International Laser Ranging Service

Improvements in Satellite Laser Ranging: Towards the mm SLR

Erricos C. Pavlis
Goddard Earth Science and Technology Center (GEST),
University of Maryland, Baltimore County
&
NASA Goddard 698

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International Laser Ranging Service

Outline

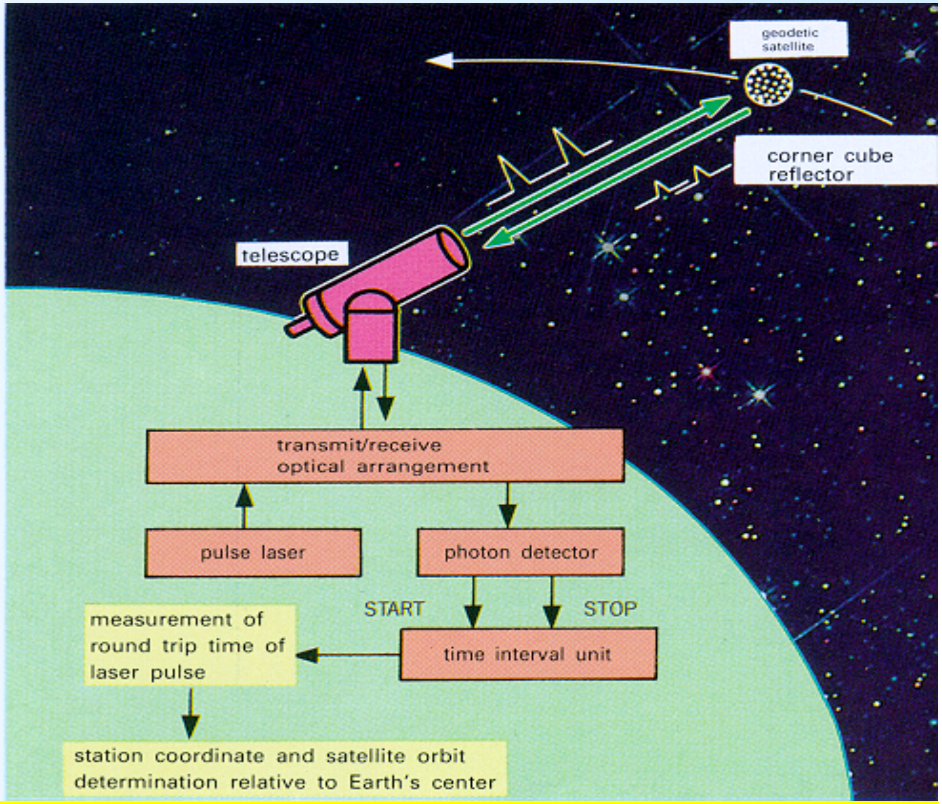
- Motivation & background information
- Technology and analysis improvements
- Examples from technology and analysis
- Schedule of implementation
- Summary and Future Plans

We gratefully acknowledge the support of the ILRS and their network for making their SLR tracking data available to us for this work, as well as the GRACE Mission Project for the release of GSM products.

Satellite Laser Ranging - the Technique

Precise range measurement between an SLR ground station and a retroreflector-equipped satellite using ultrashort laser pulses corrected for refraction, satellite center of mass, and the internal delay of the ranging system.

- Simple range measurement
- Space segment is passive
- Simple refraction model
- Night / Day Operation
- Near real-time global data availability
- Satellite altitudes from 300 km to geosynchronous satellites, and the Moon
- *cm* satellite Orbit Accuracy
- High accuracy and resolution long time series, EOP, $C/S_{n,m}$



- Unambiguous centimeter accurate orbits
- Long-term stable time series

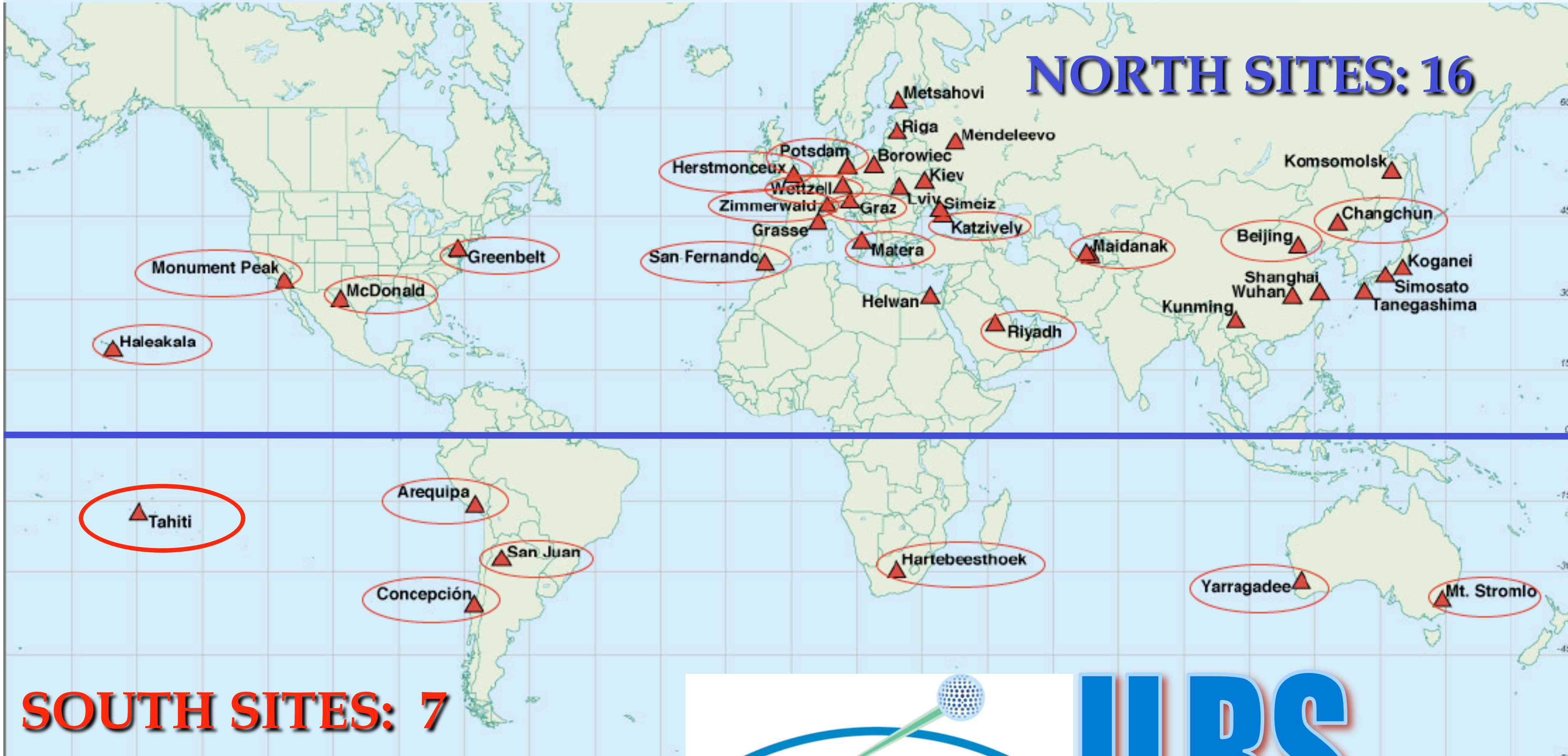
SLR single-shot range error budget

aspect	noise	systematics
epoch timing [μs]	<< 1	<< 1
troposphere [mm]		1 (5)
ionosphere [mm]	0	0
detector [mm]	2 - 5	1
satellite [mm]	2 - 15	0 – 6
time of flight [mm]	1 - 5	0 – 5
total [mm]	3 - 16	1 – 8 (10)

ILRS:

- founded in 1998
- stimulates technology development
- coordinates missions, tracking, archival, analysis
- Analysis Working Group: quality control, analysis standards, formats, TRF products, 8 active AC and 4 candidate AC
- effective data period SLR: from 1983 onwards
- http://ilrs.gsfc.nasa.gov

The ILRS Network



ILRS

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Selected SLR Stations Around the World

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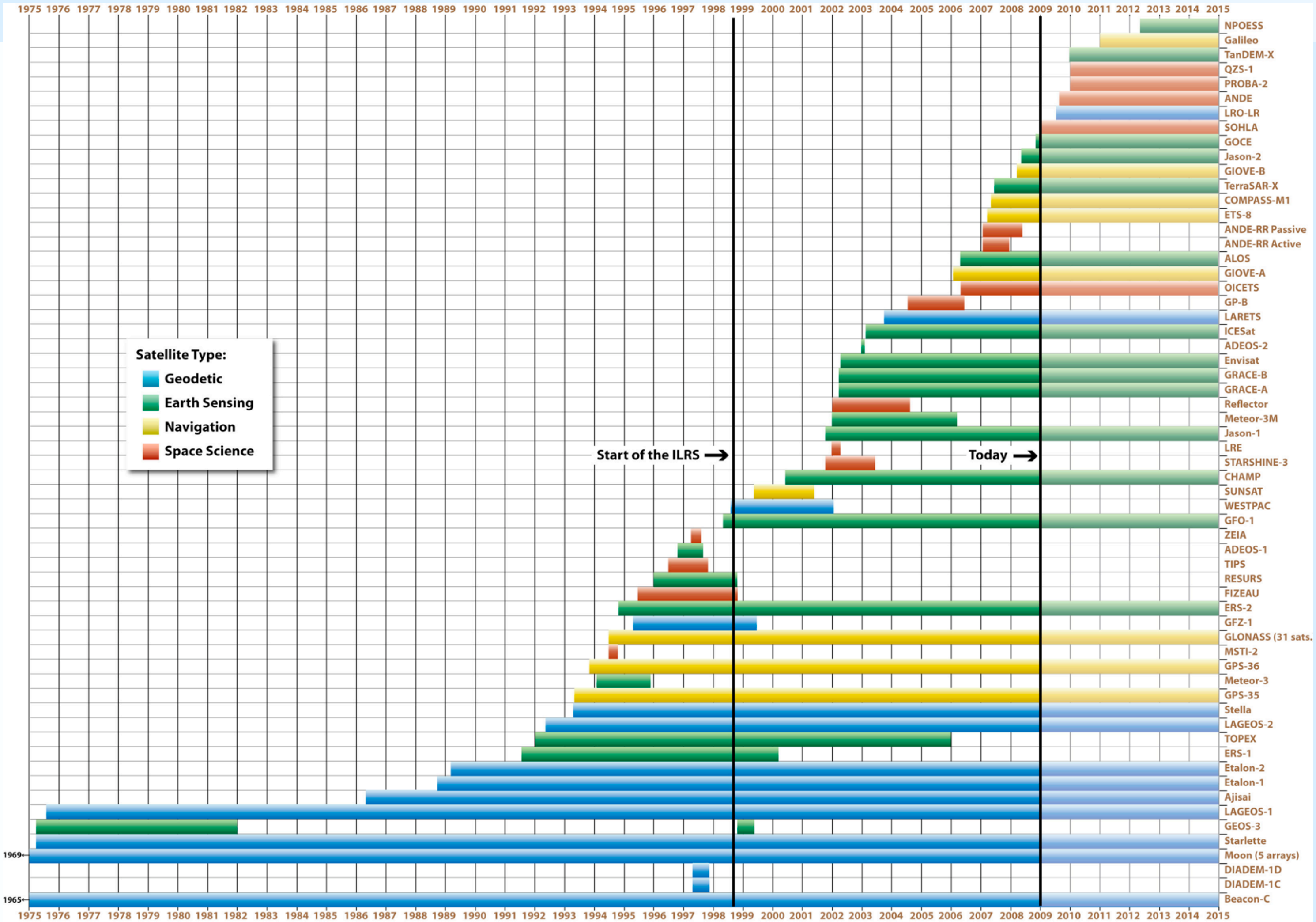
ILRS-Tracked Satellite Missions
(POD Support)

