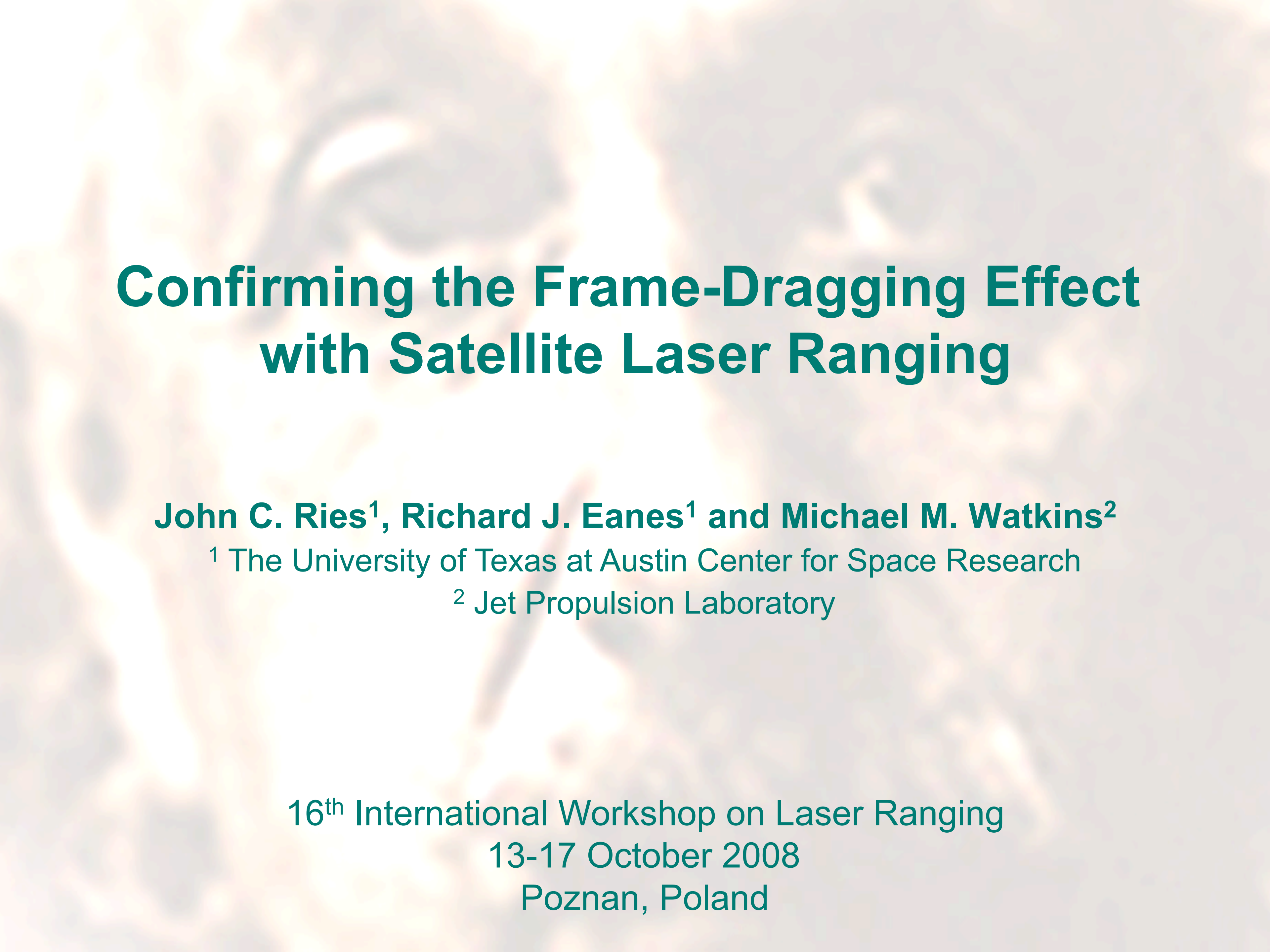

Confirming the Frame-Dragging Effect with Satellite Laser Ranging

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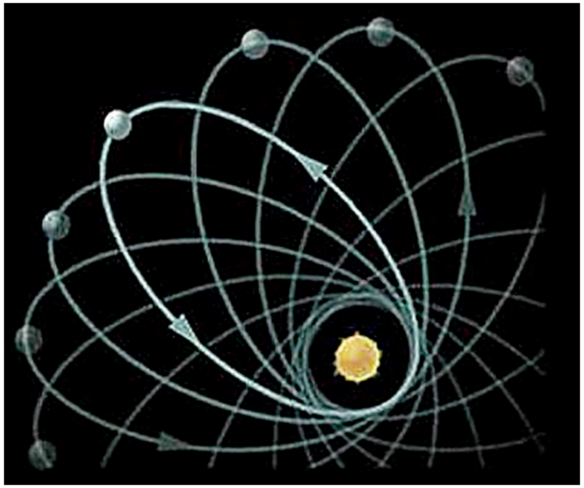
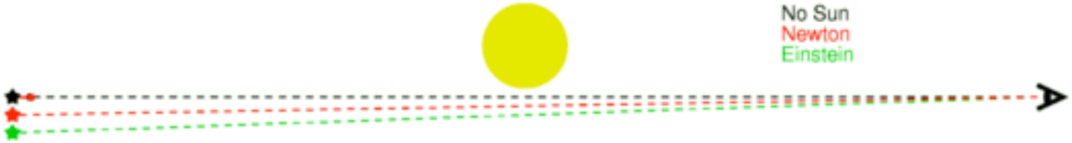
16th International Workshop on Laser Ranging
13-17 October 2008
Poznan, Poland

