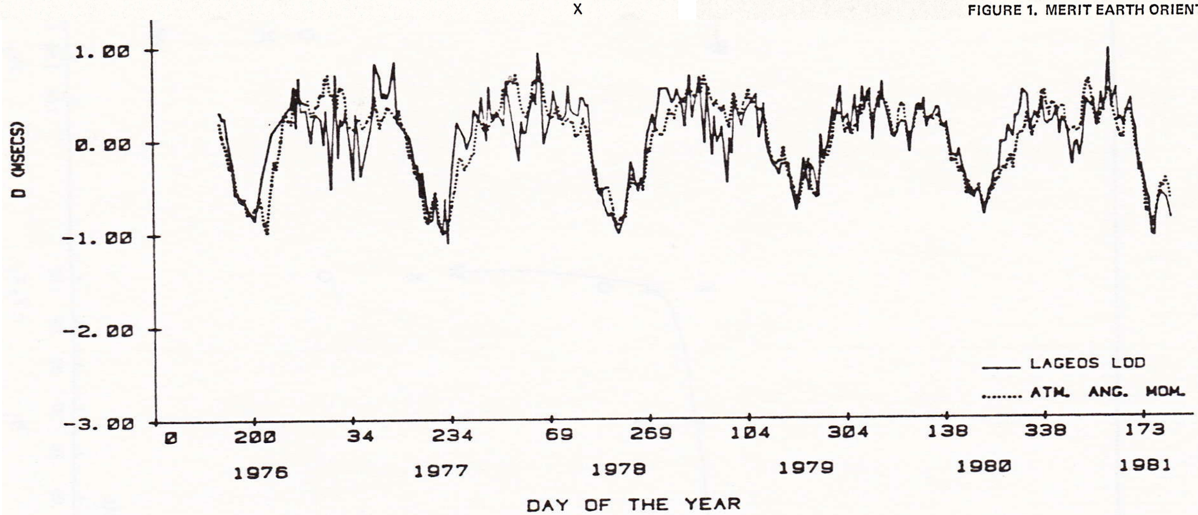


FIGURE 1. MERIT EARTH ORIENTATION RESULTS

Smith et al./GSFC

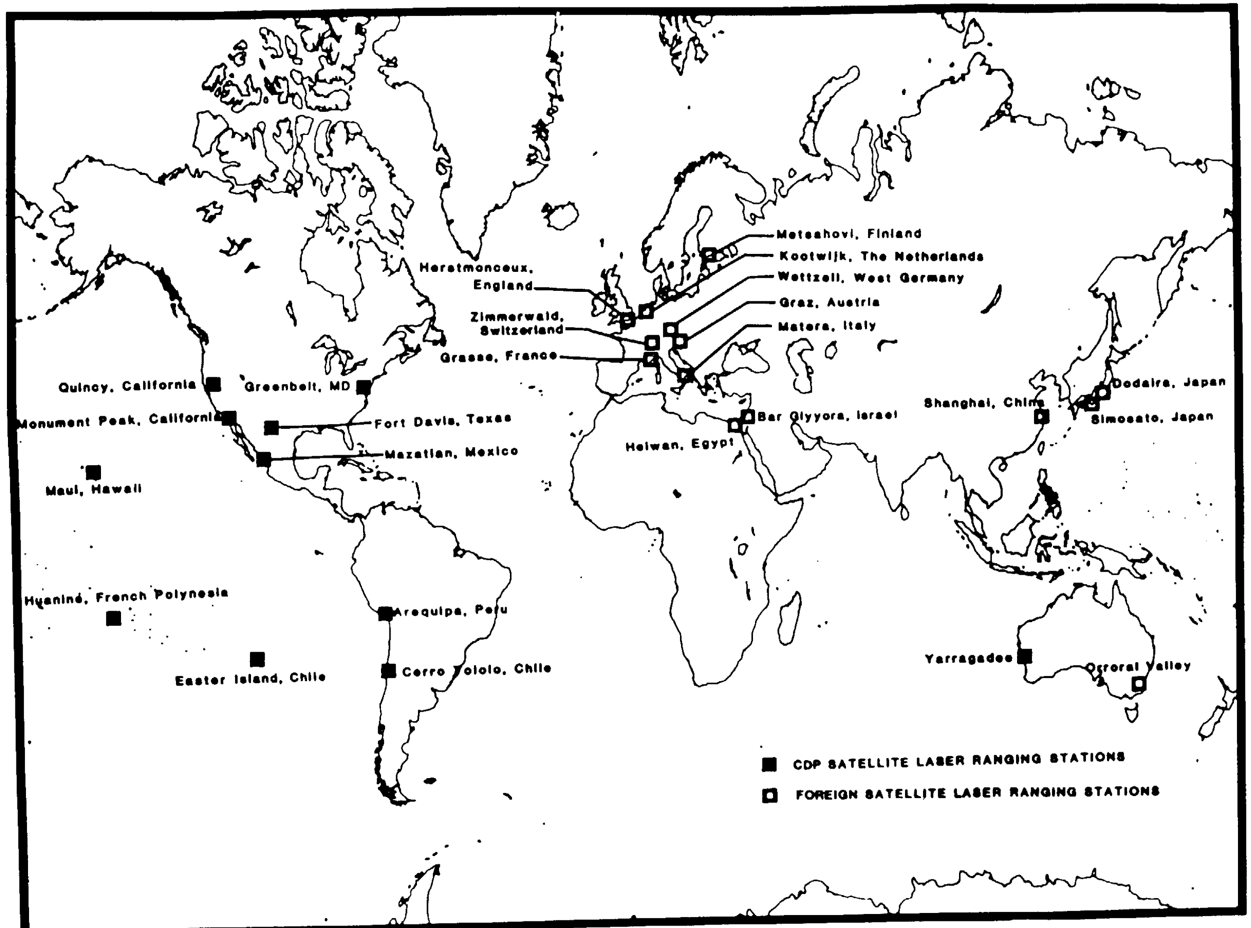


LAGEOS derived LOD vs. Atmospheric Angular Momentum from NCEP

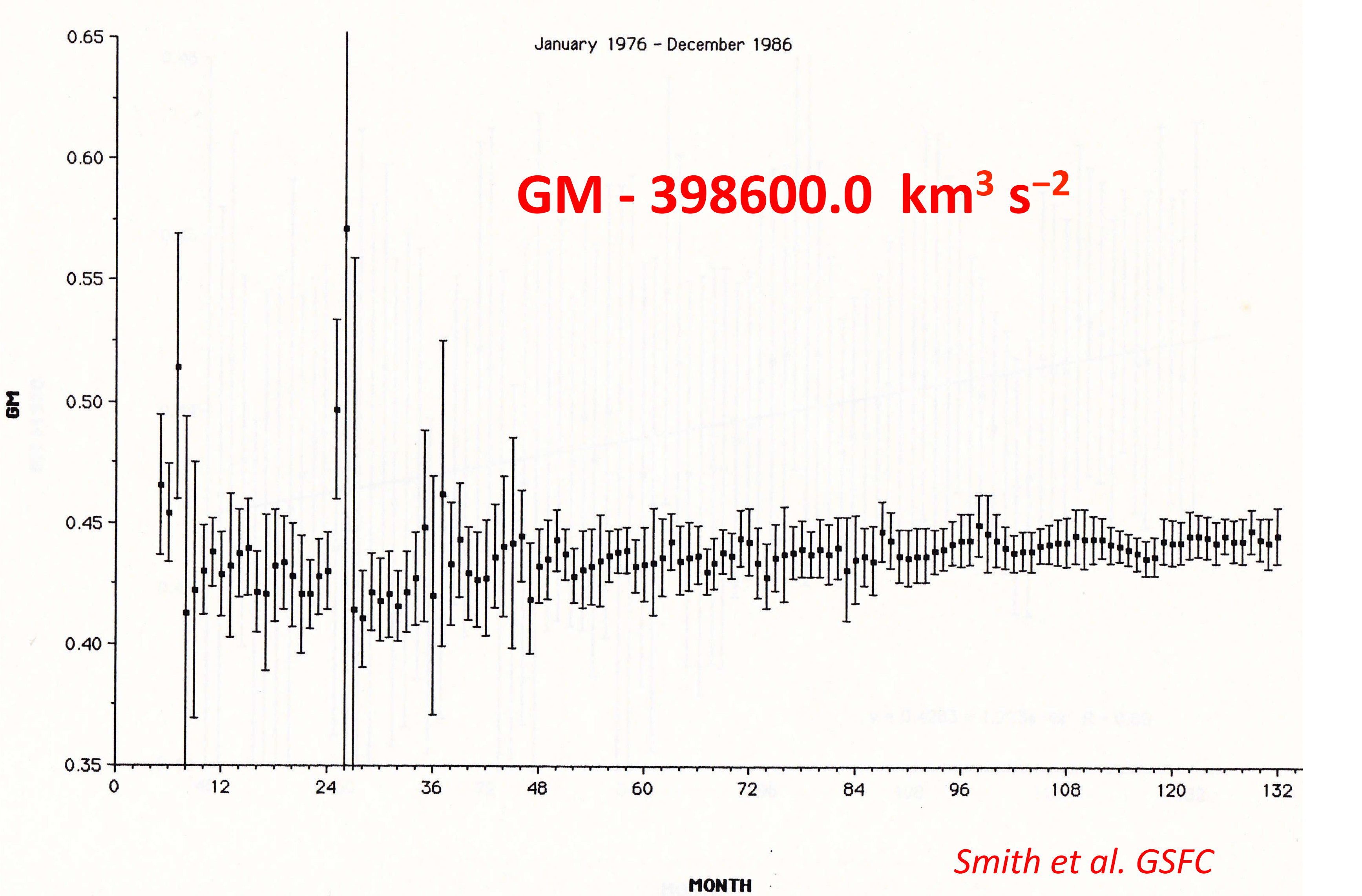
Beyond MERIT: The CDP Years

- The full MERIT campaign in 1983-84 completed successfully and demonstrated the central role of LAGEOS as the new satellite tool for Space Geodesy
- NASA's Crustal Dynamics Project (CDP) is launched in 1979 and as it turned out, LAGEOS took again center stage for satellite techniques

NASA Network and international partner sites (ca. 1984)