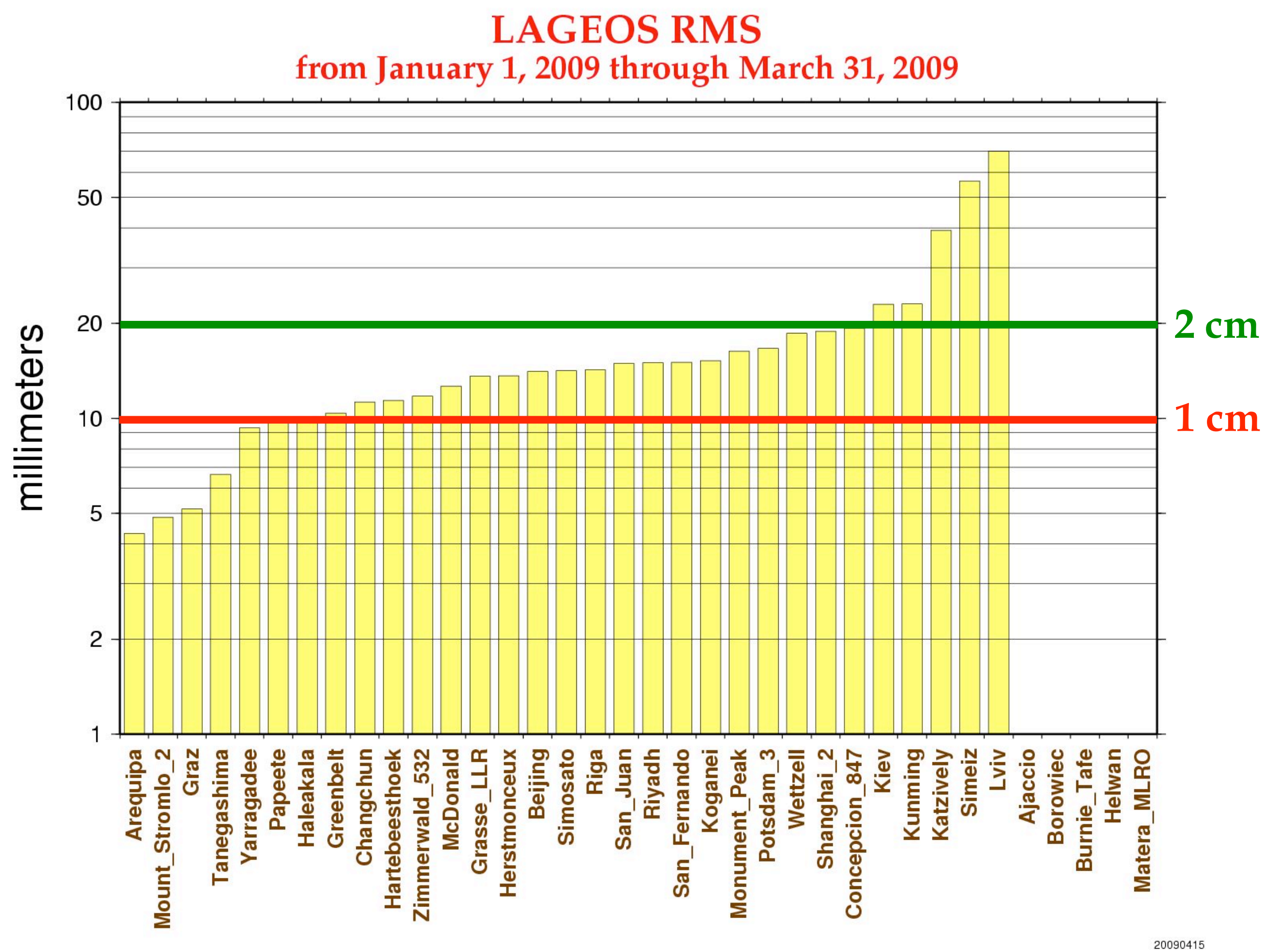


GODDARD SPACE FLIGHT CENTER

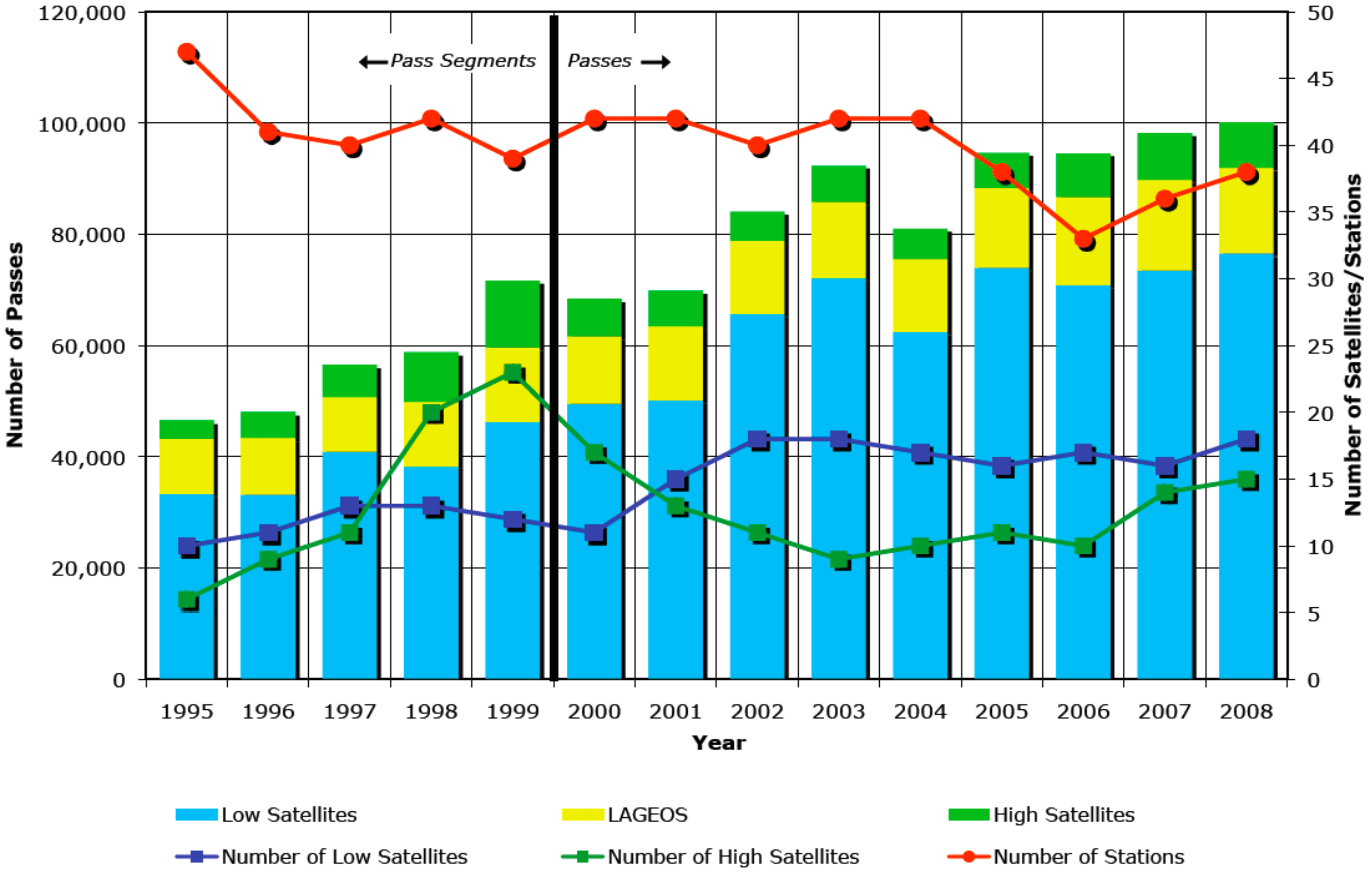
UMBC

The 1st International LARES Science Workshop, Rome, Italy *3-4 July, 2009*

ILRS-Station Performance

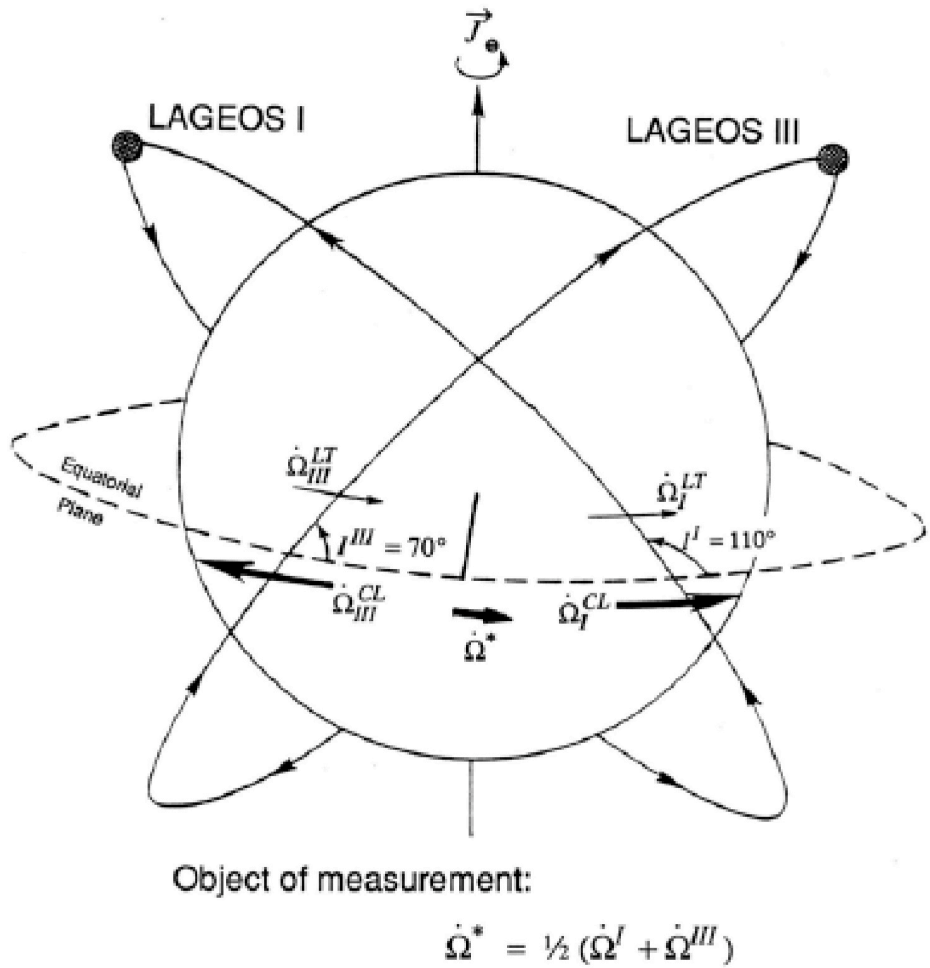


Annual Data Yield



The LAGEOS III Experiment

The original SLR experiment (LAGEOS III) expected exactly counter-rotating satellites in supplementary inclinations, to cancel classical Newtonian rates and isolate the gravitomagnetic precession



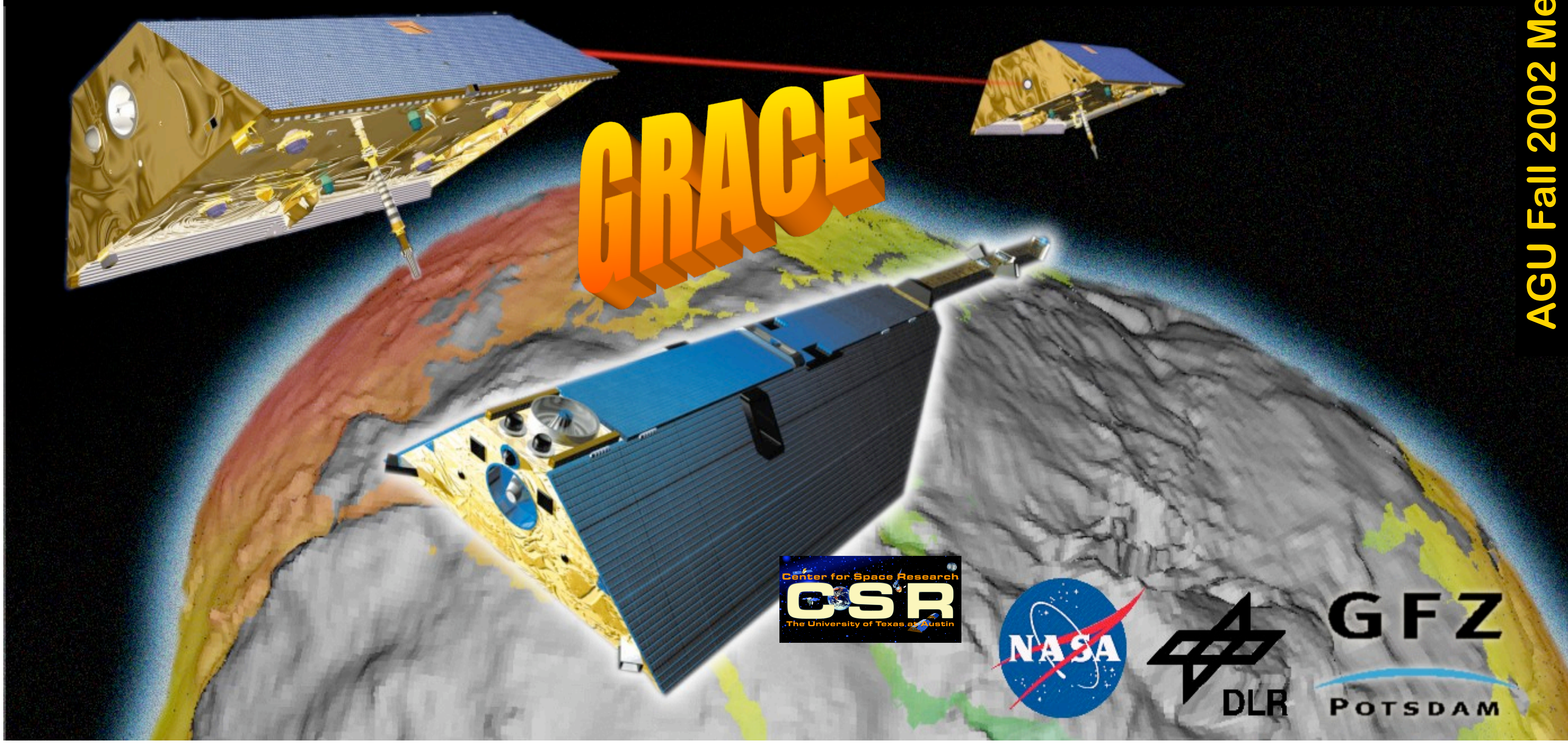
1986 Proposal at Univ. of Texas, Austin

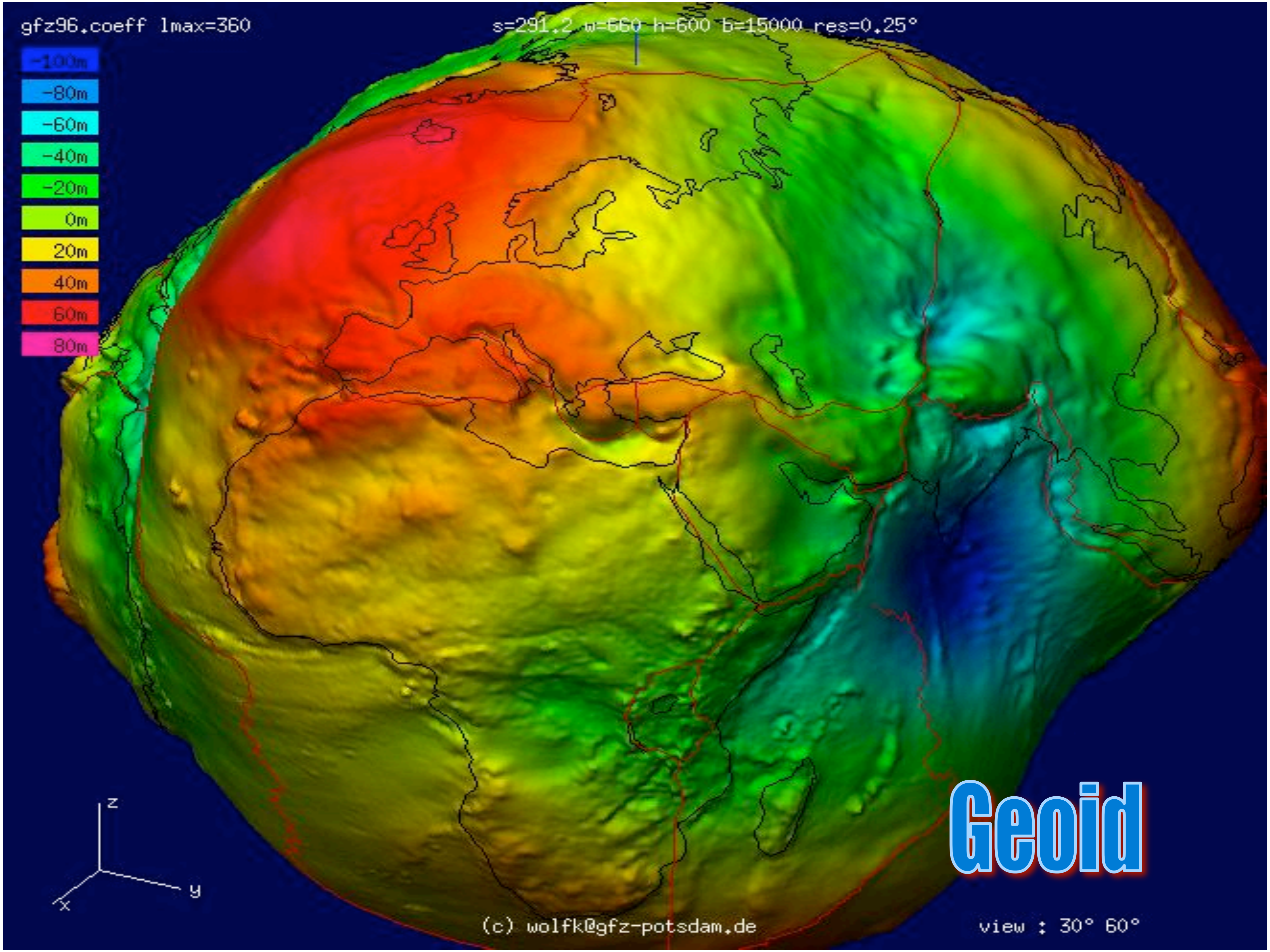
GRACE Orbit and Gravity Field Recovery at GFZ Potsdam

**Ch. Reigber, F. Flechtner, R. König, U. Meyer,
K. Neumayer, R. Schmidt, P. Schwintzer, S. Zhu**

GeoForschungsZentrum Potsdam

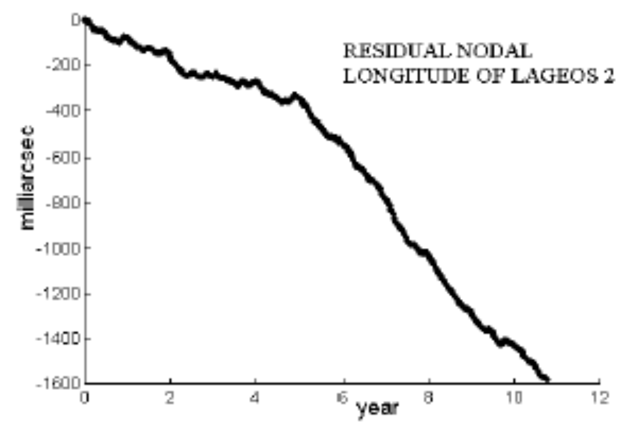
AGU Fall 2002 Meeting



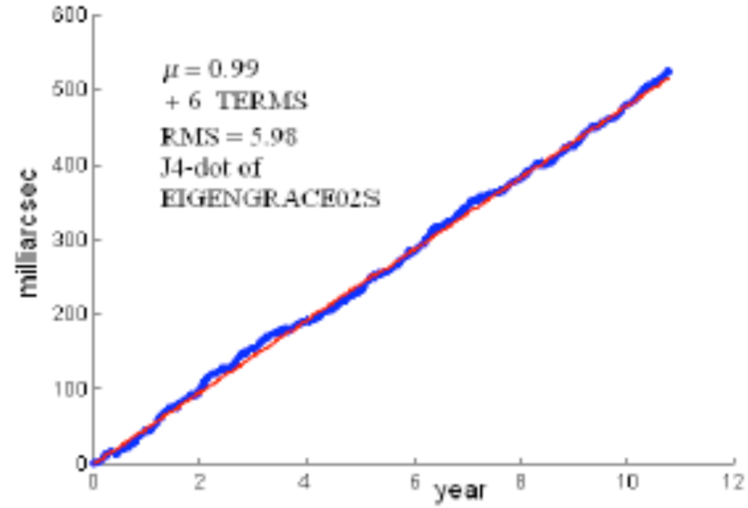

gfz96.coeff lmax=360
s=291.2 w=660 h=600 b=15000 res=0.25°
-100m
-80m
-60m
-40m
-20m
0m
20m
40m
60m
80m
z
y
x
(c) wolfk@gfz-potsdam.de
view : 30° 60°
Geoid