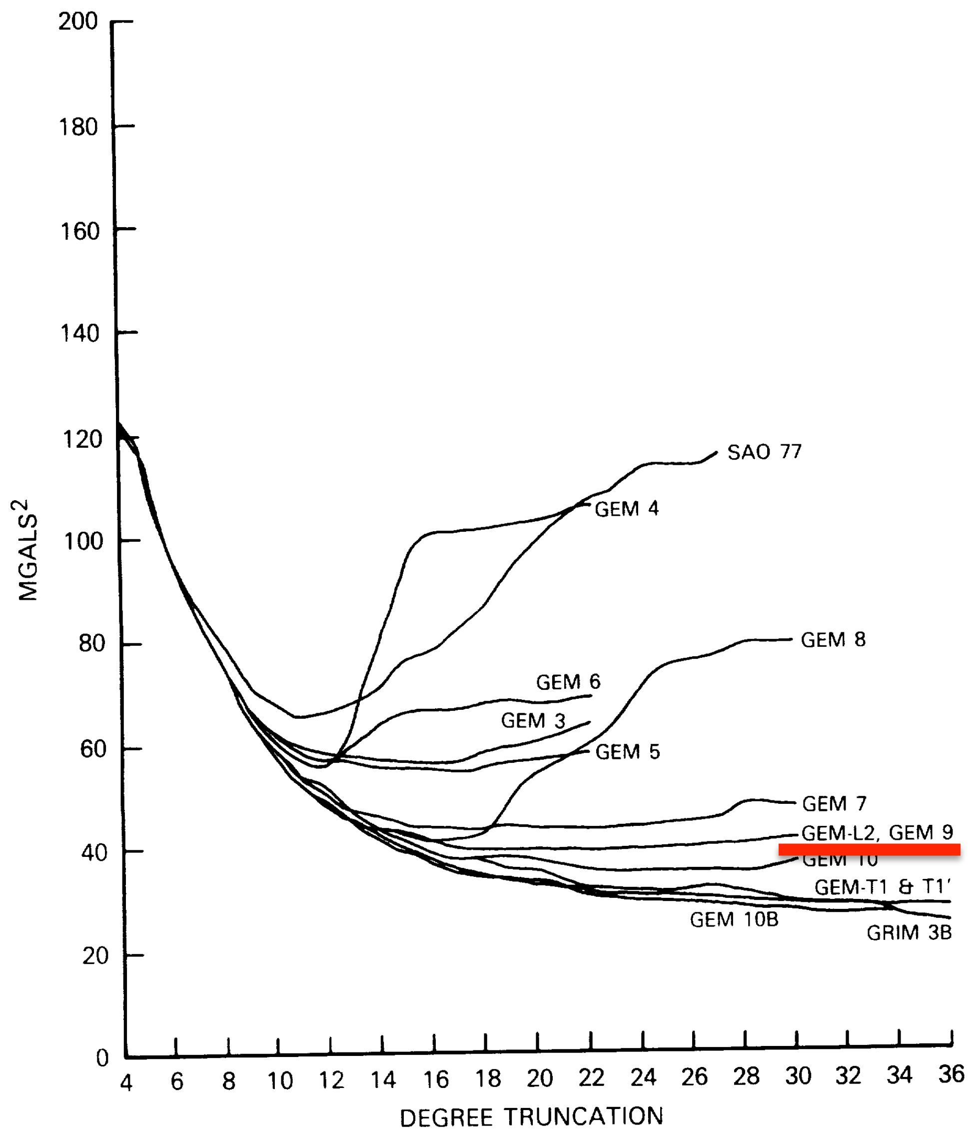
GM Accurately Measured



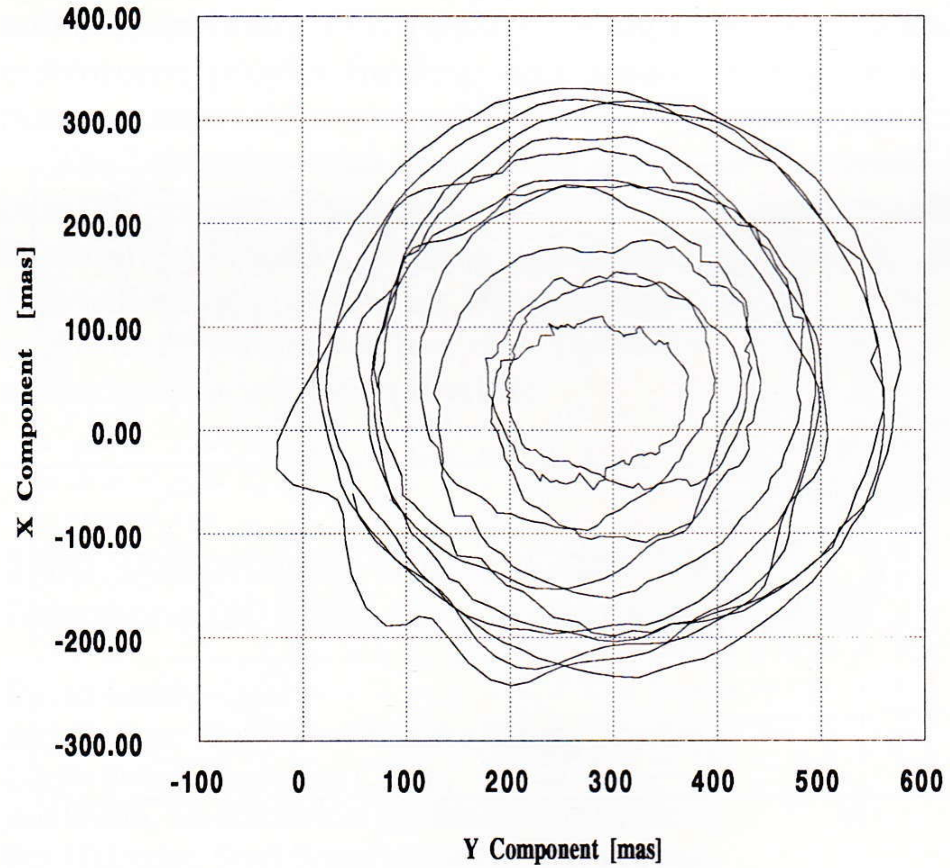
Gravitational Model Improvements

Inclusion of LAGEOS data in the data set used to produce the Goddard Earth Model 9 (GEM-9) resulted in an improved model with higher resolution used for several years as the best mode for Precise Orbit Determination (POD).

As LAGEOS data accumulated new models followed, primarily as part of the TOPEX/POSEIDON pre-launch model development, models GEM-T1, -T2, -T3 and JGM-3 from Univ. of Texas/CSR.

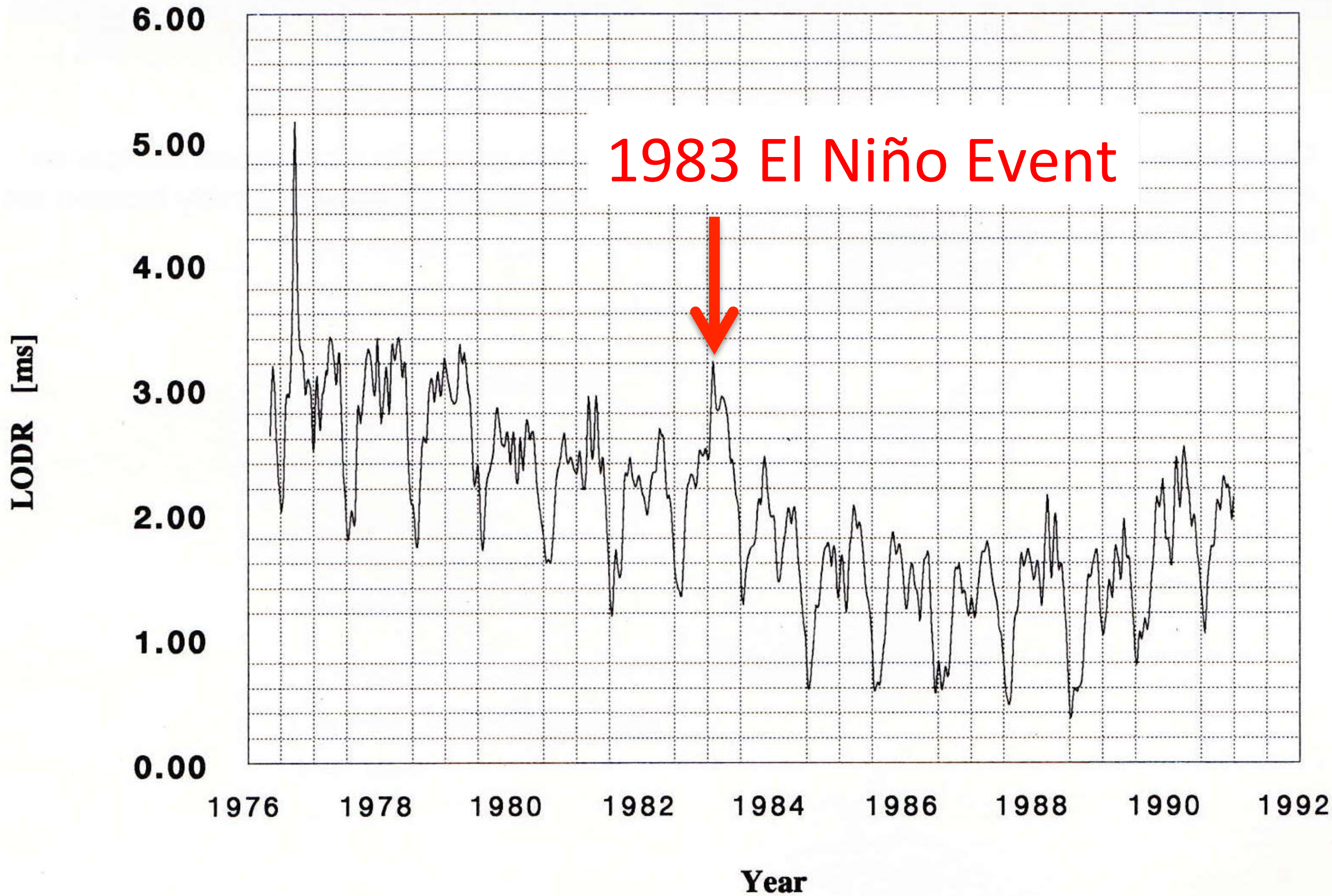


Polar Motion at 3^{d} Intervals



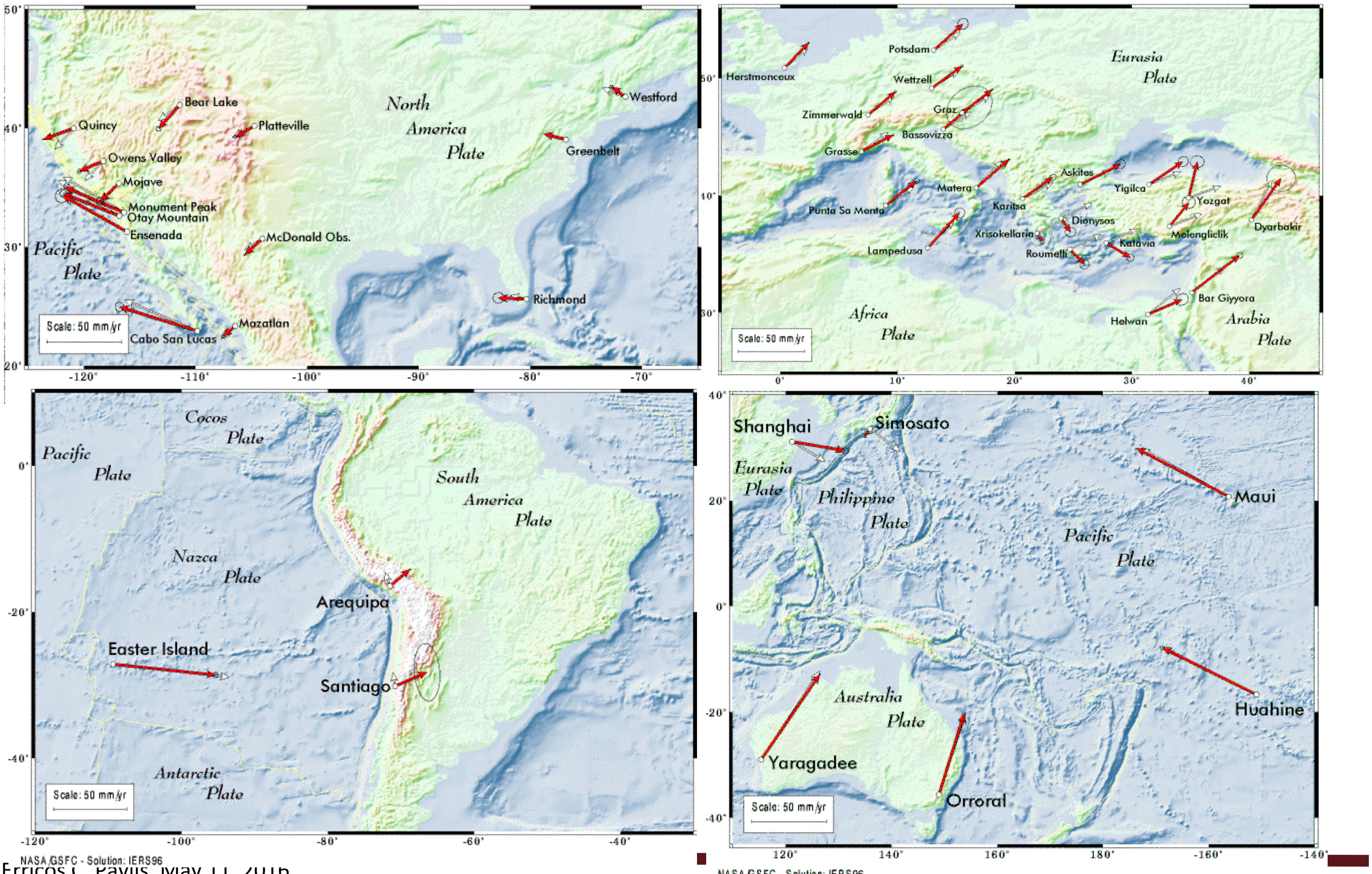
The path of the rotation axis of the Earth as determined from laser ranging observations to LAGEOS during the interval from 1976 to 1988. The variable amplitude of the path is mainly due to the beating of the two primary frequencies involved: the annual and the Chandler (1.2 years).

Length of Day Variations



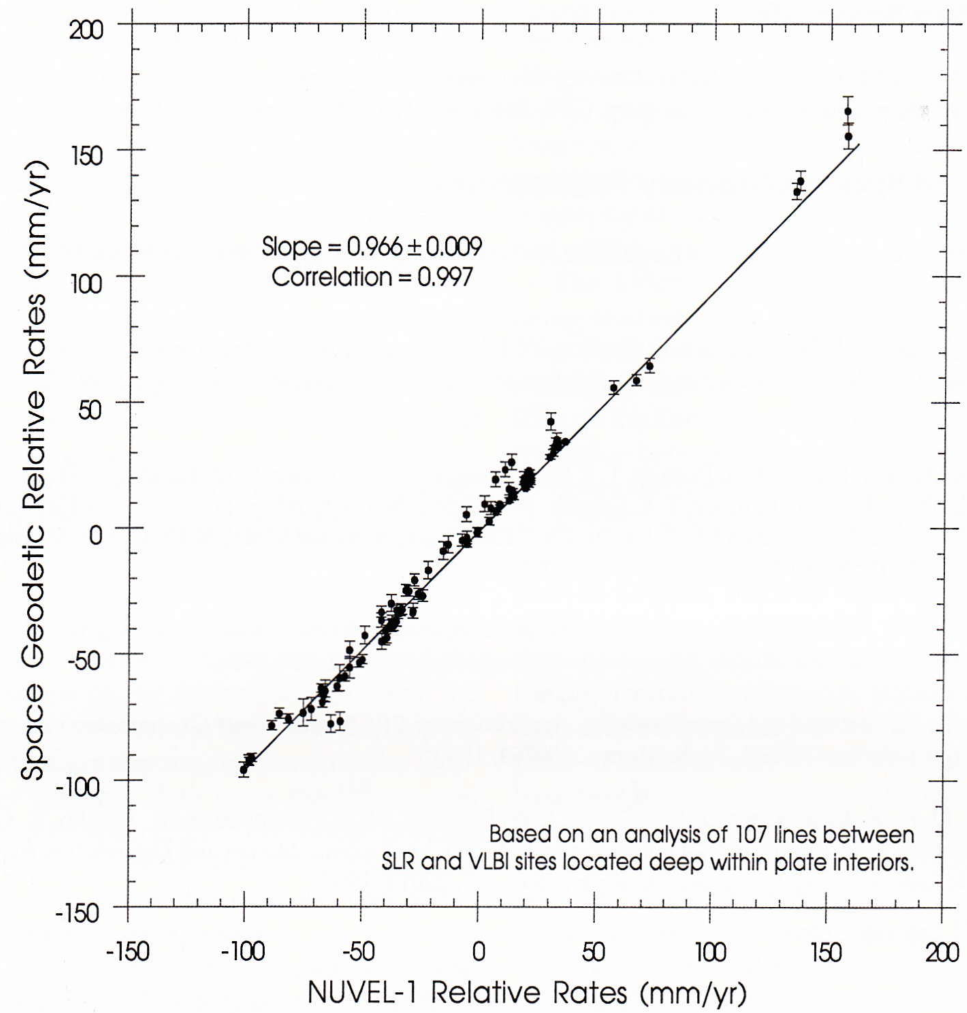
The variation in the spin rate of Earth observed from laser ranging to LAGEOS. The large periodic signature is caused by lunisolar tides, the higher frequencies are the result of exchange of angular momentum with the atmosphere. Notice the effect of the 1983 El Niño.

Global Network and Mobile Systems



Geologic Plate Motion Models Checked

After the correction of the geologic time scale, LAGEOS-derived tectonic motions agreed with those predicted by geologic models with a correlation of 99.7 %



Correlation of geodesic rates determined from space geodetic techniques compared with the NUVEL-1 Geologic Model for VLBI and SLR tracking sites centrally located on major plates.

Quarterly Variations of Geocenter

Rigid Body Transformation Parameters

Quarterly to Global Solutions

1970s

1980 - 1983

QUARTER	STATIONS	ΔX [MM]	ΔY [MM]	ΔZ [MM]	ε [MAS]	ψ [MAS]	ω [MAS]
1978 2	7	124 ±121	22 ± 99	-529 ±118	13 ± 4.4	2 ± 1.4	5 ± 3.8
1978 3	9	153 ± 66	103 ± 62	203 ± 73	-6 ± 2.3	-2 ± 0.8	7 ± 2.2
1978 4	7	127 ± 68	66 ± 71	146 ± 82	-4 ± 2.8	-1 ± 0.8	6 ± 2.6
1979 1	14	-95 ± 51	22 ± 48	-469 ± 56	11 ± 1.8	0 ± 0.7	-2 ± 1.8
1979 2	15	-36 ± 56	-44 ± 51	-194 ± 58	5 ± 1.9	0 ± 0.7	0 ± 1.9
1979 3	12	-37 ± 65	19 ± 59	333 ± 70	-8 ± 2.2	-4 ± 0.9	0 ± 2.2
1979 4	13	47 ± 31	-18 ± 30	47 ± 35	0 ± 1.0	-1 ± 0.4	2 ± 1.2
1980 1	15	51 ± 17	22 ± 16	42 ± 21	-1 ± 0.5	-1 ± 0.2	3 ± 0.7
1980 2	14	-18 ± 15	14 ± 13	5 ± 19	0 ± 0.5	-1 ± 0.2	0 ± 0.6
1980 3	17	16 ± 11	4 ± 10	14 ± 13	0 ± 0.4	0 ± 0.3	1 ± 0.5
1980 4	17	-18 ± 14	47 ± 12	38 ± 15	-1 ± 0.5	0 ± 0.3	0 ± 0.6
1981 1	14	6 ± 18	-10 ± 19	-83 ± 23	3 ± 0.7	-2 ± 0.4	2 ± 0.9
1981 2	15	21 ± 36	-1 ± 31	-83 ± 37	2 ± 1.1	-2 ± 0.9	3 ± 1.5
1981 3	14	-18 ± 12	18 ± 12	50 ± 16	-1 ± 0.4	0 ± 0.3	0 ± 0.6
1981 4	14	35 ± 23	-23 ± 20	66 ± 27	-1 ± 0.7	1 ± 0.6	0 ± 1.1
1982 1	14	14 ± 23	-16 ± 24	49 ± 33	-1 ± 0.9	1 ± 0.6	0 ± 1.3
1982 2	14	17 ± 17	-8 ± 17	53 ± 20	-1 ± 0.6	1 ± 0.4	0 ± 0.8
1982 3	14	18 ± 16	2 ± 16	133 ± 19	-4 ± 0.6	2 ± 0.4	-2 ± 0.7
1982 4	16	-4 ± 15	38 ± 15	32 ± 18	-1 ± 0.5	0 ± 0.4	0 ± 0.7
1983 1	16	-11 ± 21	68 ± 18	-87 ± 22	1 ± 0.6	-2 ± 0.5	2 ± 0.8
1983 2	16	-7 ± 21	7 ± 19	25 ± 21	0 ± 0.6	0 ± 0.5	0 ± 0.8
1983 3	18	-11 ± 13	-13 ± 16	59 ± 13	-1 ± 0.6	1 ± 0.3	-1 ± 0.4
1983 4	23	-36 ± 10	11 ± 10	49 ± 12	-1 ± 0.4	0 ± 0.2	-2 ± 0.4
1984 1	23	-13 ± 10	-37 ± 10	2 ± 11	0 ± 0.4	0 ± 0.2	0 ± 0.4
1984 2	23	-5 ± 5	-2 ± 5	-30 ± 5	0 ± 0.2	0 ± 0.1	0 ± 0.2
1984 3	21	14 ± 6	12 ± 6	-23 ± 6	0 ± 0.2	0 ± 0.1	1 ± 0.2
1984 4	23	9 ± 7	8 ± 7	41 ± 7	-1 ± 0.2	0 ± 0.1	0 ± 0.3
1985 1	17	-6 ± 17	8 ± 17	-15 ± 20	0 ± 0.7	0 ± 0.4	0 ± 0.8
1985 2	17	-6 ± 7	0 ± 7	-52 ± 8	1 ± 0.2	-1 ± 0.1	0 ± 0.3
1985 3	20	-3 ± 8	0 ± 8	45 ± 9	-1 ± 0.3	0 ± 0.2	-1 ± 0.3
1985 4	20	-1 ± 5	1 ± 6	33 ± 7	-1 ± 0.2	0 ± 0.1	0 ± 0.2
1986 1	19	12 ± 6	-2 ± 6	-61 ± 7	1 ± 0.2	-1 ± 0.1	1 ± 0.3
1986 2	20	-5 ± 8	-7 ± 8	-83 ± 9	2 ± 0.3	-1 ± 0.2	1 ± 0.3
1986 3	19	-4 ± 6	15 ± 5	-40 ± 6	0 ± 0.2	0 ± 0.1	0 ± 0.2
1986 4	19	-5 ± 6	10 ± 6	-40 ± 7	1 ± 0.2	0 ± 0.1	0 ± 0.2
1987 1	15	-24 ± 9	4 ± 9	61 ± 11	-1 ± 0.3	0 ± 0.2	-1 ± 0.4
1987 2	11	-1 ± 10	9 ± 12	-47 ± 14	1 ± 0.4	-1 ± 0.3	1 ± 0.5