2004 L-T Results

$$\delta\dot{\Omega}_I + 0.545\,\delta\dot{\Omega}_{II} = 48.2\mu$$



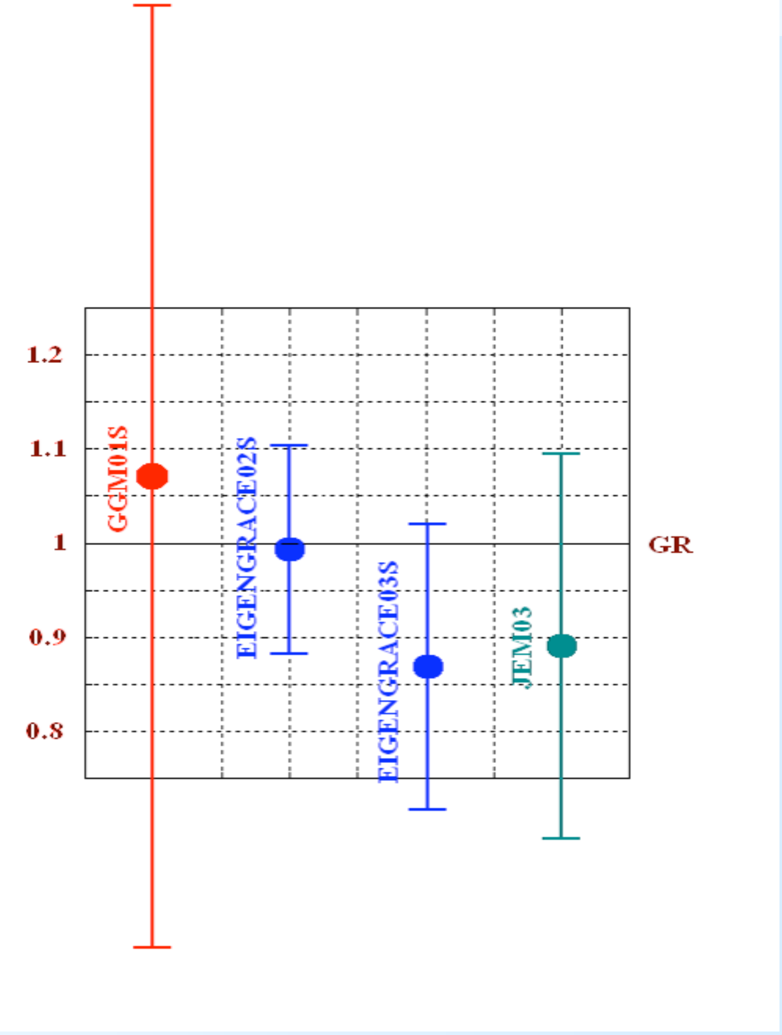
EIGEN-GRACE02S



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

GR Test Results for LT signal

- Collaborative work with Ignazio Ciufolini (UL), Rolf König (GFZ) and J. Ries
- Results up to now with GEODYN and EPOS for several GRACE models, soon to be expanded with the latest EIGEN-GRACE-4
- Positive results used to convince funding agencies for a dedicated mission (LARES) of small LAGEOS-type s/c



EPOS Validation of 2004 LT Results

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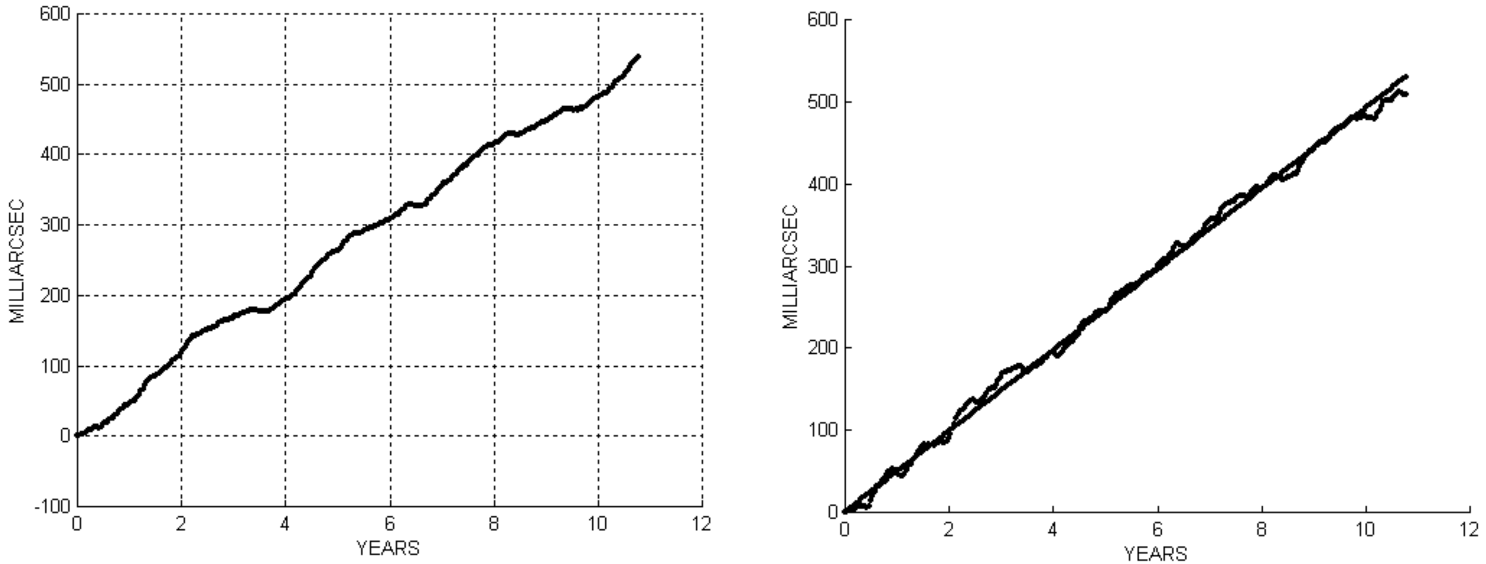

6 frequencies fit
mu=1.02 , rms=8.57

EIGEN-GRACE02S: $\mu = 1.02$ (cf. 0.99 *Nature* 2004)

- Collaborative work with Rolf König (GFZ)

GFZ POTSDAM

Why do we need improvements?

- SLR is an indispensable technique for the development of the terrestrial reference frame (origin & scale) and for geodetic metrology
- The current state-of-the-art is not meeting science requirements due to poor area coverage and aging equipment
- To meet the stringent future requirements (e.g. GGOS), we need to design a new network and, in coordination with the other techniques, deploy modern hardware systems

Sample of SLR Satellite Constellation
(Geodetic Satellites)

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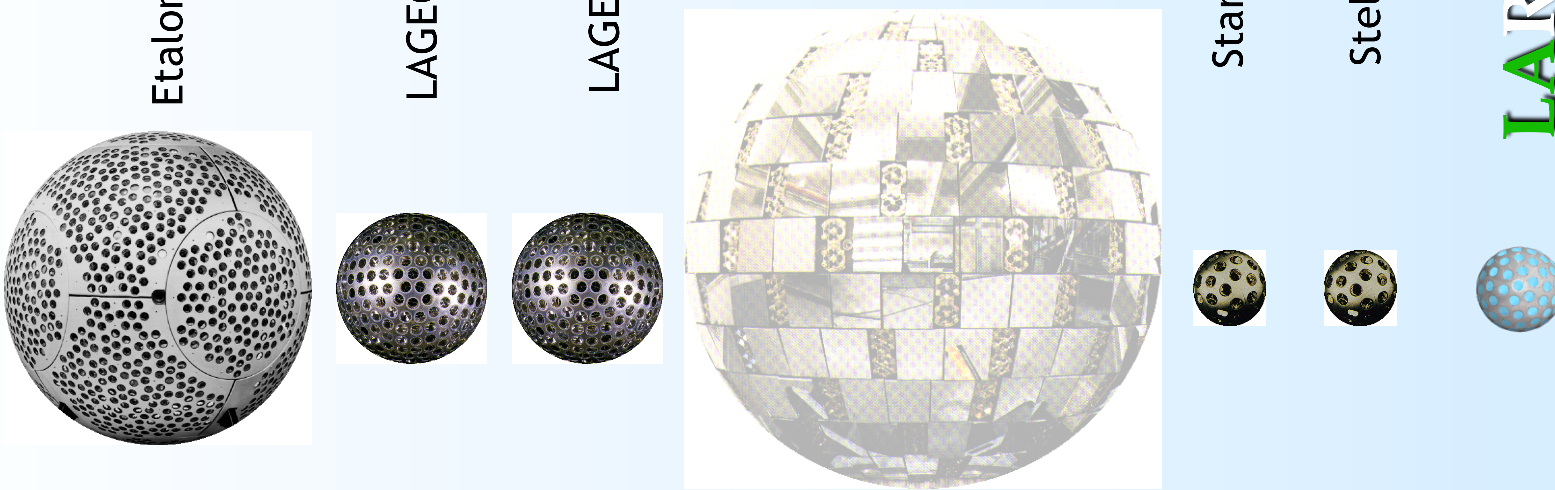
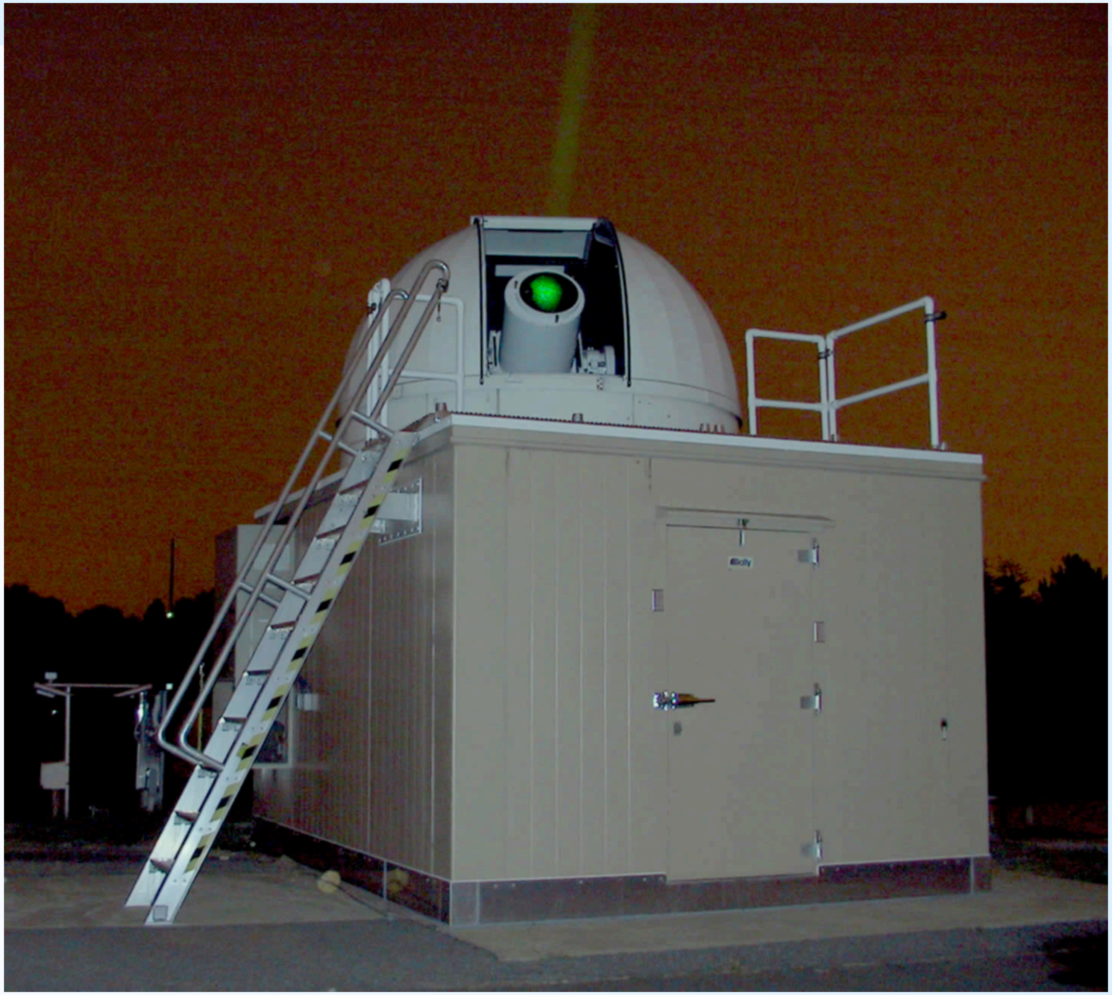


	Etalon-I & -II	LAGEOS-1	LAGEOS-2	Ajisai	Starlette	Stella	LARES
Inclination	64.8°	109.8°	52.6°	50°	50°	98.6°	~70°
Perigee ht. (km)	19,120	5,860	5,620	1,490	810	800	~1500
Diameter (cm)	129.4	60	60	215	24	24	36
Mass (kg)	1415	407	405.4	685	47.3	47.3	~400

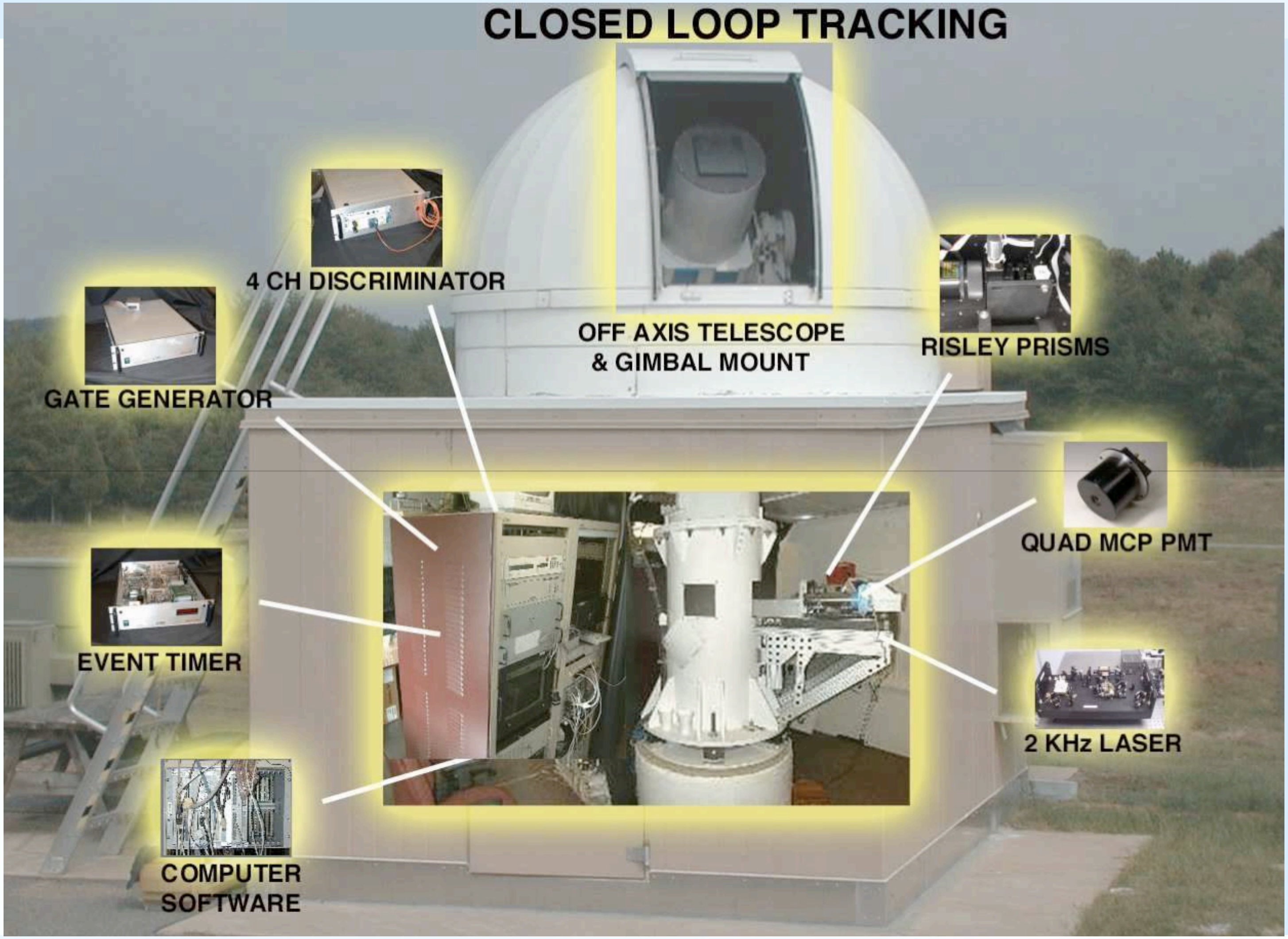
LARES $_{A/m}$ = 0.36 x LAGEOS

NASA Next Generation SLR System



NASA's Next Generation SLR (NGSLR), GGAO, Greenbelt, MD

NGSLR Components



Future kHz SLR Sites

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Increasing Number of Stations upgrading to kHz:

➢ Graz	2 kHz	Operational since 4 years
➢ NSGF	2 kHz	Operational
➢ Potsdam	2 kHz	Software in development
➢ Zimmerwald	0.1 kHz	Laser ordered, Software in progress OPERATIONAL
➢ SLR 2000	2 kHz	Tracking demonstrated
➢ TIGO	0.1 kHz	2-Color, operational
➢ SOS-W	1 kHz	2-Color; expected in mid 2008
➢ Metsahovi	2 kHz	Laser installed; needs telescope etc
➢ Matera	? kHz	Applying for money
➢ China	2 kHz	Up to 5 Stations planned
➢ FTLRS	0.1 kHz	Planned (French Mobile System)
➢ ???		