Scientific Results by 1985

- Plate tectonics checked at a global and regional scale
- Earth orientation monitored at a 3-day resolution and Earth rotation variations' correlation with AAM demonstrated over years, including the detection of ENSO events (1983)
- GM accurately measured
- Gravity model improvements at long wavelengths (GEM-L2)

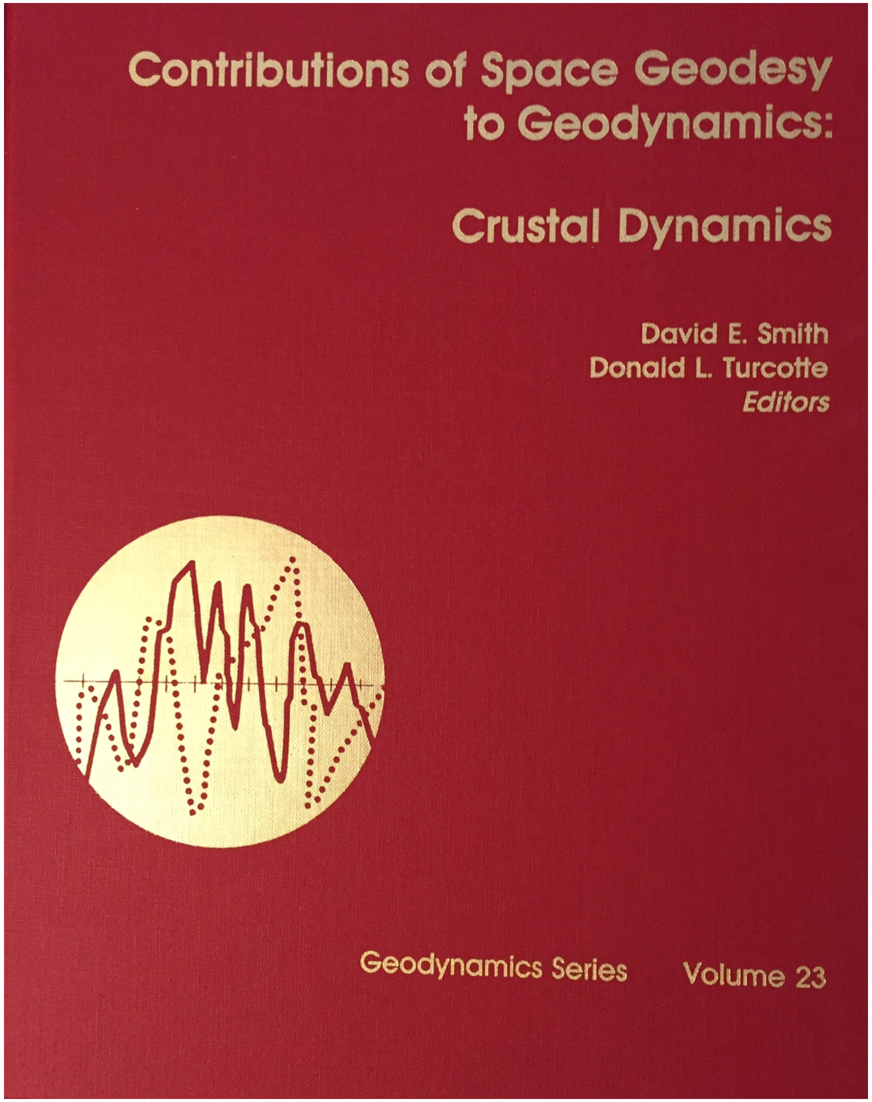
LAGEOS
Scientific Results

Reprinted from Journal of Geophysical Research
Volume 90, Number B11, September 30, 1985

Published by the American Geophysical Union

NASA's Crustal Dynamics Project (CDP)

- Launched in late 1979, spanned over a decade and LAGEOS held a central role as the SLR primary target
- CDP created an international community focused on solving geodynamics problems with space geodesy
- The numerous scientific results were compiled in a 3-volume publication of the AGU



Globalization of Space Geodesy

- One of the outcomes of the main MERIT campaign was the establishment of a new "Service" to coordinate such activities in a routine fashion and provide the community with results adhering to established standards (an outgrowth of the "MERIT Standards")
- This led to the establishment of the IERS (*International Earth Rotation Service*) in 1987, starting its operations on Jan. 1, 1988, and later renamed (2003) to: *International Earth Rotation* ***and Reference Systems*** *Service*
- Eventually, all space geodetic techniques were organized in a similar fashion, with an international participation

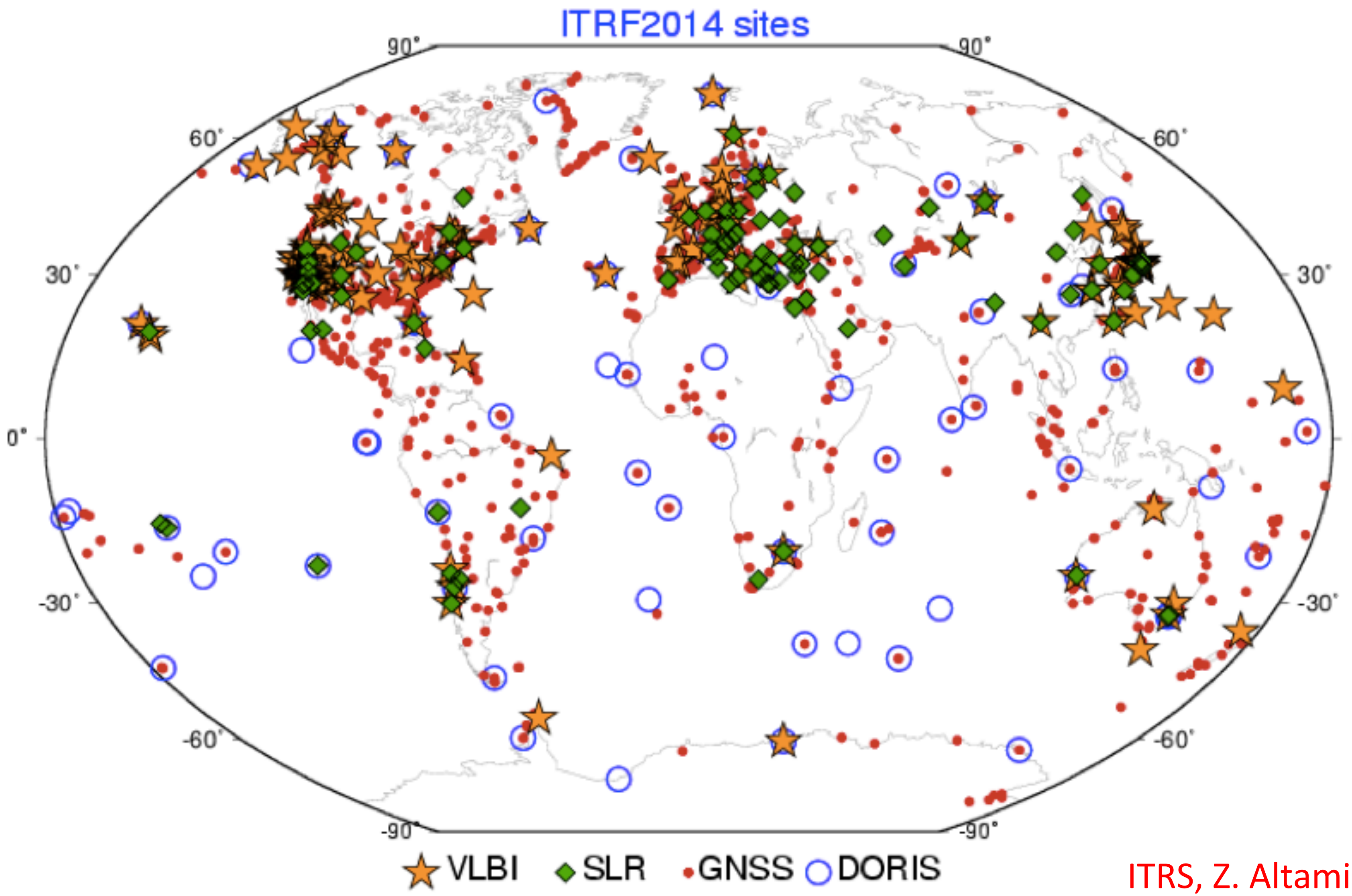
LAGEOS and the Reference Frame

- When IERS was established LAGEOS had already proven itself as the pillar of the global network's station coordinate estimation tool during the various projects (MERIT, CDP, WEGENER/MEDLAS, etc.) and a main contributor to gravity modeling efforts
- Soon after, in 1992 a second spacecraft with identical design, LAGEOS-2, was launched as a joint project of NASA and ASI, the Italian Space Agency
- IERS identified the two as the unique contributors to the definition of the origin of the ITRF (International Terrestrial Reference Frame) and along with Very Long Baseline Interferometry (VLBI), the scale of the ITRF