2 kHz SLR @ Graz, Austria

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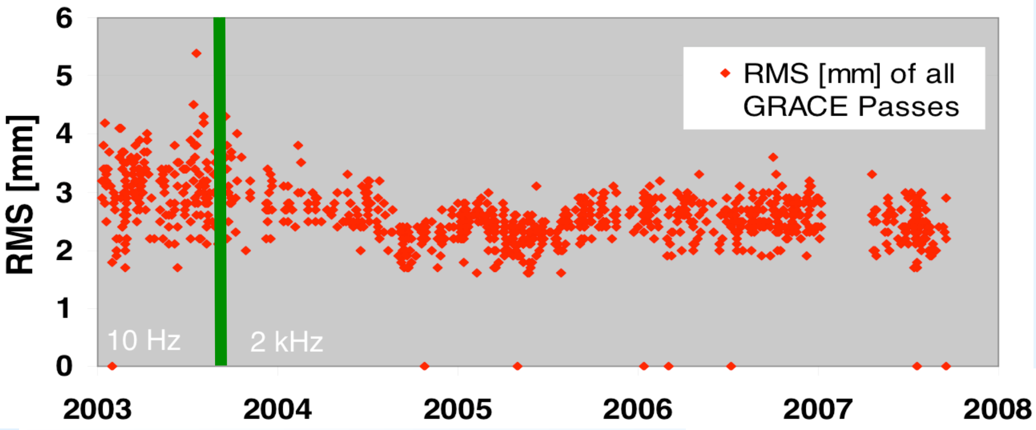
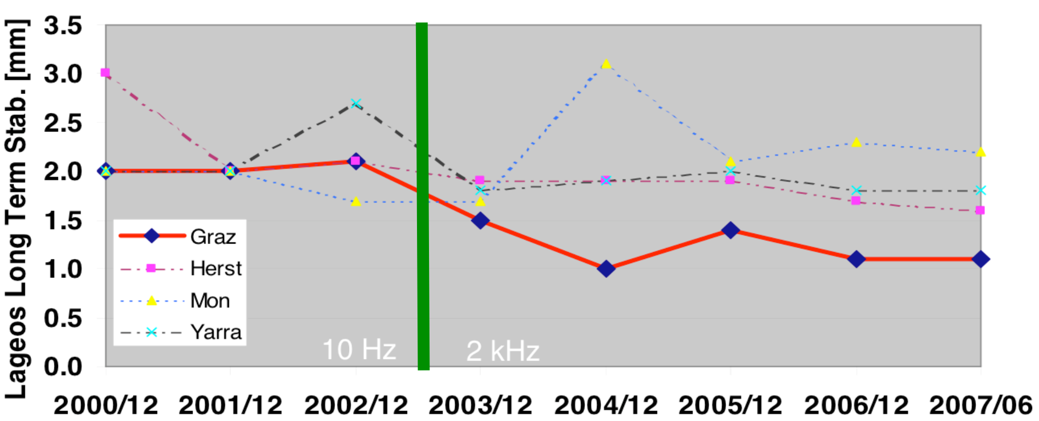
GRAZ: GRACE 2003-2007: SS RMS:
3.0 mm @ 10 Hz; 2.5 mm @ 2 kHz



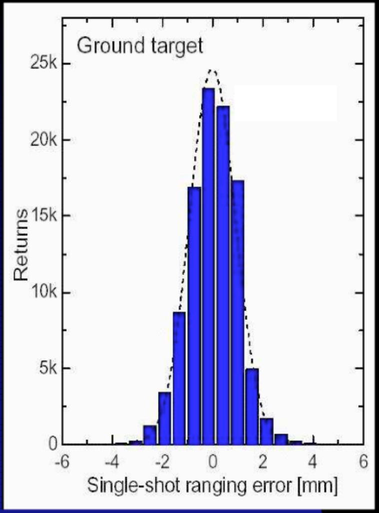
Lageos Long Term Stability [mm]

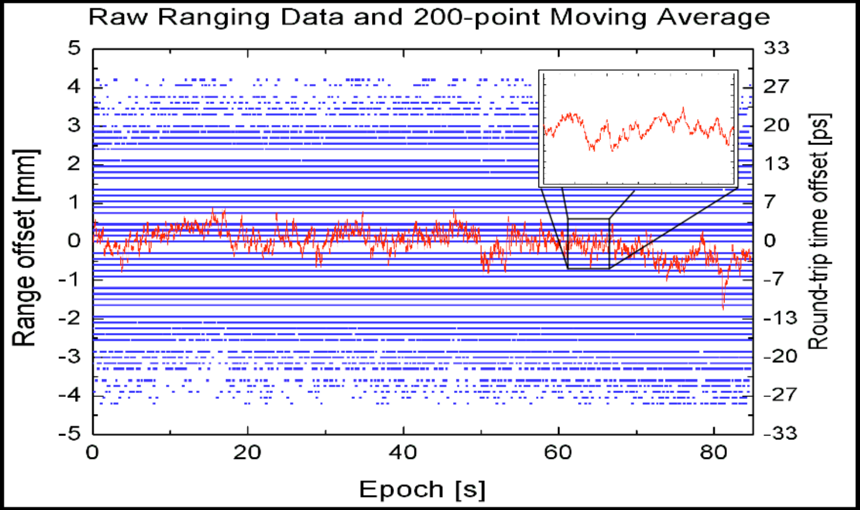


Seeing Effects in SLR

Ground target laser ranging, 4 km, Graz

Atmospheric fluctuations resolving





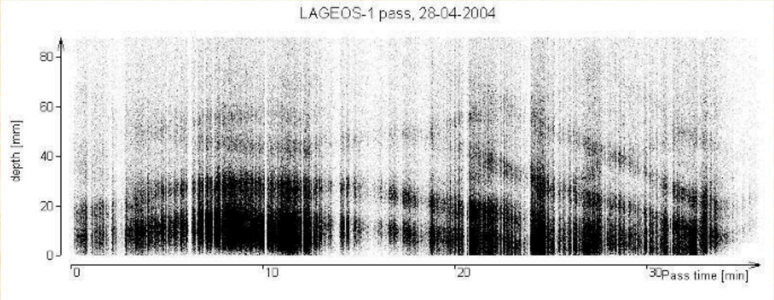
- the atmospheric turbulence-induced contribution to the overall jitter determined for the first time
- instrumental 0.9 mm rms
- atmospheric 0.6 mm rms => 1.1 mm total

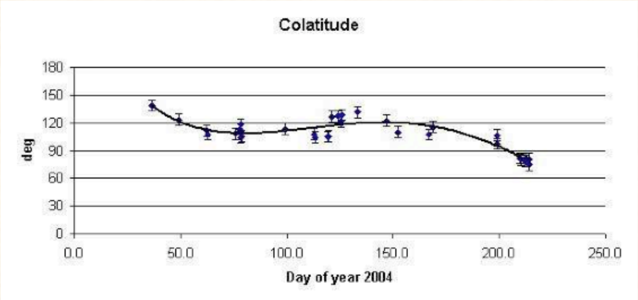
L.Kral, I.Prochazka, Grasse, September 2007

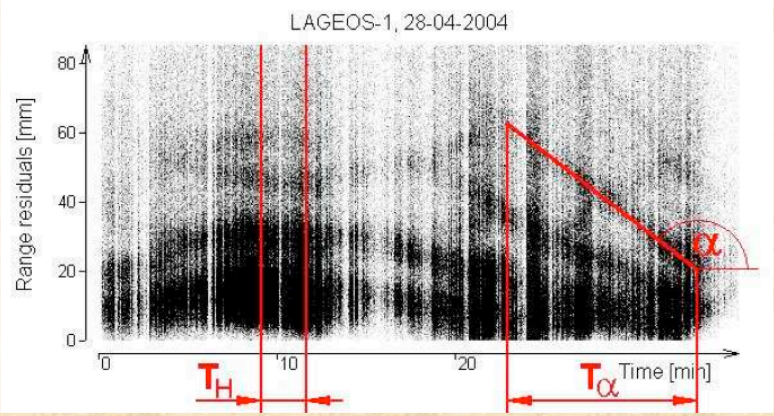
Spin-axis Orientation

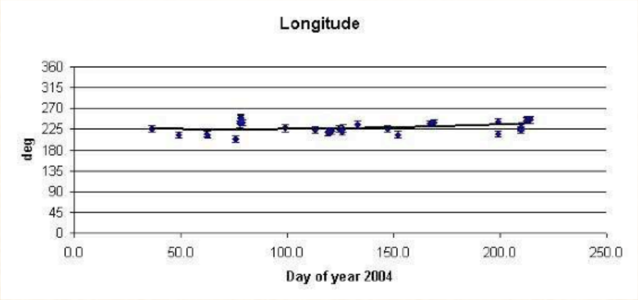
Spin determination from kHz SLR

LAGEOS-1





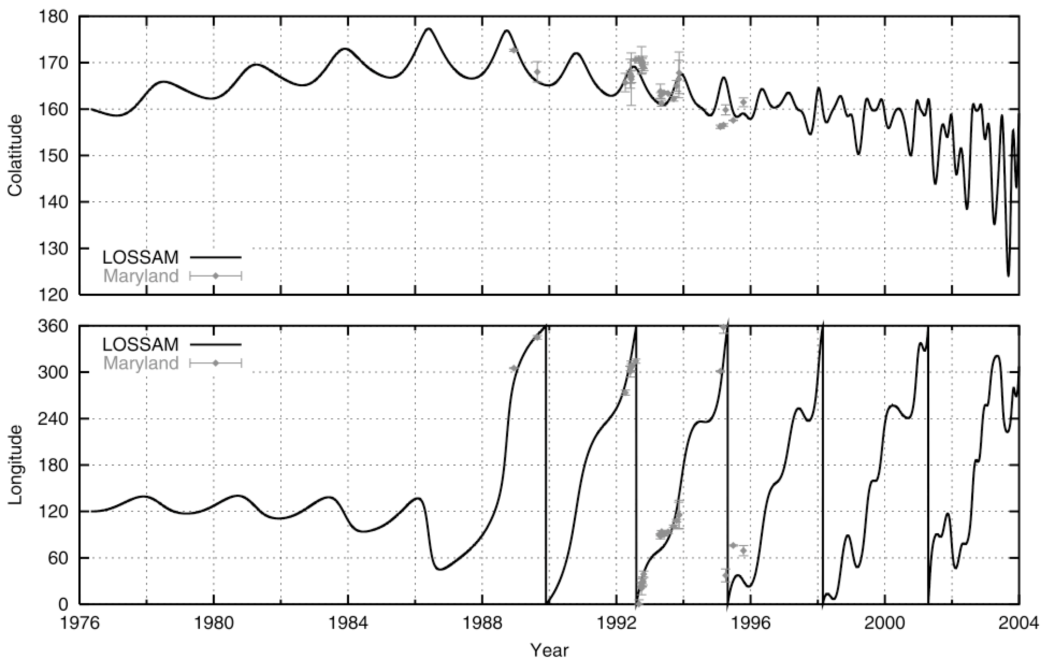




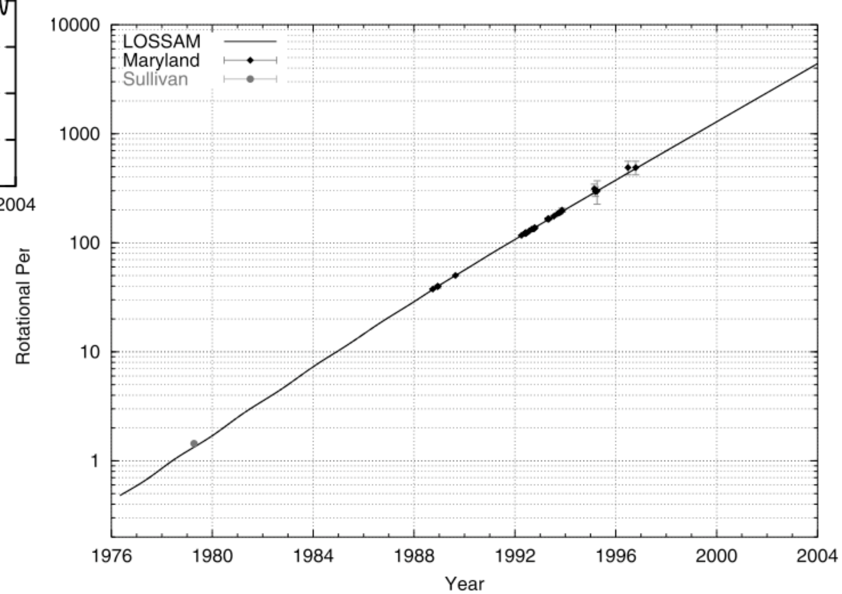
T=5775 s

Kucharski, D., Kirchner, G., Schillak, S., et al. Spin determination of LAGEOS-1 from kHz laser observations. J. Adv. Space Res., 39(10), 1581, doi:10.1016/j.asr.2007.02.045, 2007