Contribution to ITRF

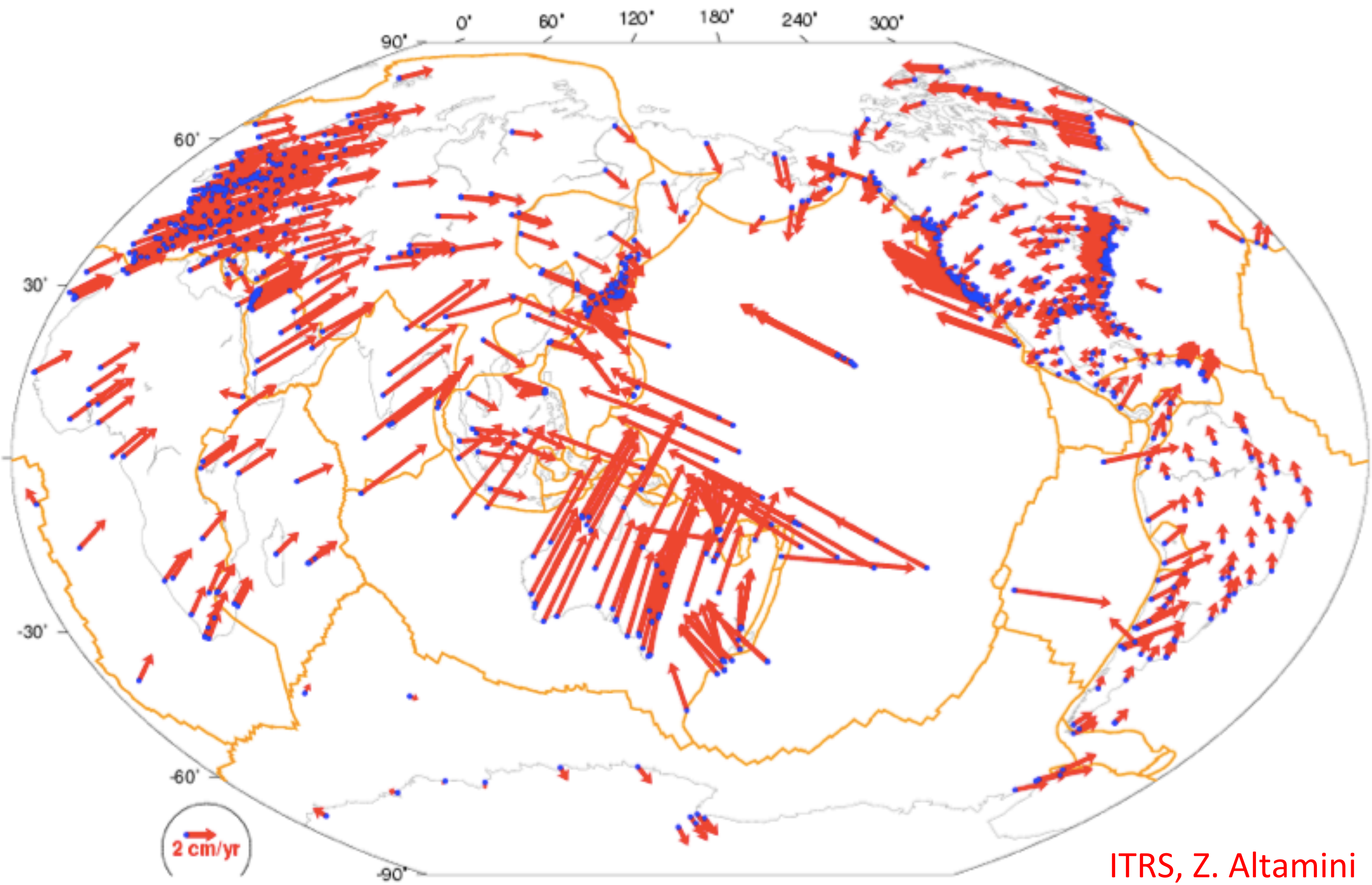
- Analysis of LAGEOS and LAGEOS-2 SLR data have contributed to the all ITRF realizations of the ITRS
- In recent years the analysis delivers weekly estimates of the coordinates of the stations and daily-averaged EOP, updated on a daily basis
- When a new ITRF model is to be realized, a complete reanalysis of the SLR data to the two LAGEOS s/c is performed, using the latest models for gravity, tides, etc.
- The quality of the ILRS analysis products is continuously monitored and discrepancies with respect to various parameters (e.g. ITRF scale) are investigated
- Since several years, ILRS is focused on mitigating the effect of systematic errors in the data, and the two LAGEOS s/c data are the main standards against which all stations are compared and evaluated

ITRF2014 Networks



ITRS, Z. Altamini

ITRF2014 Velocities



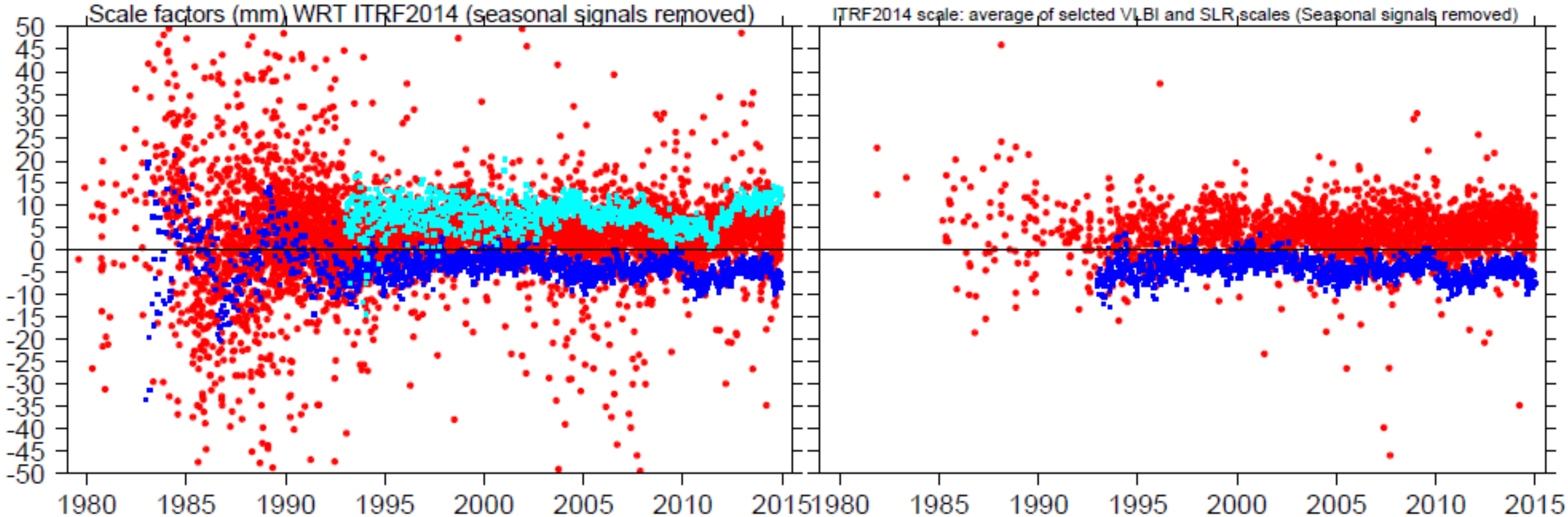
ITRS, Z. Altamini

SLR, DORIS & VLBI scales wrt ITRF2014

ITRF2014 Scale defined as the mean of SLR and VLBI scales

Full time series of scale factors

Scale factors of SLR and VLBI solutions selected to define ITRF2014 scale



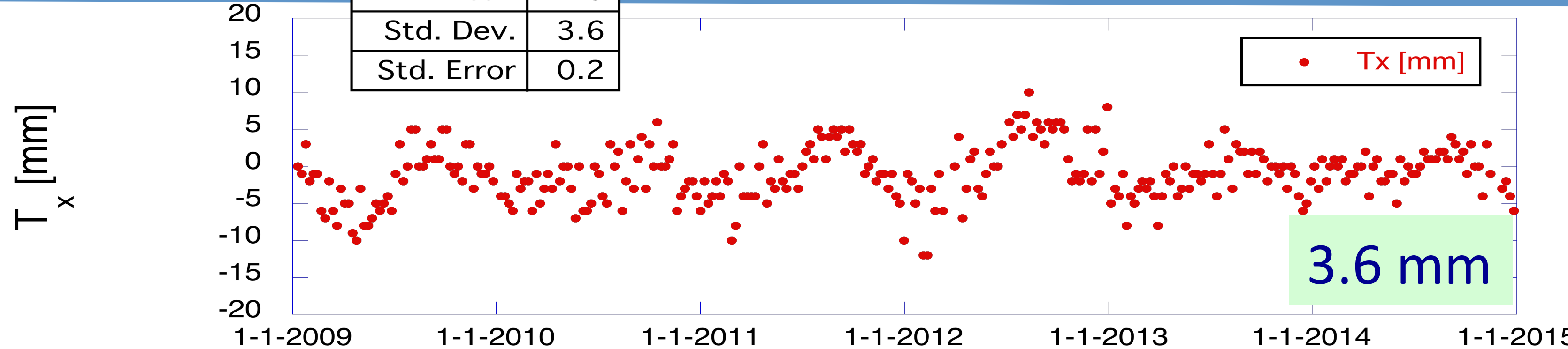
SLR-VLBI Scale difference **DORIS** **SLR** **VLBI**

VLBI & SLR co-locations, No GPS **1.37 ± 0.26 ppb** **9 sites (good distribution): 13 LT vectors, properly weighted**

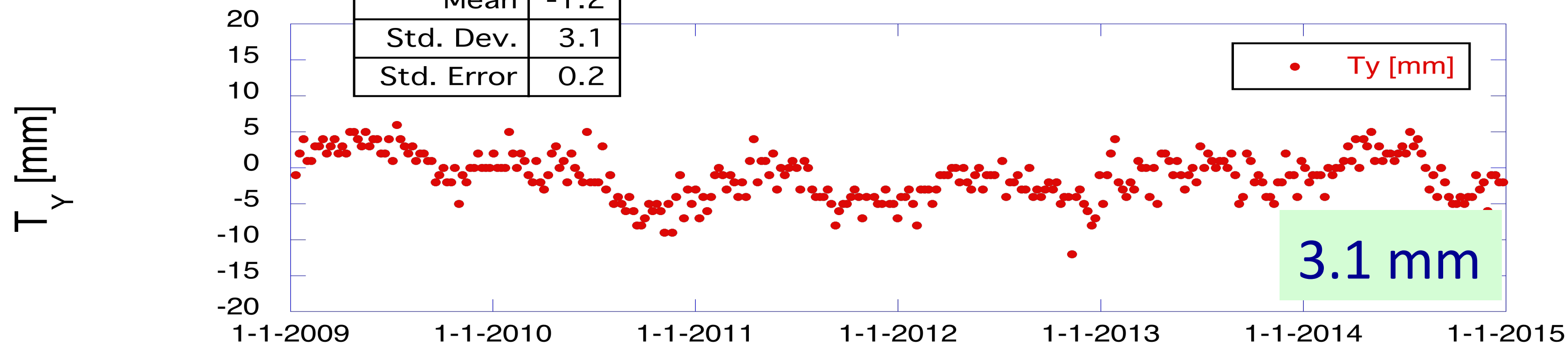
ITRS, Z. Altamini

Origin Translation Offsets wrt ITRF2014

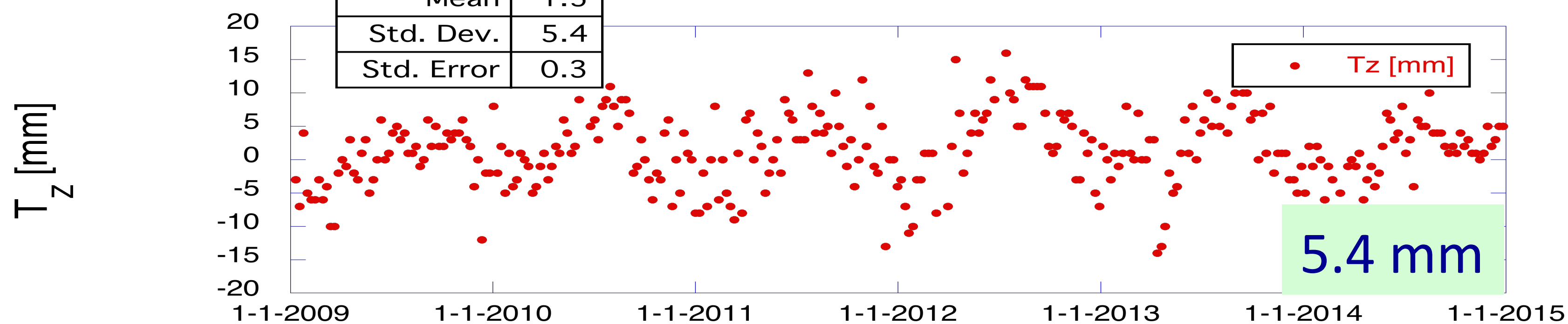
Mean	-1.0
Std. Dev.	3.6
Std. Error	0.2



Mean	-1.2
Std. Dev.	3.1
Std. Error	0.2



Mean	1.5
Std. Dev.	5.4
Std. Error	0.3



Site Coordinate Residuals – Statistics ITRF2014 & PSD

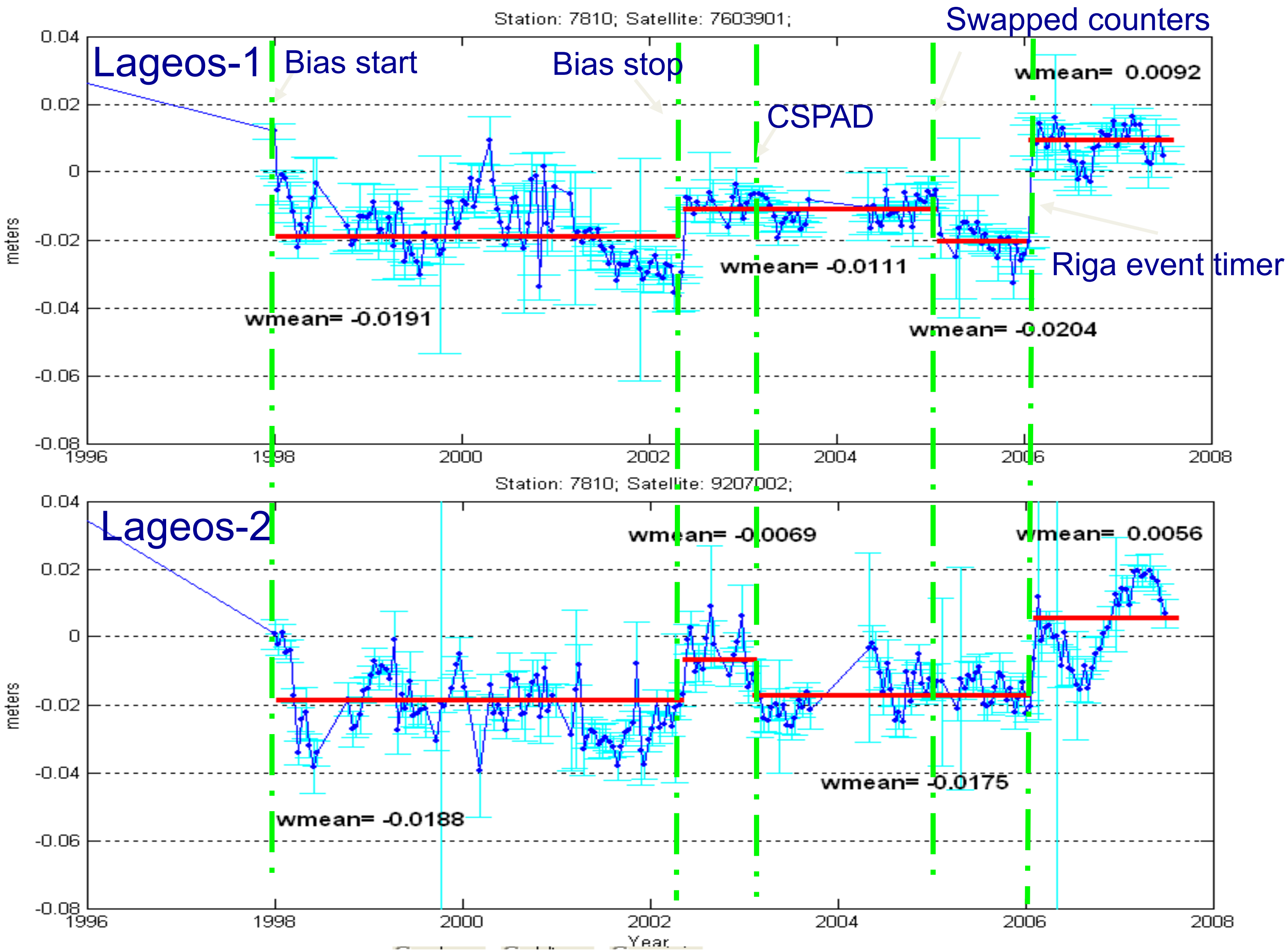
	vs SLRF2008		vs ITRF2014		ITRF2014+PSD	
	Mean WRMS [mm]	**STD WRMS [mm]**	**Mean WRMS [mm]**	**STD WRMS [mm]**	**Mean WRMS [mm]**	**STD WRMS [mm]**
All Sites	**9.7**	***6.2***	**9.0**	***6.5***	**7.7**	***5.4***
Core Sites	**6.5**	***4.9***	**6.0**	***4.3***	**6.0**	***4.8***

The performance of the new TRF model looks very good, even at this very preliminary stage of implementation

Systematic Error Tracking at ILRS Sites

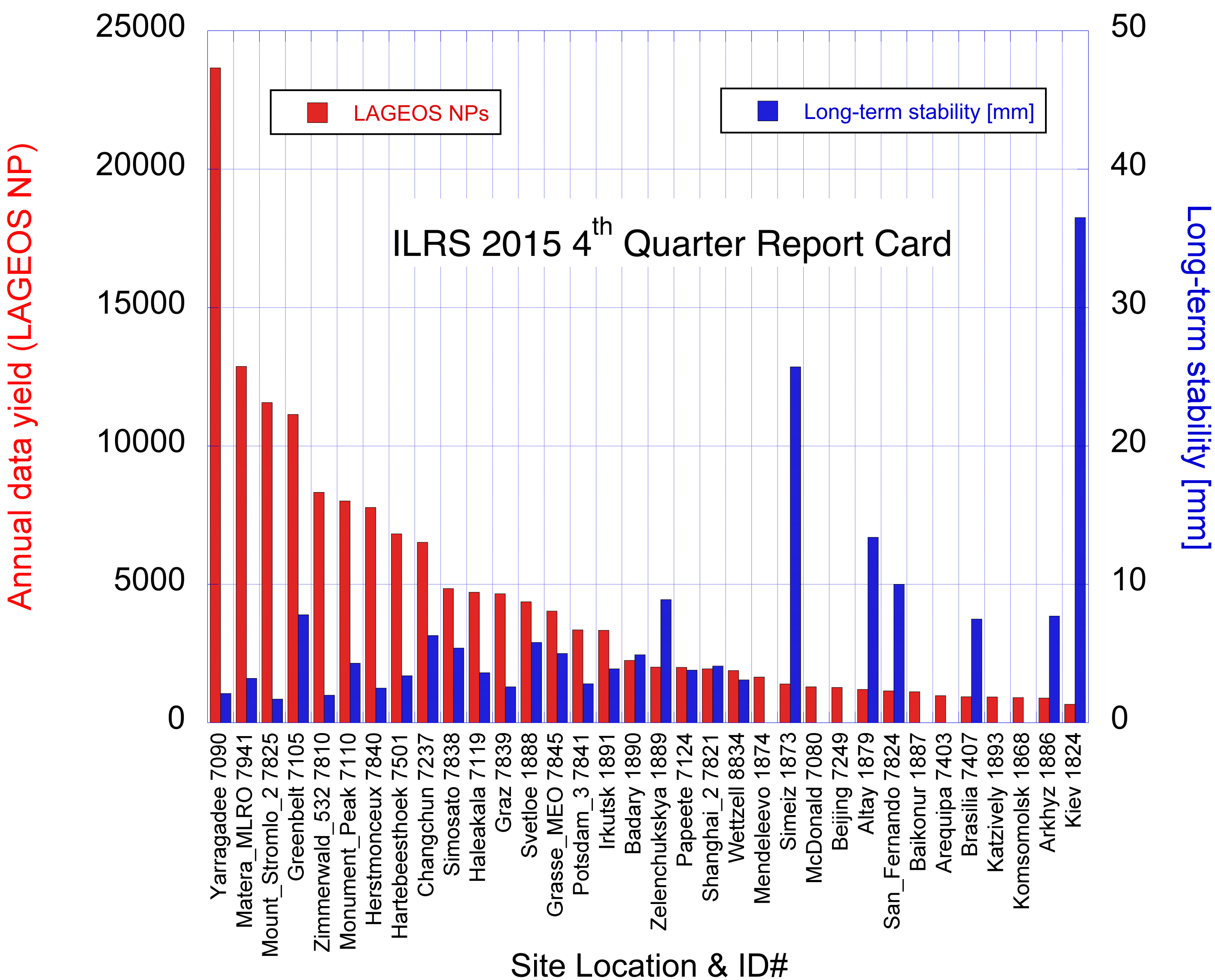
- The current major task that LAGEOS data contribute to is monitoring the quality of the network data on a daily basis
- Engineers cannot detect small errors below the 1-2 cm level, orbital fitting to global solutions are necessary
- Today's accuracy requirements make errors of even a few millimeters a major issue
- The Quality Control (QC) of the ILRS data is one of the areas where LAGEOS data is now playing a central role
- The ILRS has established a Quality Control Board to oversee these efforts on a routine basis