LAGEOS Spin-axis Model

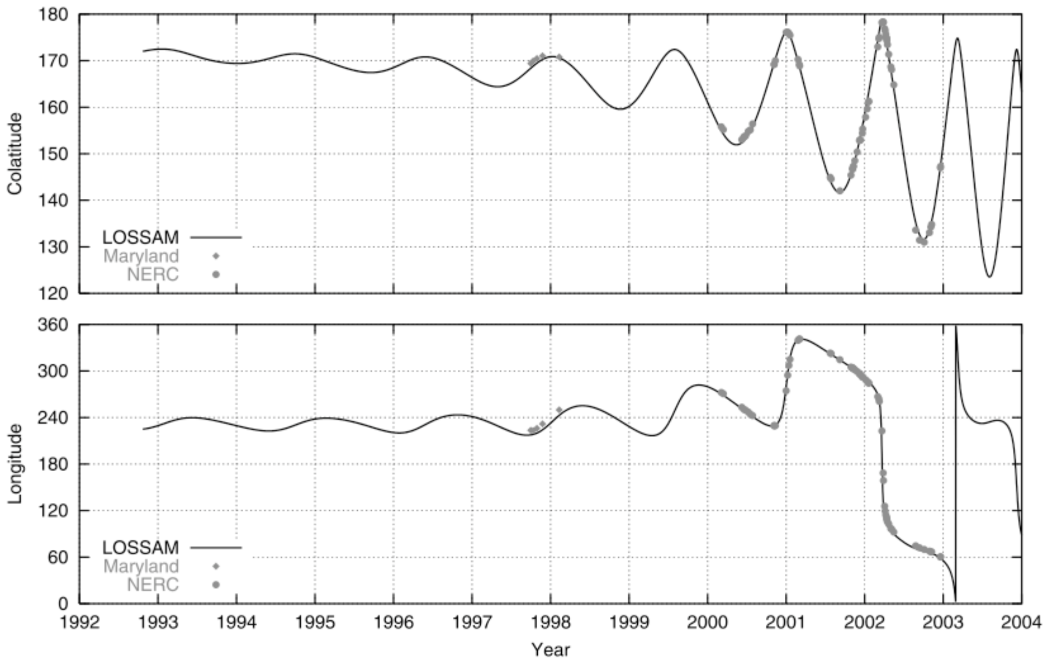


LOSSAM

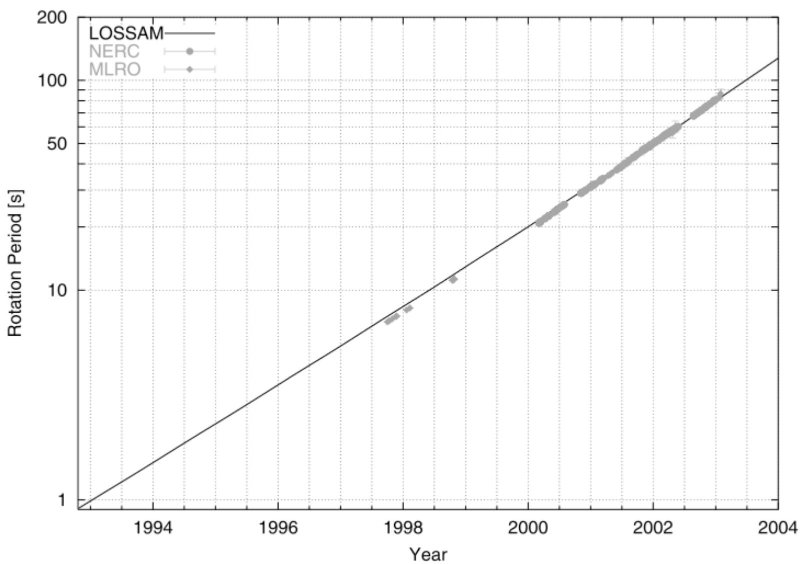


J. I. Andres, et al.
JOURNAL OF GEOPHYSICAL RESEARCH,
VOL. 109, B06403, doi:10.1029/2003JB002692, 2004

LAGEOS 2 Spin-axis Model

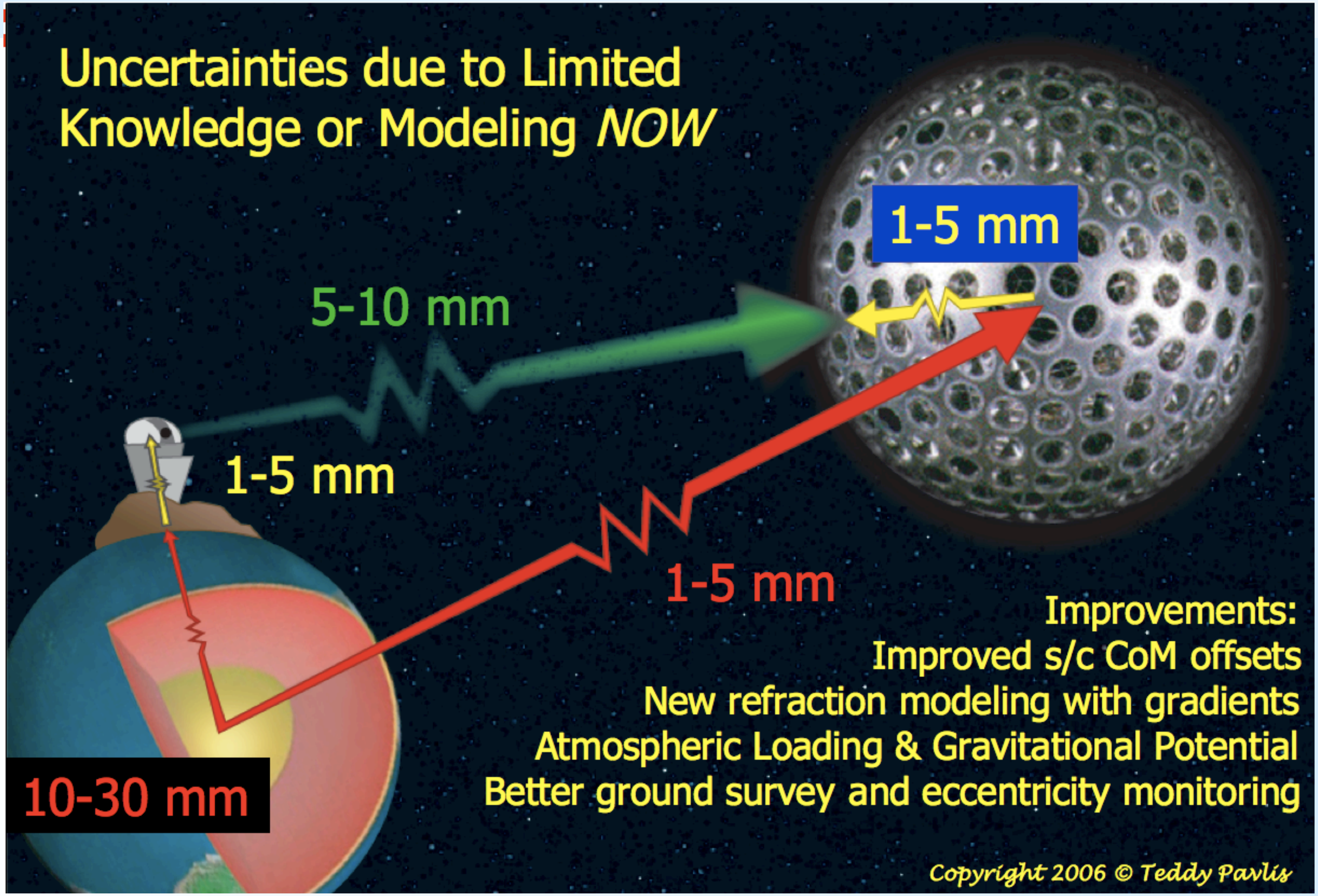


LOSSAM

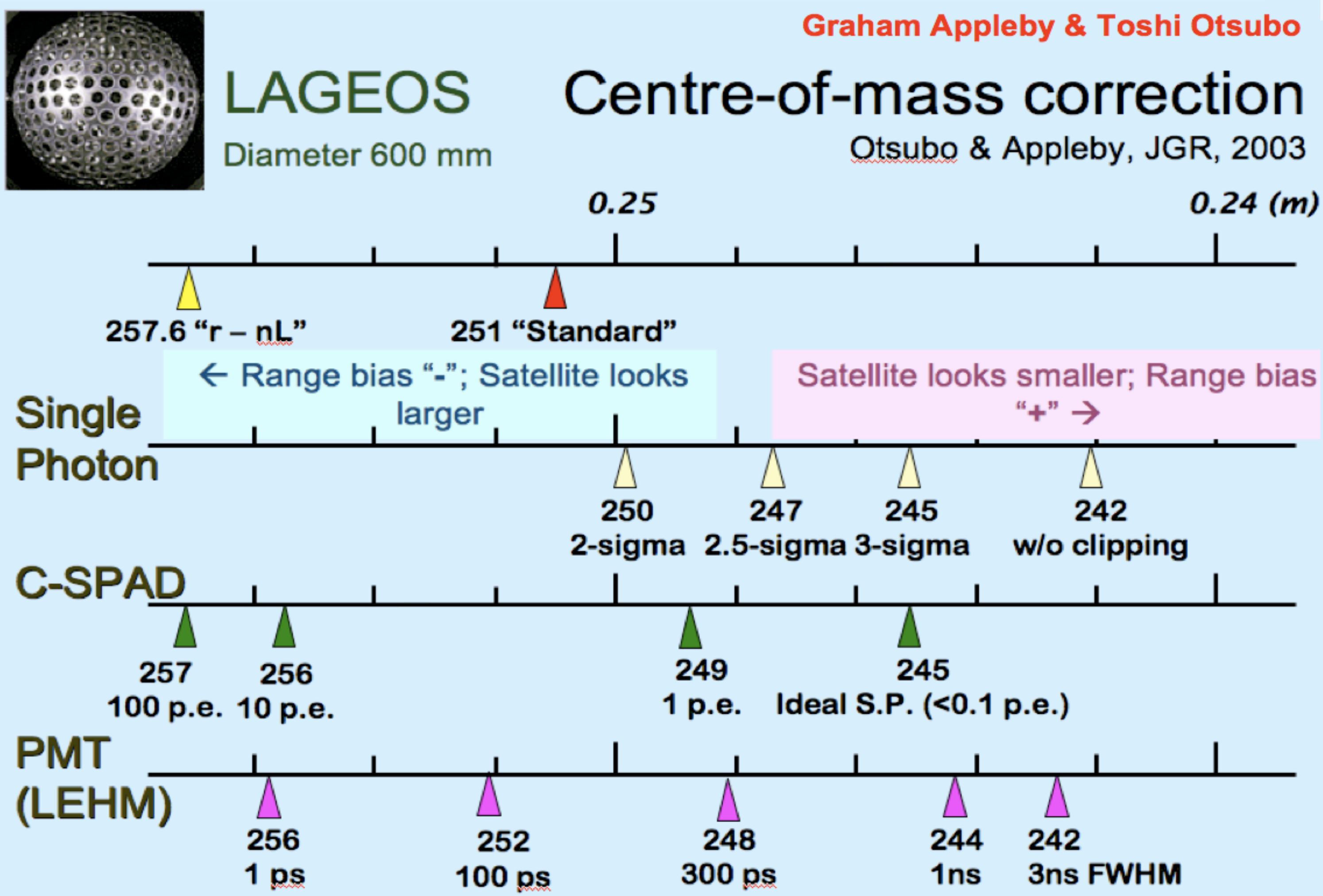


J. I. Andres, et al.
JOURNAL OF GEOPHYSICAL RESEARCH,
VOL. 109, B06403, doi:10.1029/2003JB002692, 2004

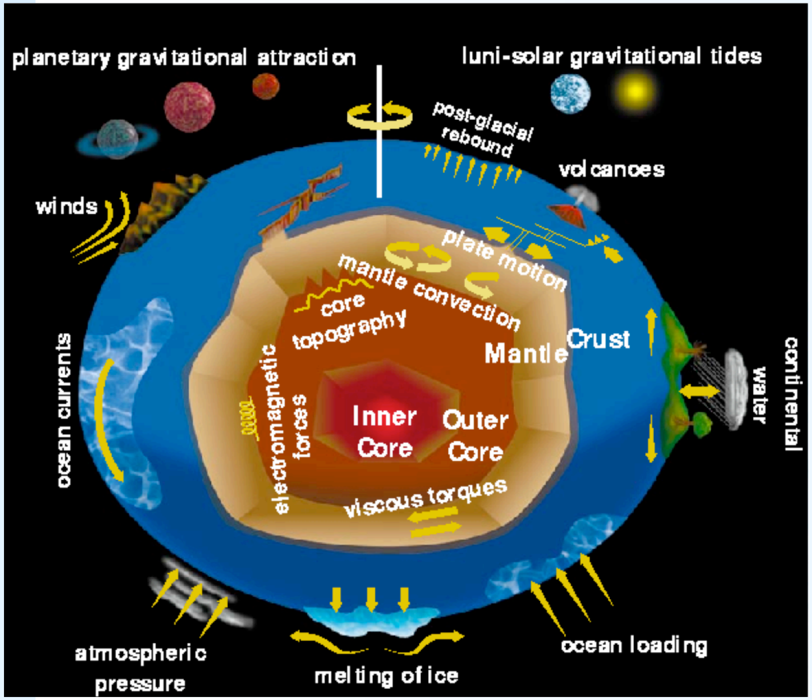
Current SLR Model Status



Target signature (CoG)



Earth System Interactions

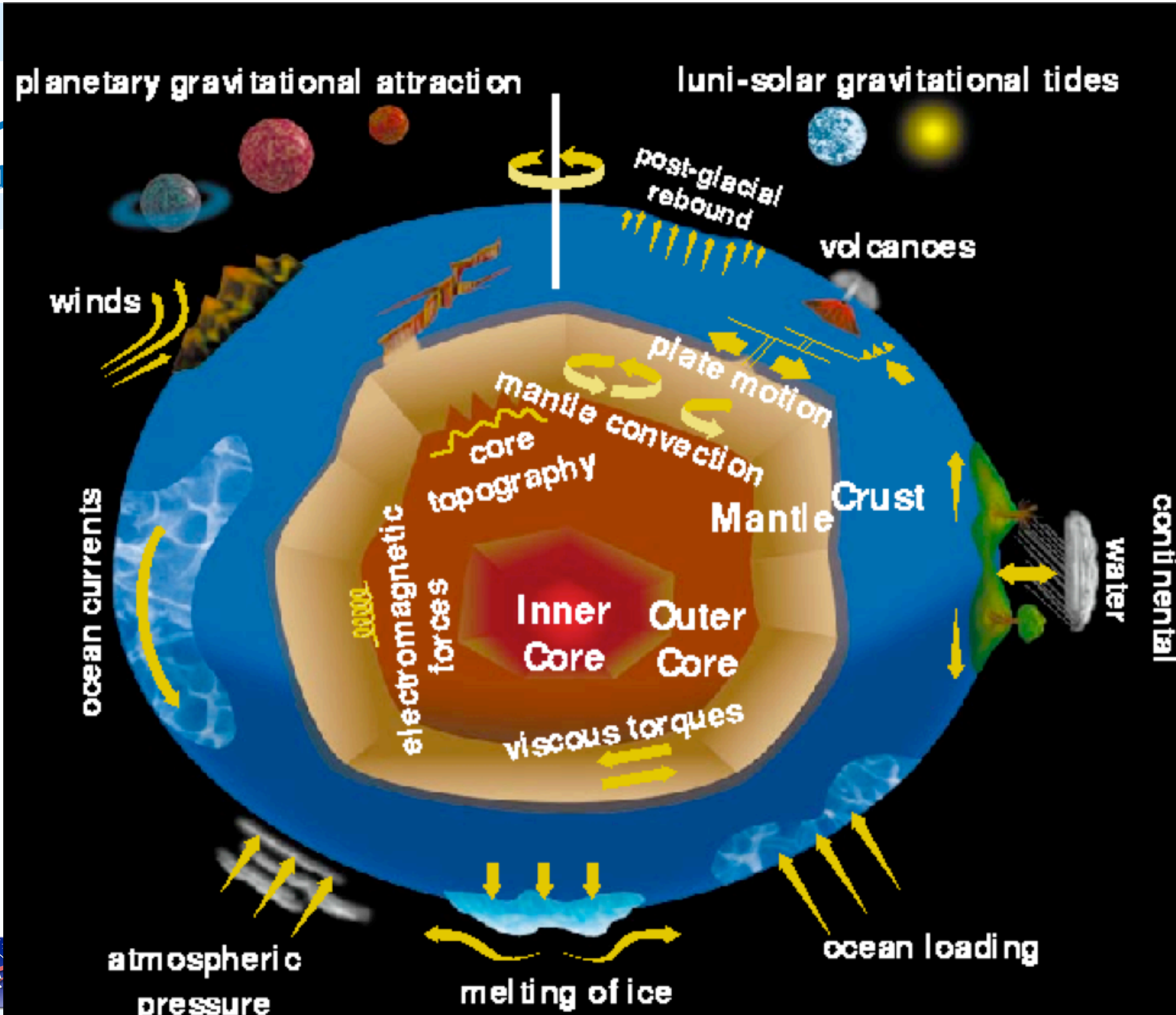


Mass redistribution in Earth System monitored regularly by various remote sensing techniques (*atmosphere & oceans*).

Global fields with increasingly higher spatiotemporal resolution readily available to the analysts.

Technology is advancing with rapid pace in recent years worldwide

As LR data become more accurate we will soon face the limitation of our modeling standards, generally of 20th century vintage.



planetary gravitational attraction
luni-solar gravitational tides
post-glacial rebound
volcanoes
winds
plate motion
mantle convection
core topography
Crust
Mantle
electromagnetic forces
Inner Core
Outer Core
viscous torques
ocean currents
water
continental
atmospheric pressure
melting of ice
ocean loading

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Multiple techniques to solve the puzzle

- **High precision geodesy is very challenging**
  - 0.1 mm/yr stability required for sea level monitoring
- **Fundamentally different observations with unique capabilities**
- **Together provide redundancy, cross validation and increased accuracy for TRF**
- **Strength from improvement of techniques and integration of techniques**

- Fundamental prerequisite: ***Well-distributed, co-located network with accurate ties***

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

TRF Requirement

- Future ITRFs* should exhibit consistently and reliably accuracy and stability at the level of:

<1 mm in epoch position, and

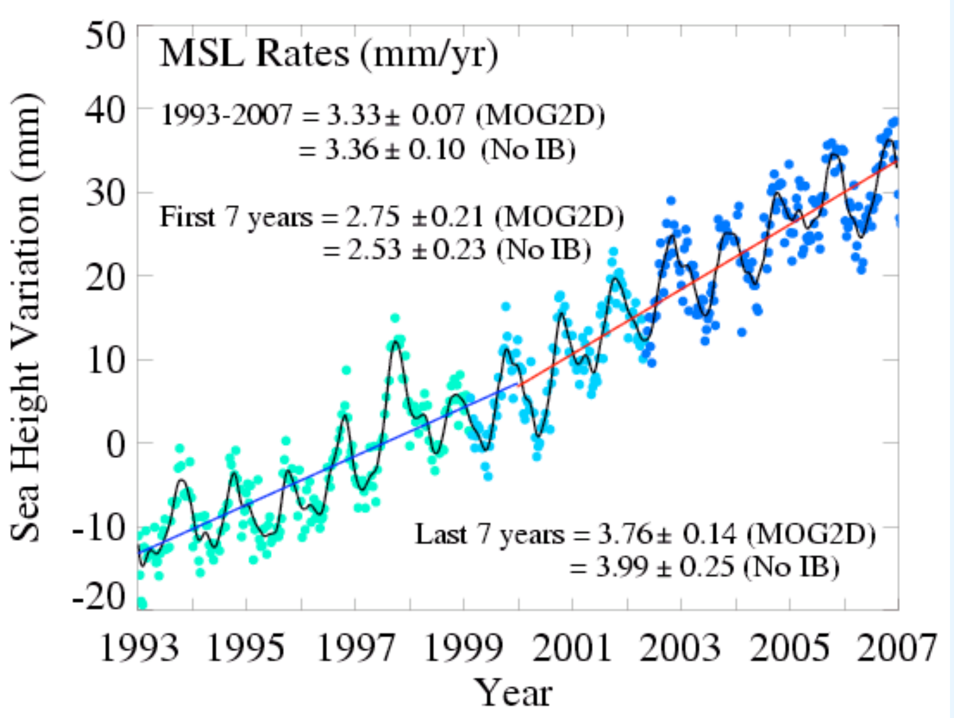
< 0.1 mm/yr in secular change

***Current performance: ~ 10 mm and ~ 1 mm/yr**

- **Increased accuracy for fundamental physics tests and LT in particular (goal is < 1%)**

Why 1 mm / 0.1 mm/yr ?