Systematic Errors at Zimmerwald



C. Luceri, CGS, e-GEOS/ASI

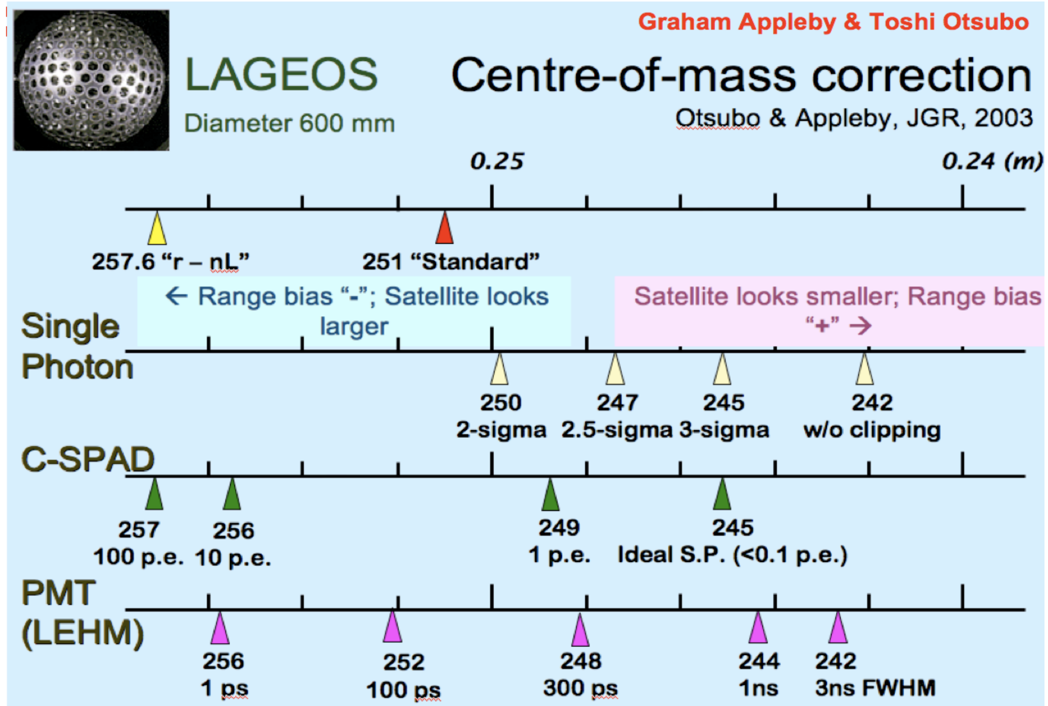
2015 ILRS Monthly QC "Report Card"



GM Correction due to LAGEOS CoM Offset

- The important role of an accurate correction of the data for the effective reflection plane of the laser pulse was demonstrated with the improvement of the GM estimate from LAGEOS data, once this offset was corrected from 240 mm to 251 mm

Ries, J.C., R.J. Eanes, C.K. Shum and M.M. Watkins,(1992): Progress in the determination of the gravitational coefficient of the Earth



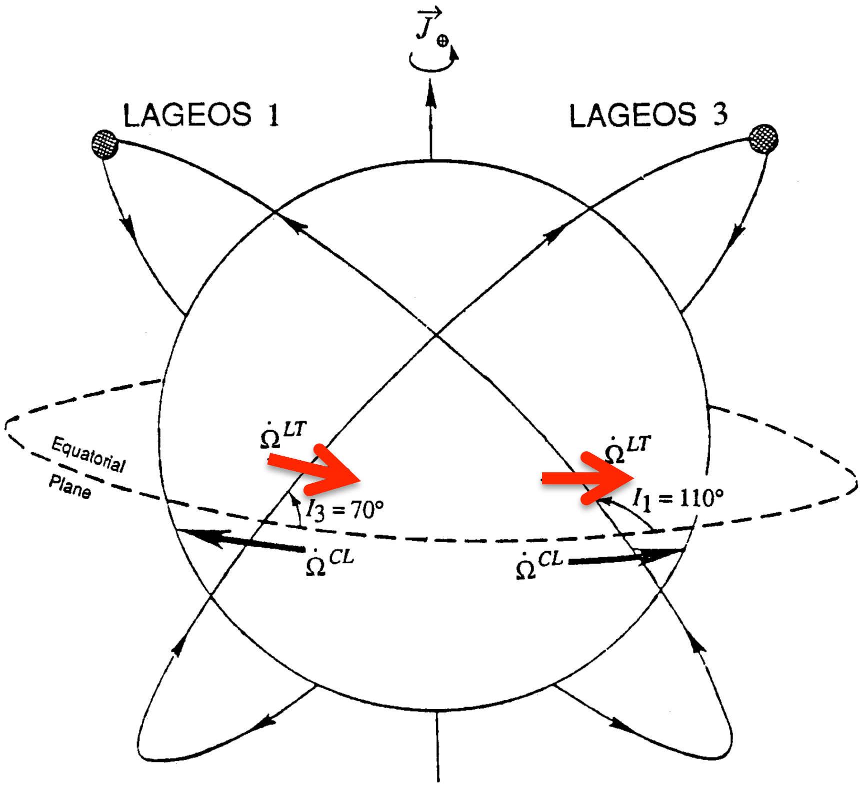
A complete reevaluation of the various systems deployed in the global network resulted in a set of individual corrections applicable for each site and mode of operation, limiting the error from this source to about ± 2 mm on average.

398600.4415 ± 0.0008 km^3/s^2

LAGEOS Contributions Beyond Geodesy

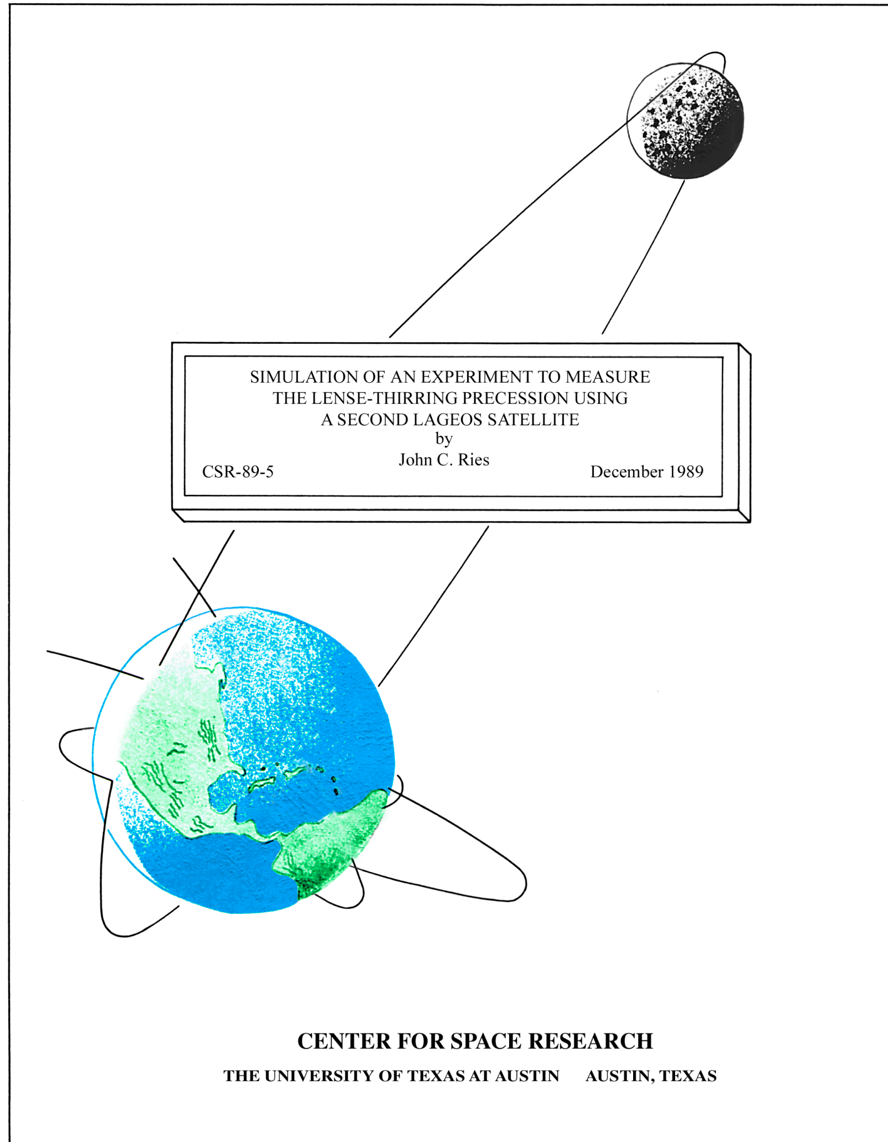
1986 Proposal for a Relativity Experiment

Simulation of LAGEOS 1 & 3 Experiment



Frame-dragging or Lense-Thirring effect (**LT**)

Figure 1.1. The Lageos-1/Lageos-3 mission: the Lense-Thirring precession is identical for both satellites, whereas the classical precession due to the Earth's oblateness is equal and opposite.



SIMULATION OF AN EXPERIMENT TO MEASURE
THE LENSE-THIRRING PRECESSION USING
A SECOND LAGEOS SATELLITE
by
John C. Ries

CSR-89-5

December 1989

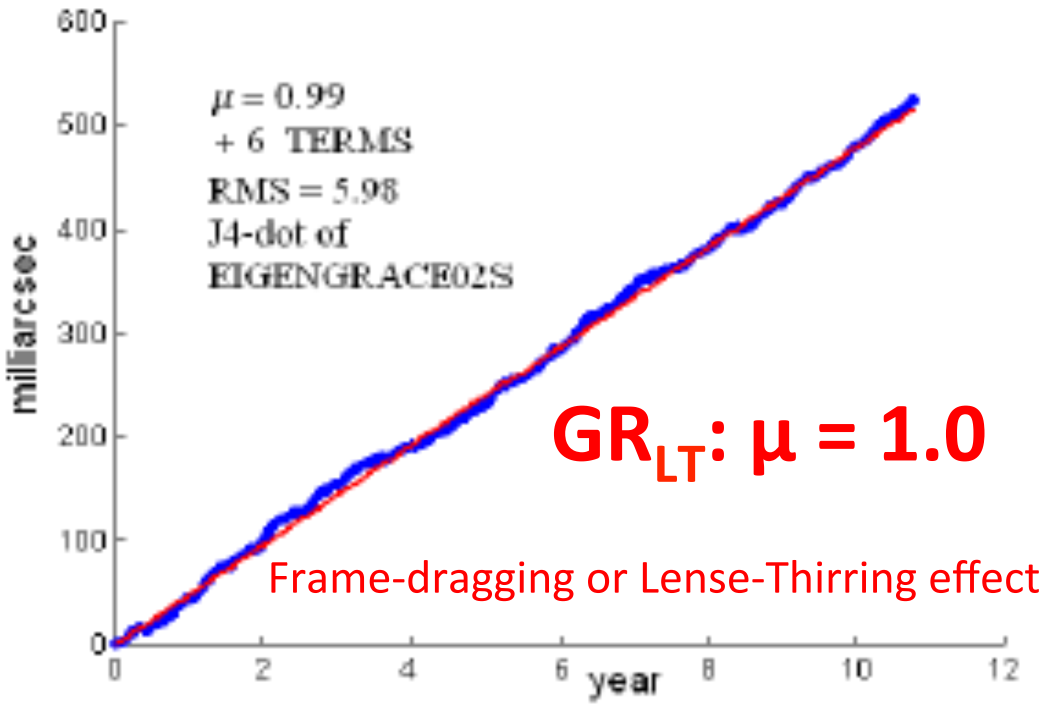
CENTER FOR SPACE RESEARCH

THE UNIVERSITY OF TEXAS AT AUSTIN AUSTIN, TEXAS

Measurement of LT with LAGEOS 1 & 2

Ciufolini & Pavlis, 2004

EIGEN-GRACE02S



$\mu_{EIGEN\text{-}GRACE02S} = 0.992 \pm 0.05$

Realistic Error Estimate ≈ 10%

LT from LAGEOS 1 & 2 and LARES (2016)

Eur. Phys. J. C (2016) 76:120
DOI 10.1140/epjc/s10052-016-3961-8

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

A test of general relativity using the LARES and LAGEOS satellites and a GRACE Earth gravity model

Measurement of Earth's dragging of inertial frames

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Abstract We present a test of general relativity, the measurement of the Earth's dragging of inertial frames. Our result is obtained using about 3.5 years of laser-ranged observations of the LARES, LAGEOS, and LAGEOS 2 laser-ranged satellites together with the Earth gravity field model GGM05S produced by the space geodesy mission GRACE. We measure $\mu = (0.994 \pm 0.002) \pm 0.05$, where μ is the Earth's dragging of inertial frames normalized to its general relativity value, 0.002 is the 1-sigma formal error and 0.05 is our preliminary estimate of systematic error mainly due to the uncertainties in the Earth gravity model GGM05S. Our result is in agreement with the prediction of general relativity.