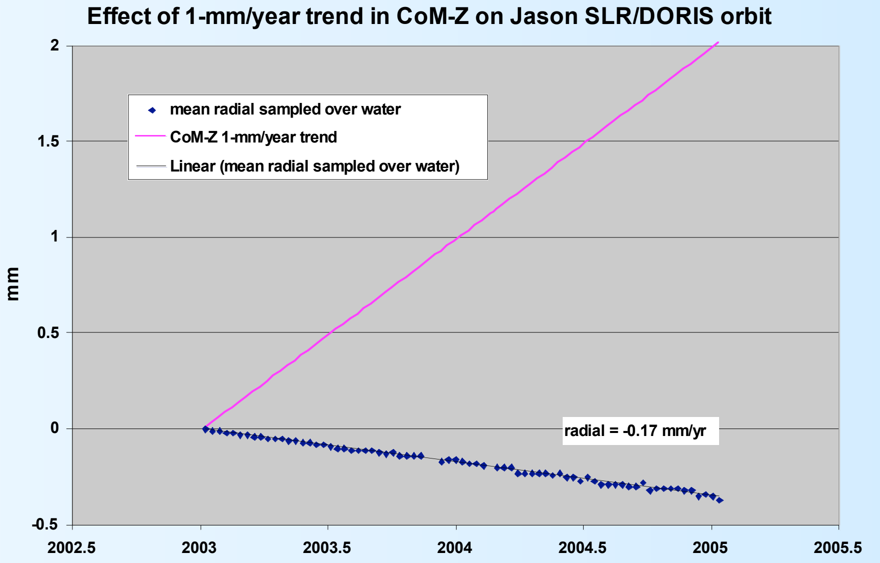
ITRF2005: 3.3 +/- 0.07 mm/yr



Beckley et al. (2007), *GRL, Fig 4*

For every 1 mm/yr Z-trend in the TRF origin, sea-level rates are affected by ~ 0.2 mm/yr

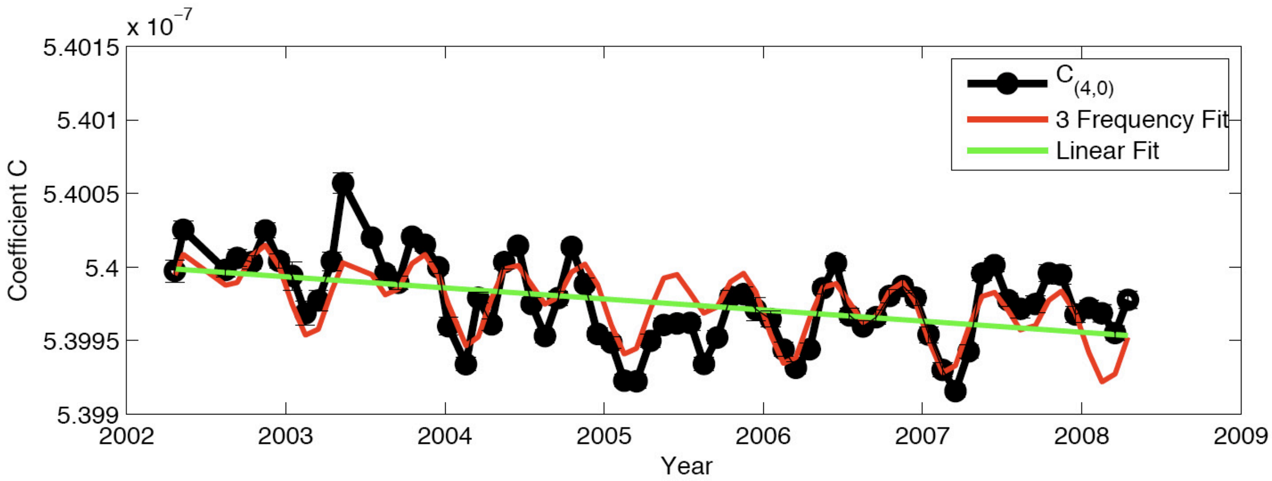
Lemoine et al. (2008), EGU2008-A-11368

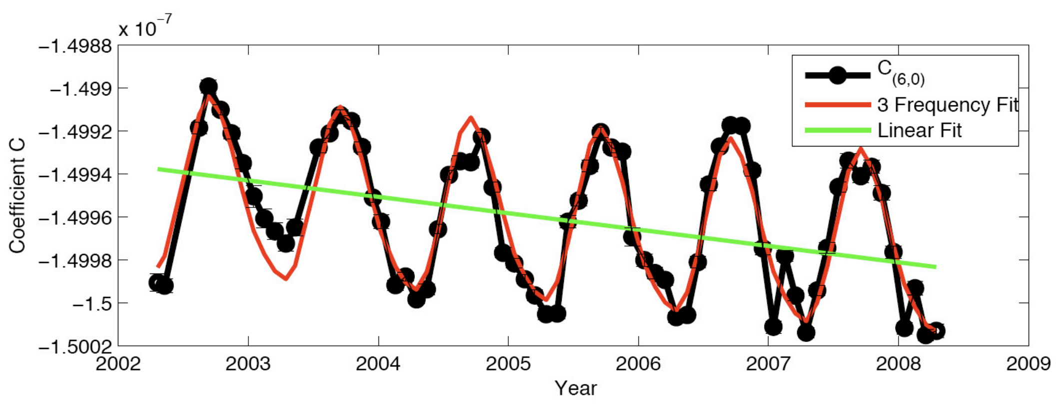


Candidate Models

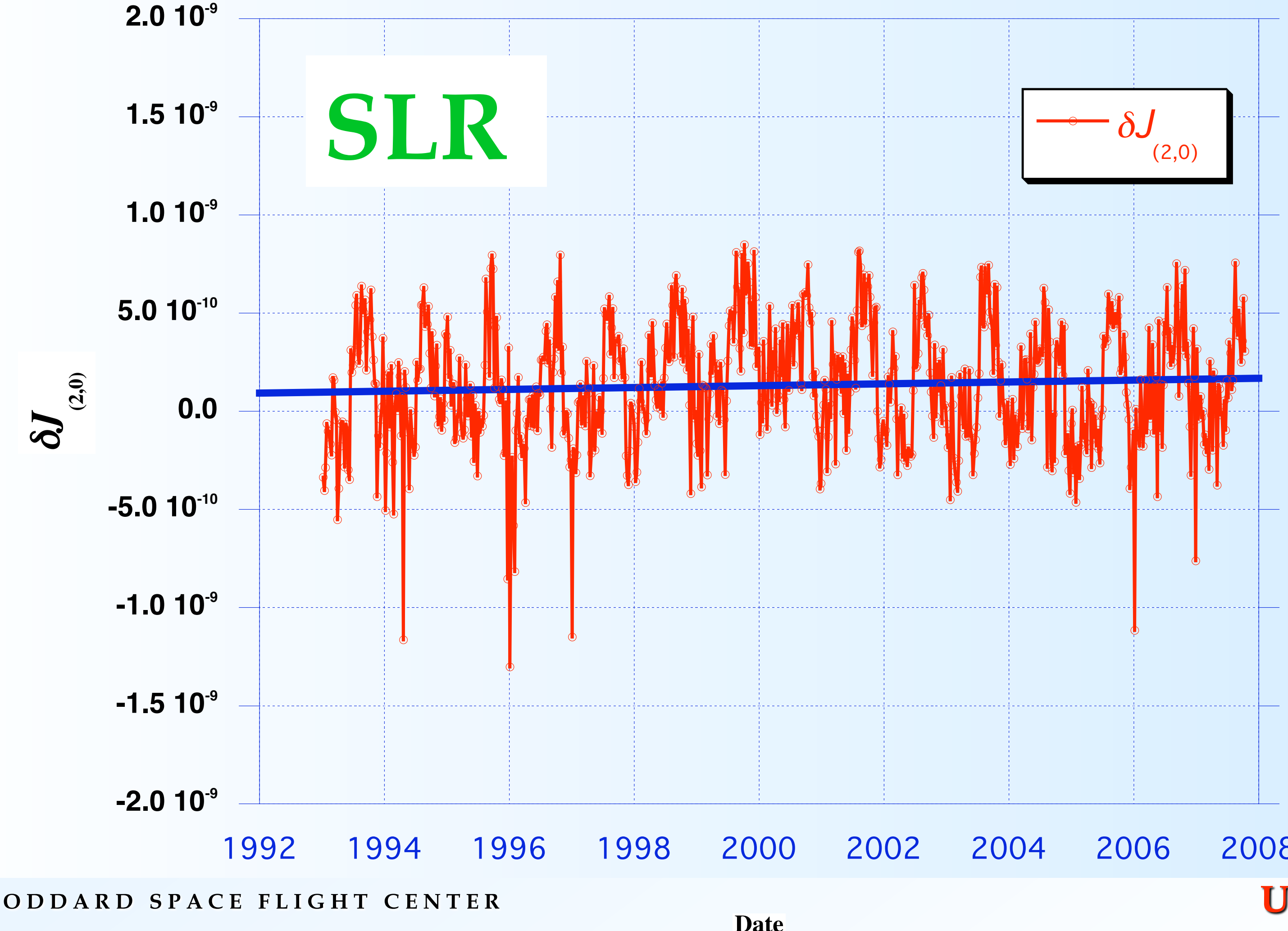
- Extended temporal gravity variations
  - NCEP or ECMWF (3 or 6 hr *t*-resolution, 0°.25,…)
  - GRACE-derived monthly fields & de-aliasing products
  - Other combinations
- Atmospheric loading (NCEP, ECMWF as above), hydrological loading (GLDAS)
- New ocean tides (GOT04.7 or more recent) with proper atmospheric tide treatment
- Atmospheric refraction from 3D ART to include gradients
- Albedo (e.g. higher degree-order seasonal model)
- …

Zonals $C_{4,0}$ and $C_{6,0}$





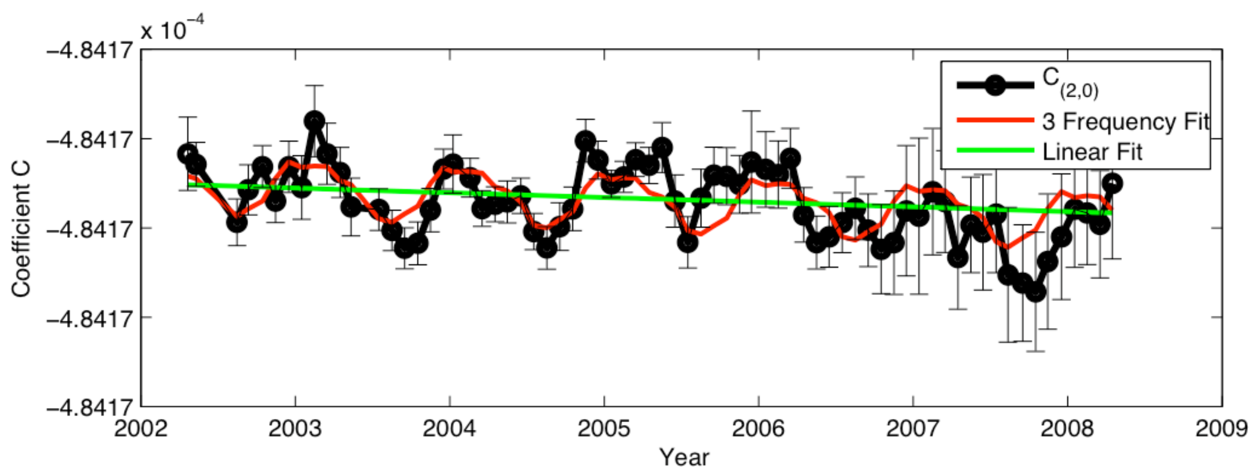
Second Degree Variations - J_2

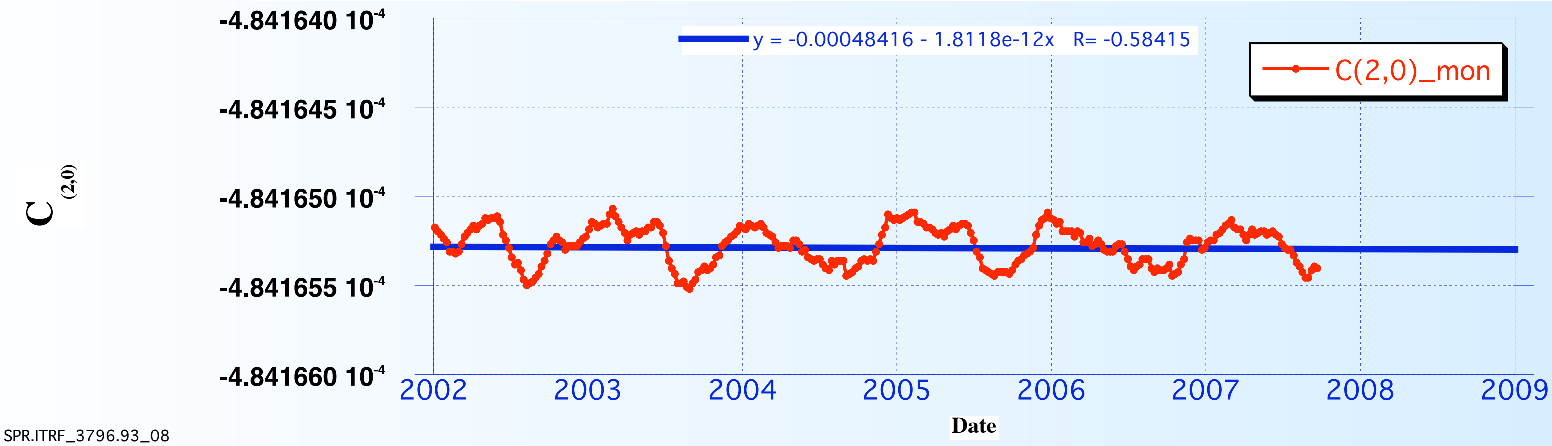


Second Degree Variations - $C_{(2,0)}$

GRACE Monthly Product (●)

Trend (---) & 3 Frq. Fit





SPR.ITRF_3796.93_08

Second Degree Variations - $C_{(2,0)}$

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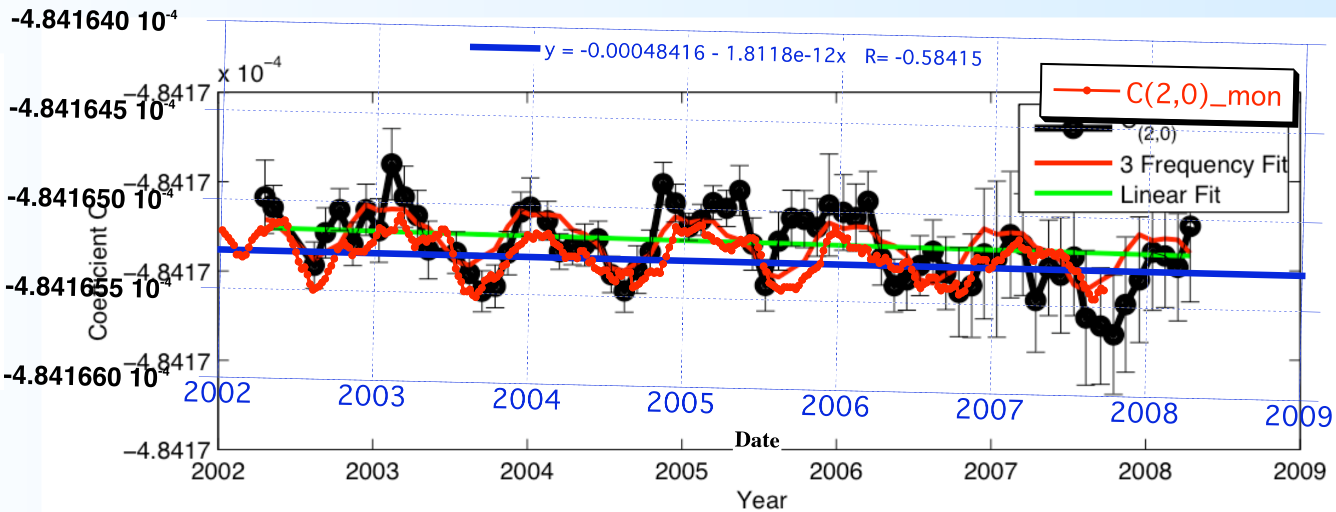
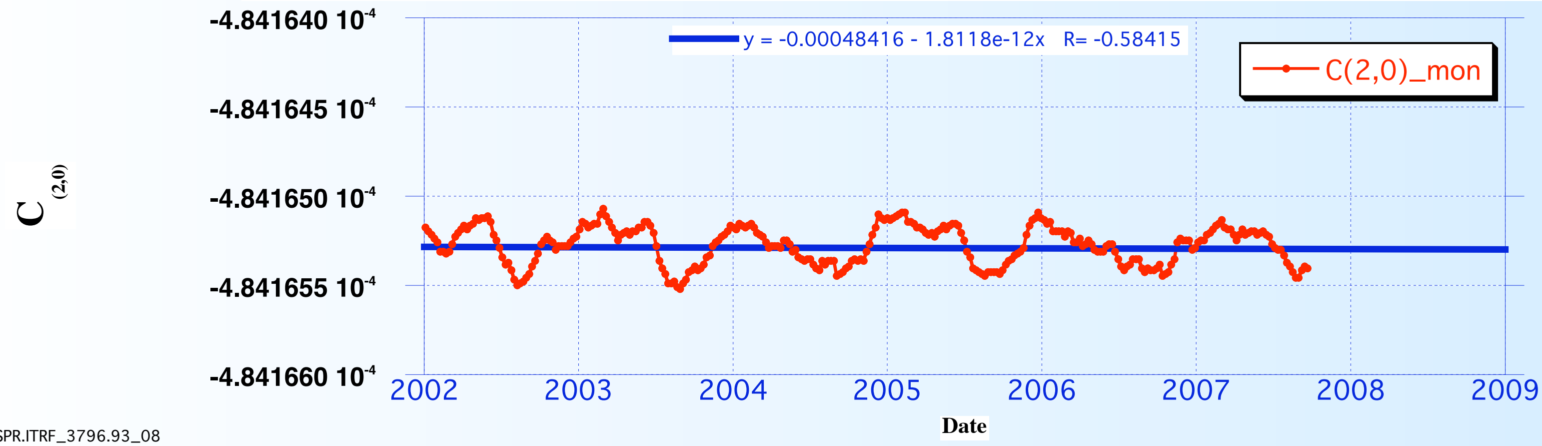
GRACE Monthly Product (●)

Trend (---) & 3 Frq. Fit



SPR.ITRF_3796.93_08



SPR.ITRF_3796.93_08

Atmospheric Loading (ECMWF)

Difference in the RMS of fit of weekly arcs of LAGEOS SLR for 2001 & 2006

and four Atmospheric loading treatments (one being NO loading)

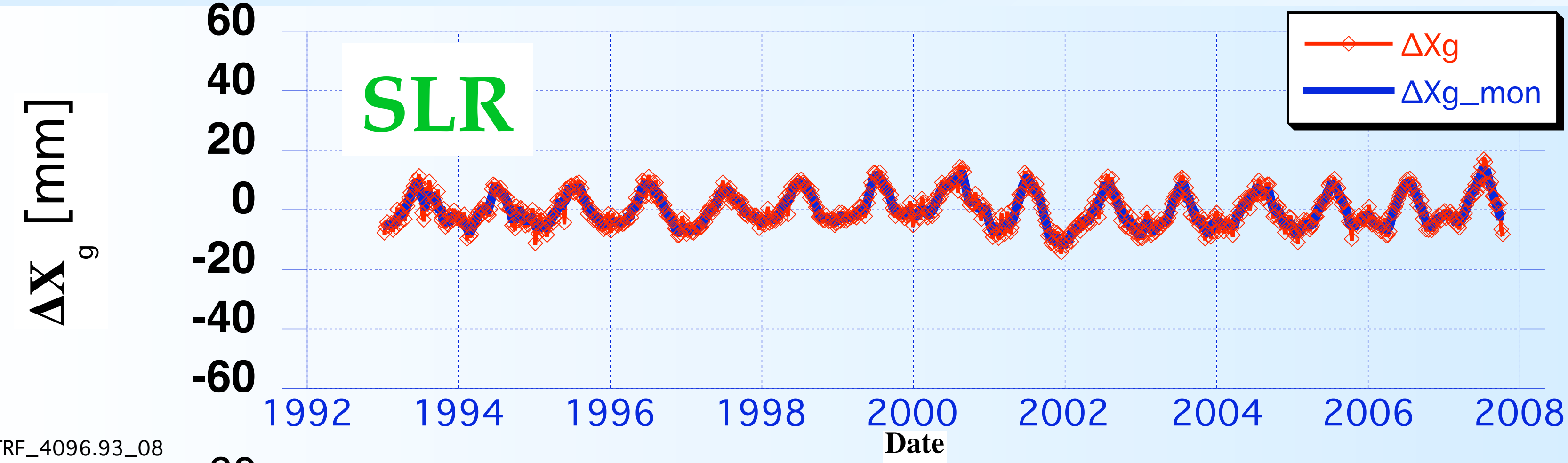
Variable	Points	Mean	Median	RMS	Std Deviatio
ΔRMS v0-NO	52	3.4	2.7	4.45	2.87
ΔRMS v1-NO	104	2.9	2.1	4.31	3.16
ΔRMS v2-NO	52	2.7	1.7	4.09	3.08
ΔRMS v1-v0	52	0.4	0.0	0.92	0.82
ΔRMS v2-v1	52	1.7	1.4	2.58	1.96

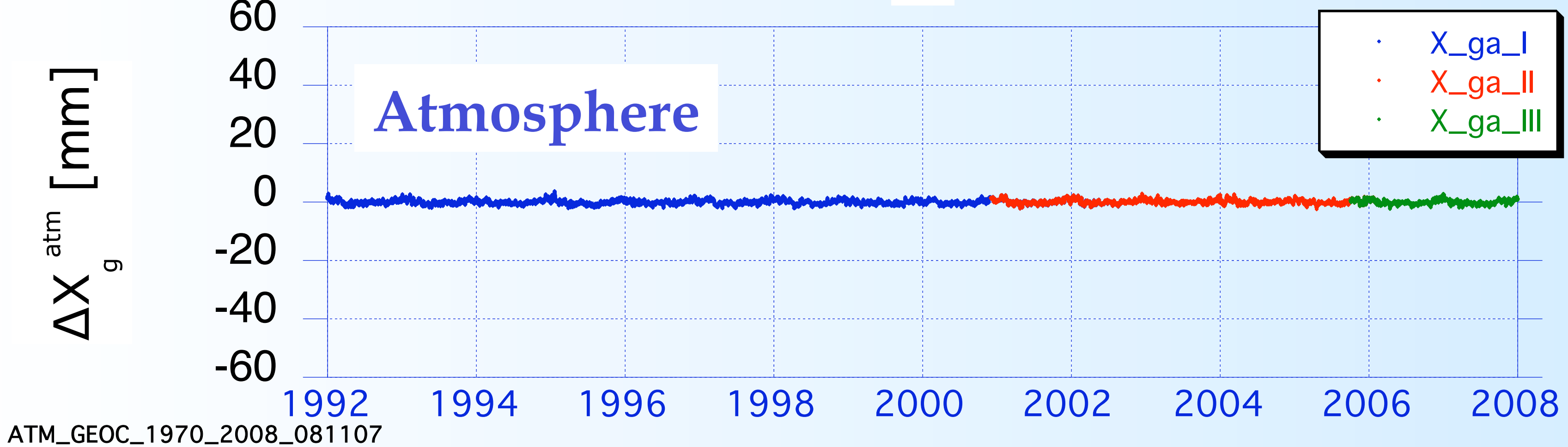
"v0": 1970/01 - 2002/08: ECMWF Reanalysis (ERA40), with a spatial resolution of 1.125 degrees

"v1": 2000/12 - 2006/12: ECMWF Operational, with a spatial resolution of about 0.350 degrees

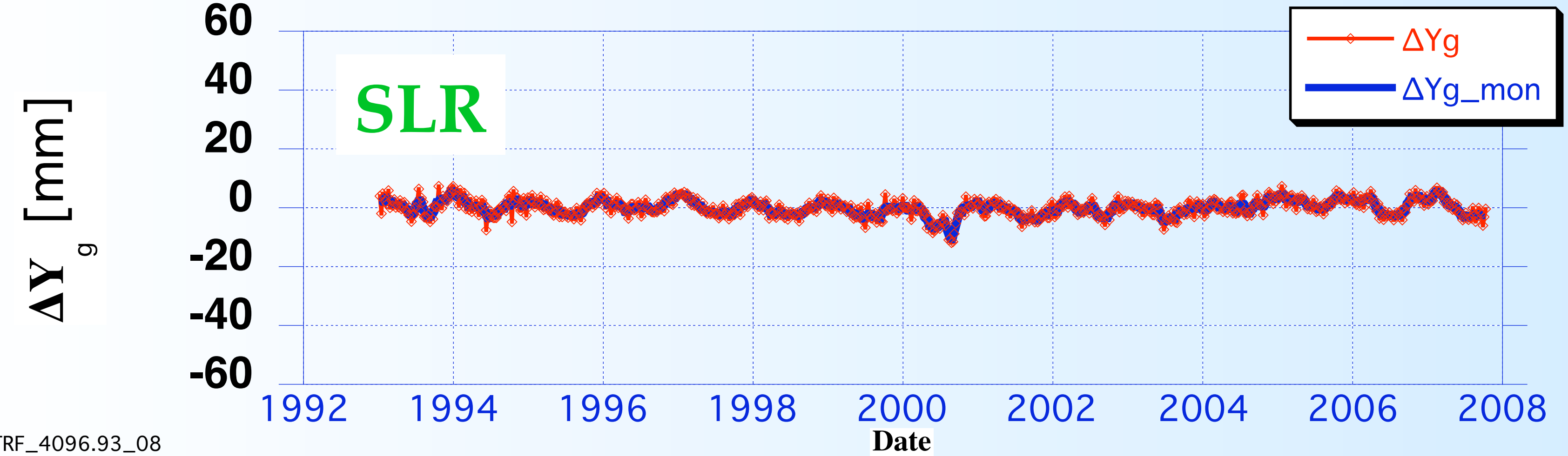
"v2": 2005/10 - now: ECMWF Operational, with a spatial resolution of about 0.250 degrees