1 Introduction

About 100 years ago Albert Einstein completed the publication of a series of fundamental papers describing the gravitational theory known as general relativity (GR) [1–7]. Since then Einstein's gravitational theory has had experimental and theoretical triumphs, including the prediction and observation of the expansion of the universe, of black holes, gravitational lensing and gravitational waves [8–14]. GR has today a number of practical applications to our everyday life [15] including its corrections that enable the Global Navigation Satellite System to reach accuracies at the level of a few decimetres [16].

Nevertheless, GR has not been reconciled with the other fundamental theory of modern physics: quantum mechanics. Further, Einstein's gravitational theory predicts the occurrence of spacetime singularities where every known physical theory ceases to be valid, the spacetime curvature diverges and time ends [17]. In 1998 observations of distant supernovae of type Ia implied the quite surprising result that the universe has an accelerated expansion [18,19]. An explanation for this mysterious result can be found in the cosmological constant introduced by Einstein to avoid a dynamical universe and later, in 1931, abandoned by Einstein himself. However, the cosmological constant corresponds to vacuum energy and quantum field theory predicts that the vacuum energy should have a value approximately 10^{122} times larger than the *dark energy* [20,21] density that is observed in the universe. To explain the accelerated expansion of the universe, dark energy should compose more than 70 % of our universe, but its real nature is unknown. Other explanations include a time dependent vacuum energy with the exotic name of quintessence, and modifications of GR such as the so-called f(R) theories. Therefore, in spite of its experimental triumphs, Einstein's gravitational theory continues to need further accurate tests at all scales from solar system tests to astrophysical and cosmological observations.

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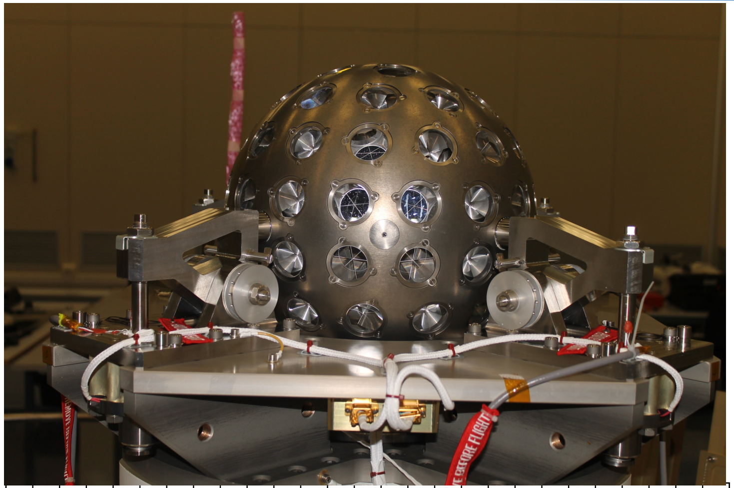


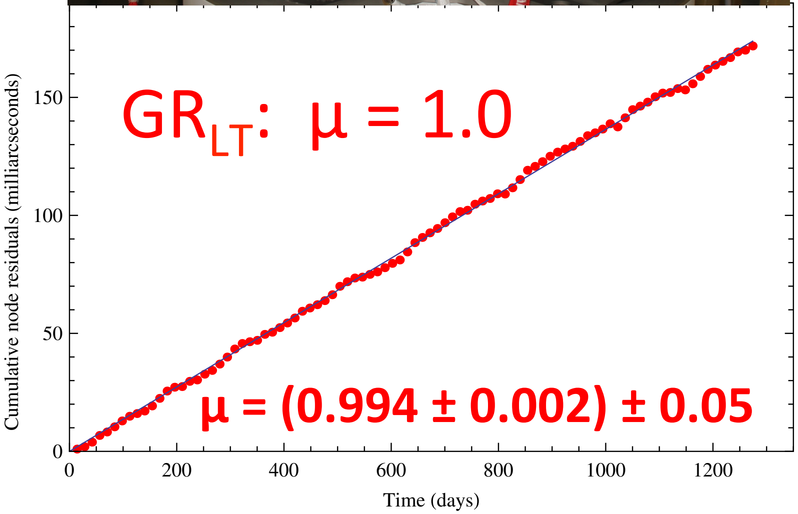


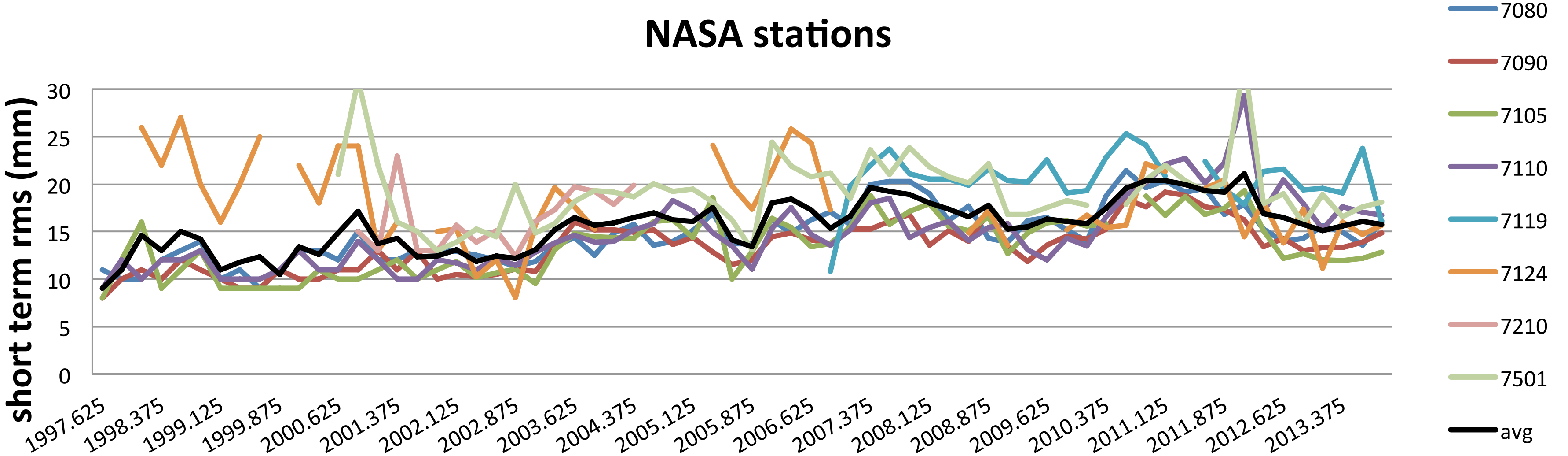
Fig. 4 Fit of the cumulative combined nodal residuals of LARES, LAGEOS, and LAGEOS 2 with a linear regression plus six periodical terms corresponding to six main tidal perturbations observed in the orbital residuals

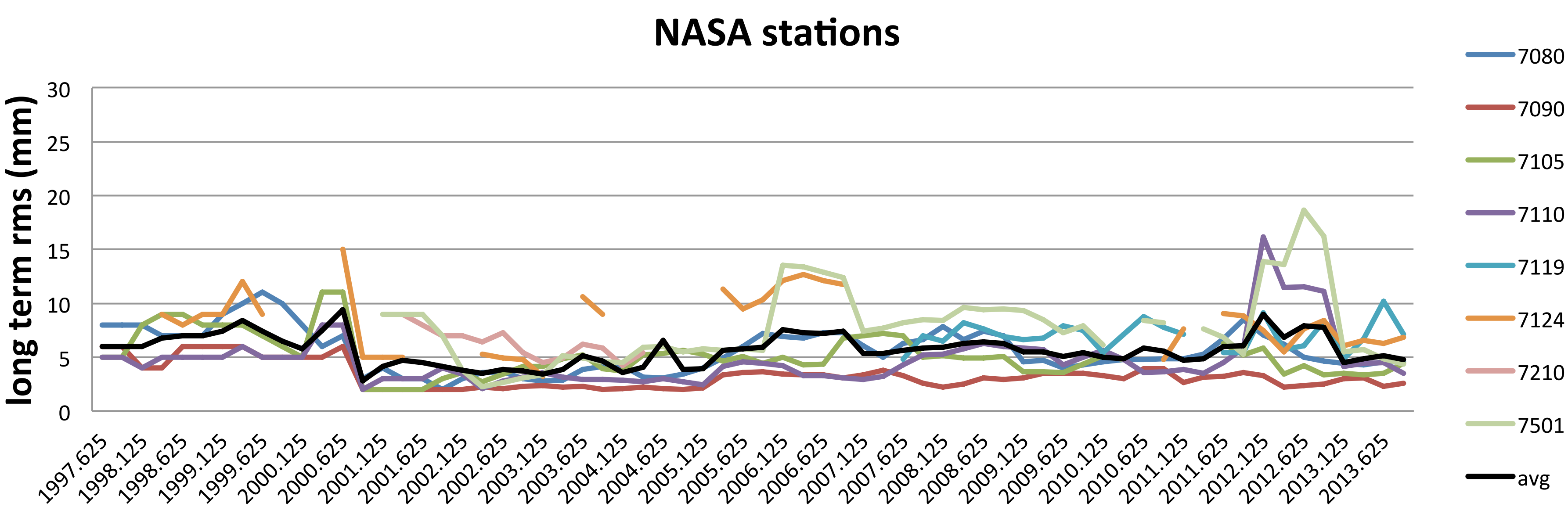
Conclusion

- LAGEOS was launched to address a handful of problems that were of high interest in the 70s, but it has proven an unfathomable tool for addressing incredibly complicated problems and we are still finding areas where the data will significant contributions
- For Geodesy, the contributions of the two LAGEOS s/c to the development of the ITRF models and the subsequent monitoring of its quality are unique, since they are the only tool that we have to define its origin and monitor its variations
- The addition of a new s/c to the current constellation, LARES and the possible future augmentation with a LARES-2, will enhance the quality and accuracy of the products since the new targets are specifically designed for millimeter accurate Geodesy

THANK YOU LAGEOS!

Short & Long-term System Stability





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