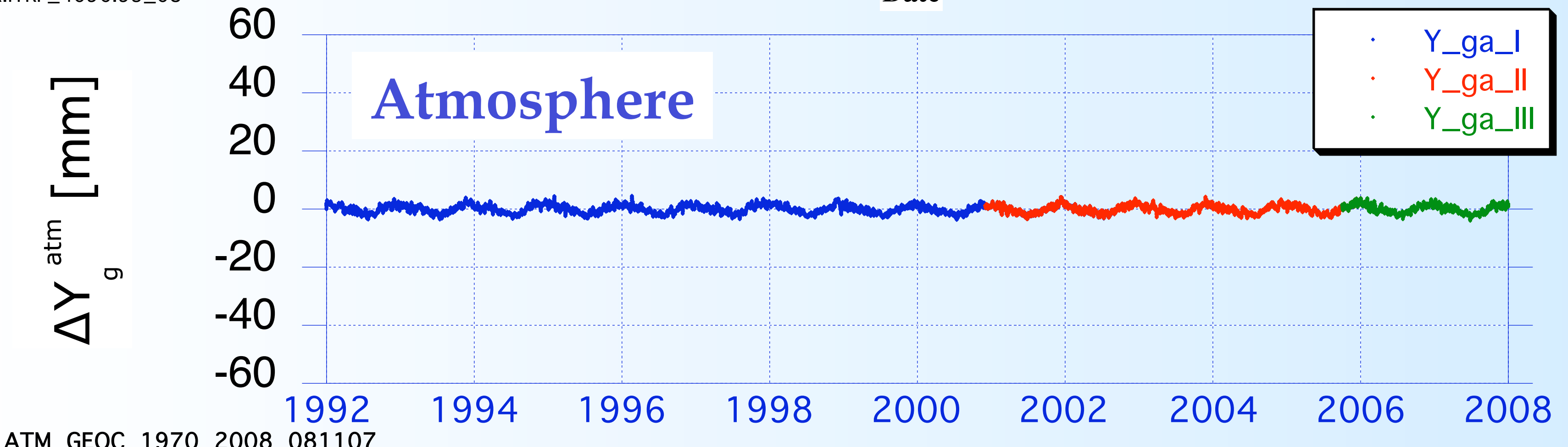
Geocenter Monitoring - X



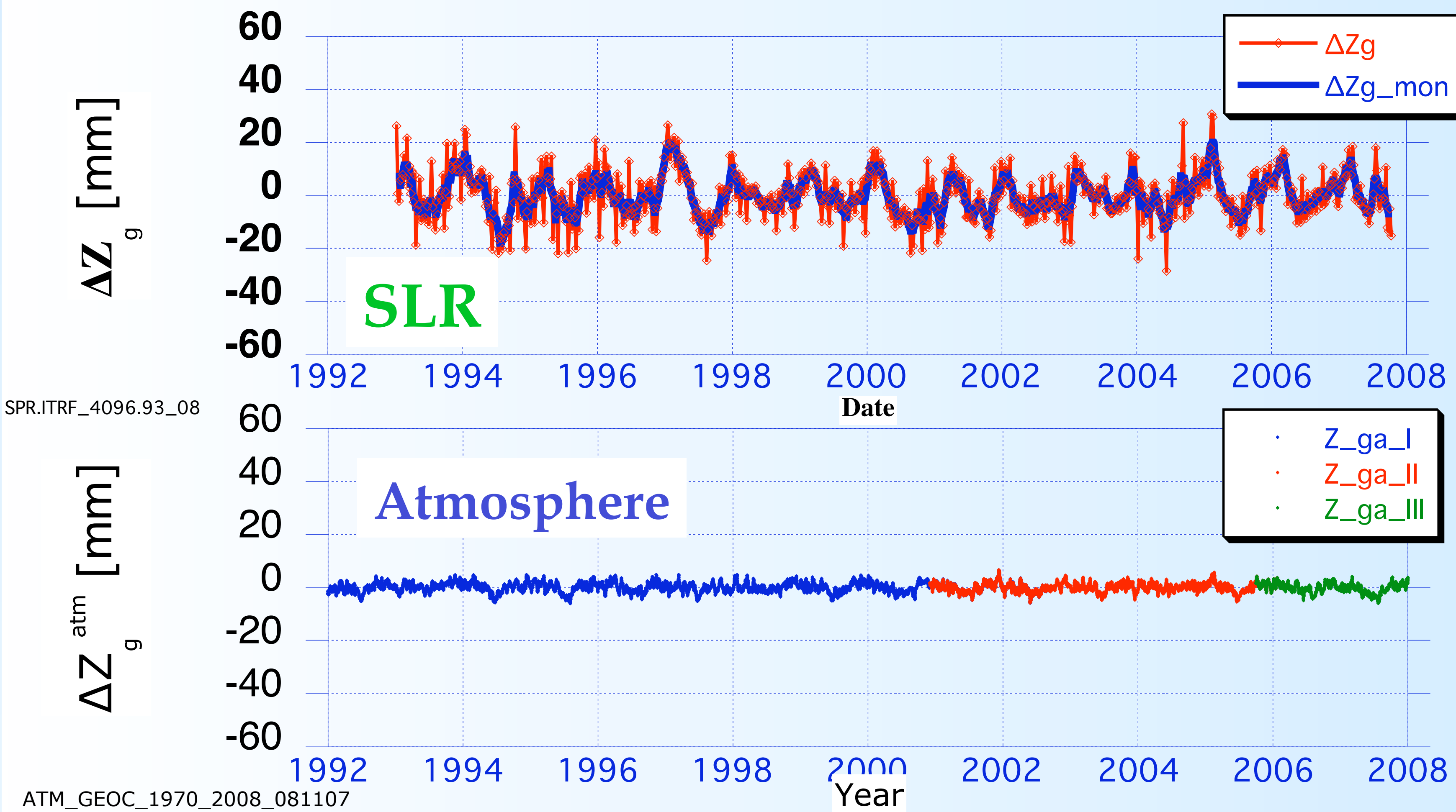


Geocenter Monitoring - Y





Geocenter Monitoring - Z

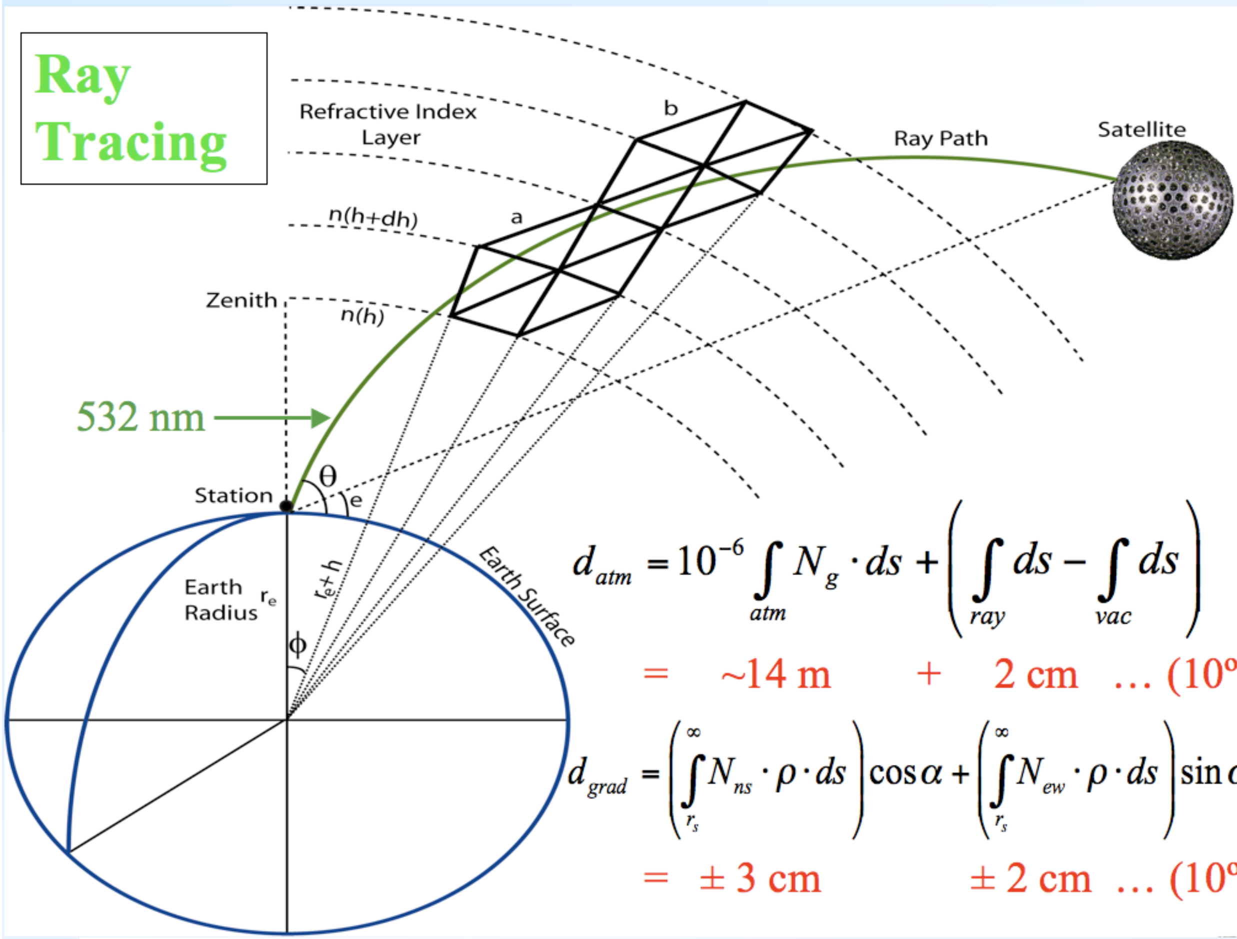


TRF Origin and Scale from SLR TODAY

(January 1993 - December 2008)

RMS ΔOrigin & ΔScale from ITRF2005	AC	Tx [mm]	Ty [mm]	Tz [mm]	Sc [mm]
Individual	ASI	5	5	10	5
	DGFI	8	6	13	5
	GA	7	6	11	5
	GFZ	6	5	11	5
	GRGS	7	7	11	7
	JCET	5	5	11	5
	NSGF	12	12	23	9
Combination	**ILRS-A**	**4**	**4**	**9**	**4**

3D Atmospheric Ray Tracing (ART)



$$d_{atm} = 10^{-6}\int_{atm} N_g \cdot ds + \left(\int_{ray} ds - \int_{vac} ds\right)$$

$= \quad$ ~14 m $\quad + \quad$ 2 cm … (10°)

$$d_{grad} = \left(\int_{r_s}^{\infty} N_{ns}\cdot\rho\cdot ds\right)\cos\alpha + \left(\int_{r_s}^{\infty} N_{ew}\cdot\rho\cdot ds\right)\sin\alpha$$

$= \quad \pm 3$ cm $\quad \pm 2$ cm … (10°)

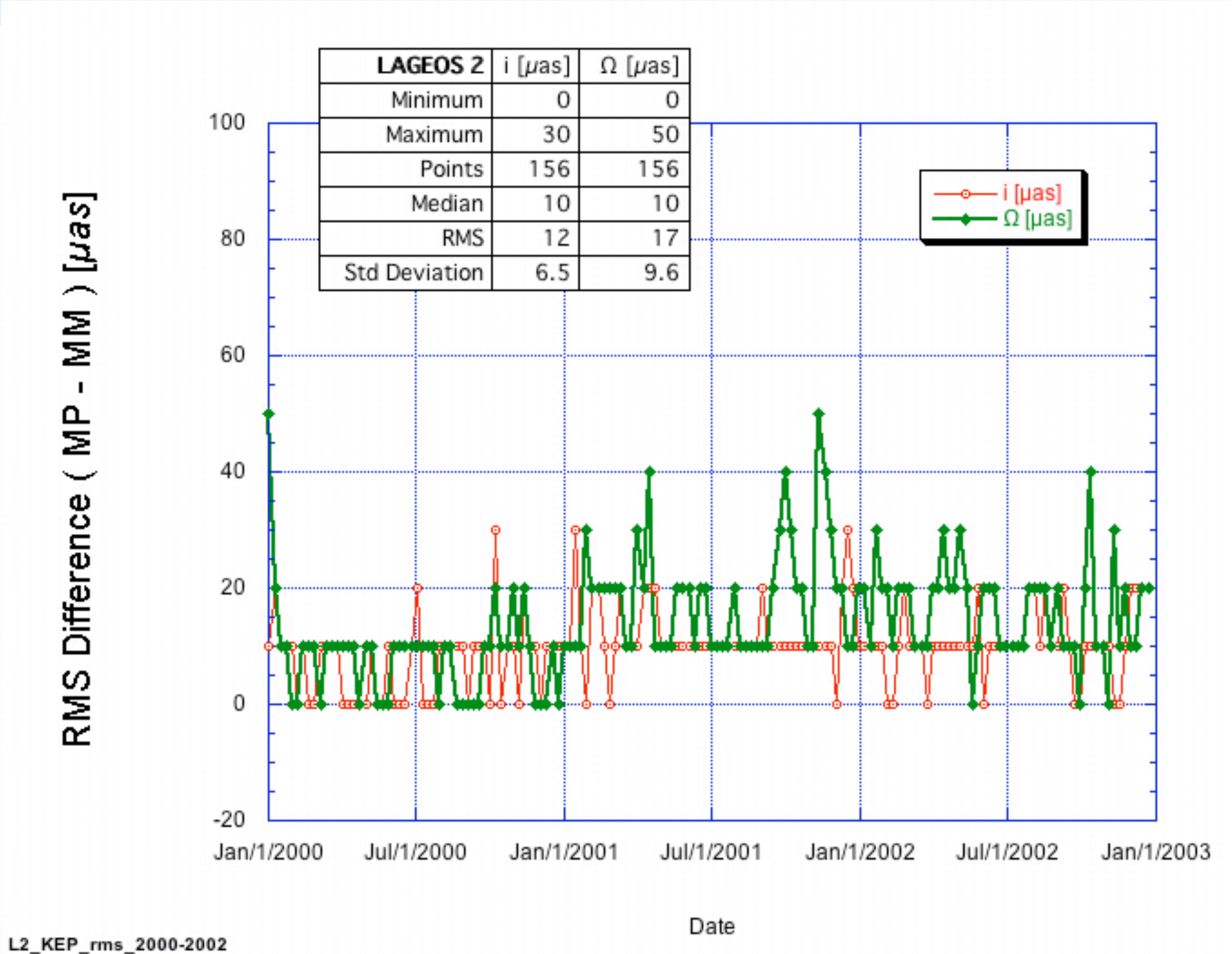
Hulley, G. C. and E. C. Pavlis, (2007), A ray-tracing technique for improving Satellite Laser Ranging atmospheric delay corrections, including the effects of horizontal refractivity gradients, *J. Geophys. Res.*, 112, B06417, doi: 10.1029/2006JB004834, 2007.

Pavlis, E. C., V. Mendes and G. Hulley, (2008), Tropospheric Model: Optical Techniques, in *IERS Conventions 2003*, G. Petit and B. Luzum *eds.*, IERS Technical 32, online version: http://tai.bipm.org/iers/convupdt/convupdt.html, Paris, France, 2008.

Gradient-corrected SLR Residuals Statistics

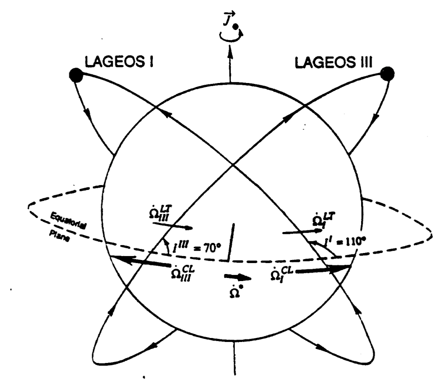
Method	ΔBias (mm)	$\Delta\sigma^2$ (%)
AIRS		
RT_{grad}	0.3 ± 0.3	14.0
RT_{3D}	0.9 ± 1.1	24.8
ECMWF		
RT_{grad}	0.1 ± 0.5	10.8
RT_{3D}	0.6 ± 1.2	22.5

Residual refraction effects on *i* and Ω



LAGEOS 2	i [µas]	Ω [µas]
Minimum	0	0
Maximum	30	50
Points	156	156
Median	10	10
RMS	12	17
Std Deviation	6.5	9.6

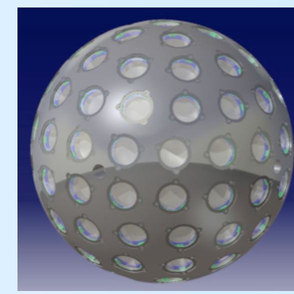
LARES -
LAser Relativity & Earth Science Satellite



Object of measurement:

$$\dot{\Omega}^* = ½ (\dot{\Omega}^I + \dot{\Omega}^{II})$$

- **LARES Parameters:**
  - Material — Tungsten alloy (95%)
  - Diameter — ~36 cm
  - Mass — ~420 kg
  - Altitude — 1500 km
  - Inclination — ~70°
  - Eccentricity — Circular orbit
  - CCRs (109) — LAGEOS type
  - A/m ratio — 0.36 x LAGEOS



Launch is with ESA's new launcher VEGA, on its inaugural test launch, in late 2009/ early 2010

Summary

- Old, aging, outdated equipment in the network soon to be replaced through international efforts spearheaded by GGOS and major national agencies
- LR analysis needs to update its modeling standards to keep in pace with technological advances and stringent scientific requirements
- Several new, improved models exist already and resources for generating additional background and de-aliasing corrections are now available globally and ready to use
- Some of the proposed improvements can be readily implemented and do not interfere with the currently accepted standards

TRF: State of the art

- Representative absolute accuracy of SLR observations at 1-8 mm dependent on time-period and tracking system

- ILRS weekly TRF origin assessments accurate in Origin (T_x, T_y and T_z) to 4, 4, and 9 mm, much lower for recent years, **BUT** we need each one < 1 mm !!!

- ILRS weekly global scale assessments accurate to ~0.6 ppb , 0.3 ppb for recent years, **BUT** we need it < 0.02 ppb !!!

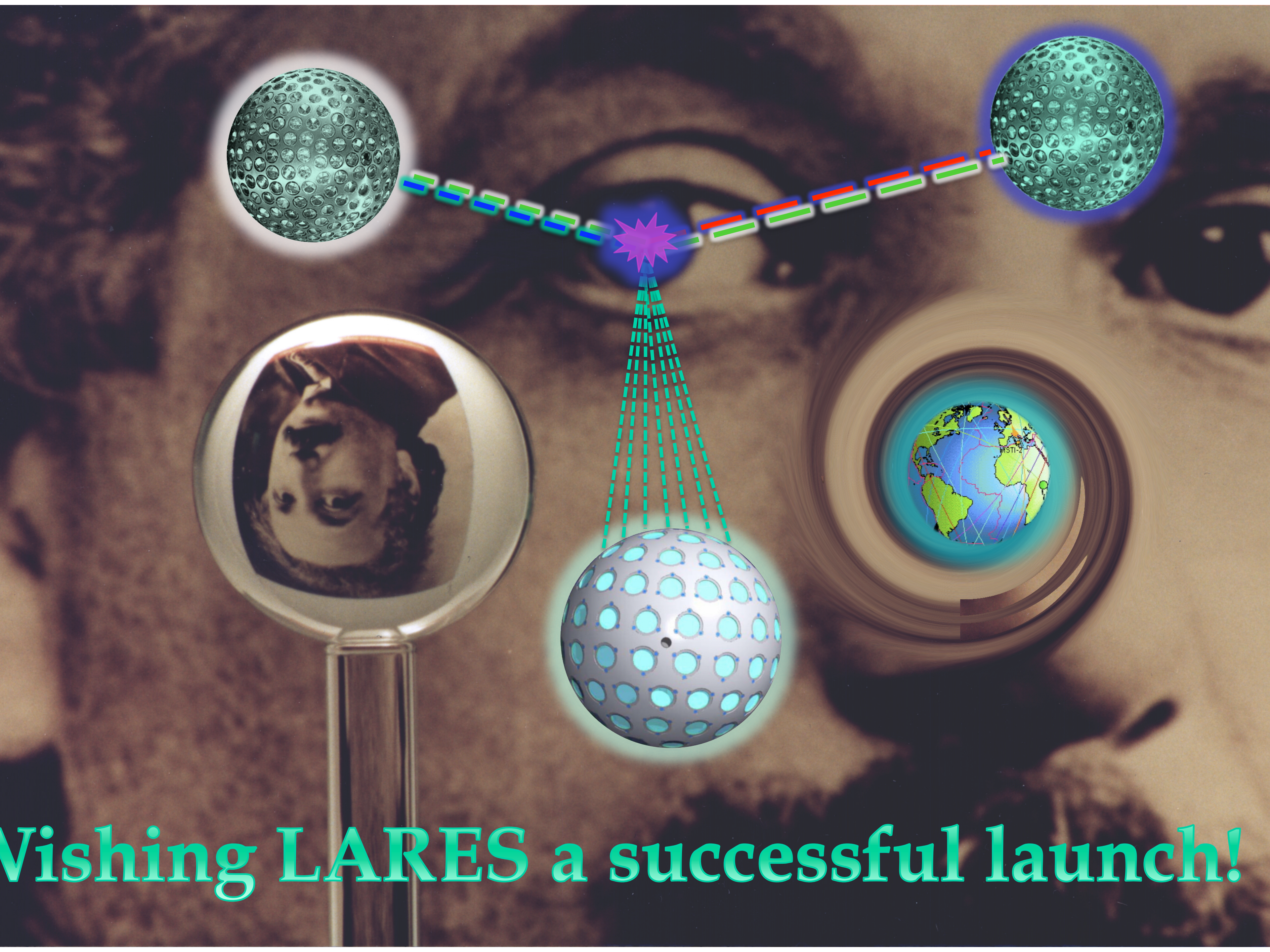
- Addition of early data (from 1983 to 1992) will improve the evolution of ITRF attributes, primarily origin and scale rates, and station velocities

Schedule for New Analysis

- Complete tests of various new models by the end of this year (2009)
- Begin re-analysis of entire LAGEOS 1 & 2 data set from ~1983 to present in early 2010, to be ready by spring 2010
- Apply similar models with appropriate resolution to LEO satellites and reduce data over the same period by the summer of 2010
- Redo LT-analysis with new formulation and compare to current results by autumn of 2010, at which point we hope to have the first LARES data also included in the new solutions

Future Work

- New (SLR and GRACE) Time Varying Gravity solution (ITRF2008 based) and inclusion of more satellites, using GRACE derived models
- Implementation of the new RL04 de-aliasing product when available, ECMWF atmospheric gravity, and new loading, ocean, and pole tide models
- Reanalysis of all SLR data with new GRACE models for LT test (1993 to present)


Wishing LARES a successful launch!