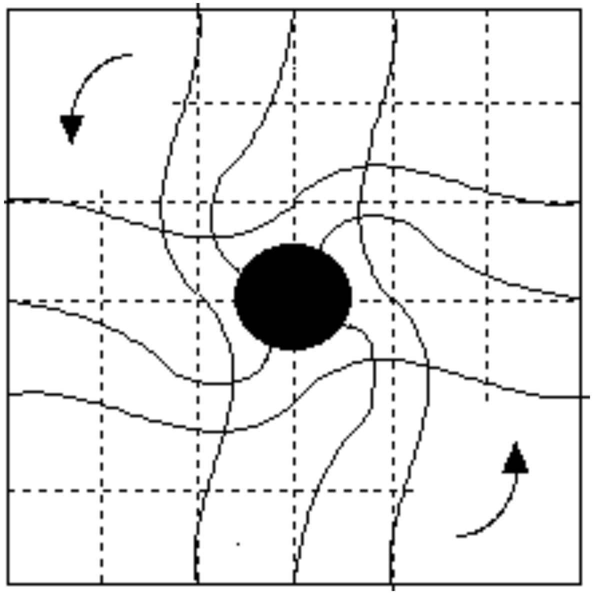
What is 'Frame-Dragging'?

- Around 1915, Einstein's General Relativity theory was published
  - Explained a small excess perigee precession in Mercury's orbit and the observed deflection of light by the Sun



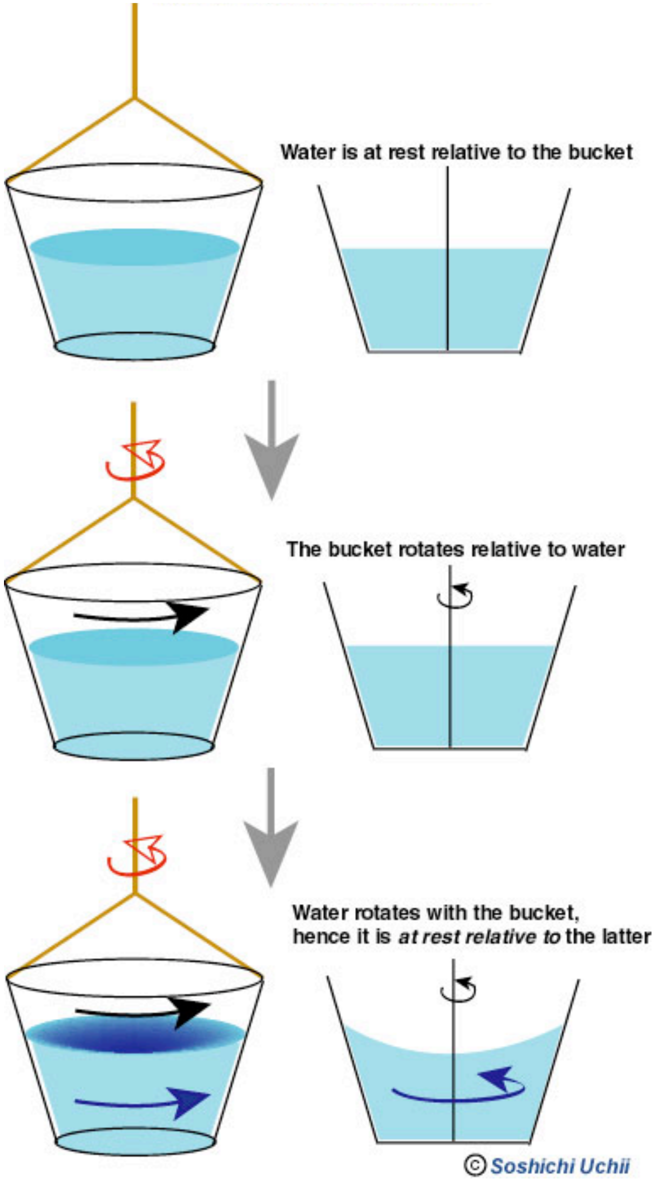


- A few years later, the Austrian physicists Josef Lense and Hans Thirring derived from GR the rotational 'frame-dragging' effect
  - The local space-time is altered by the rotating mass, 'dragging' the local inertial frame with it



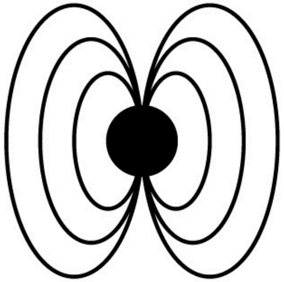
‘Frame-Dragging’ and Mach’s Principle

- The idea of ‘frame dragging’ is an entirely new phenomenon with no parallel in Newtonian physics
- Manifestation of Mach’s Principle
  - Inertia depends on the mutual action of all matter…”mass there makes inertia here”
  - Mach wrote “It does not matter if we think of the Earth as turning round on its axis, or at rest while the fixed stars revolve around it…the law of inertia must be so conceived that exactly the same thing results”



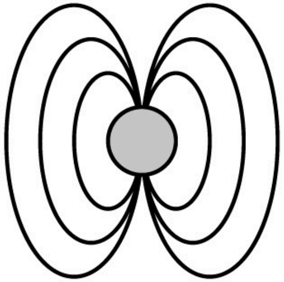
The ‘Gravitomagnetic’ Field

- Just as a spinning charge produces a magnetic field, a spinning mass produces a ‘gravitomagnetic’ field



$$\bar{F}_B = q_0 \bar{v} \times \left[\nabla \times \left(\frac{\bar{M} \times \bar{r}}{r^3} \right) \right]$$

Spinning Electron



$$\bar{F}_{LT} = m_0 \bar{v} \times \left[\nabla \times \left(\left(-(1+\gamma) \frac{G}{c^2} \frac{\bar{J}_{cb} \times \bar{r}}{r^3} \right) \right) \right]$$

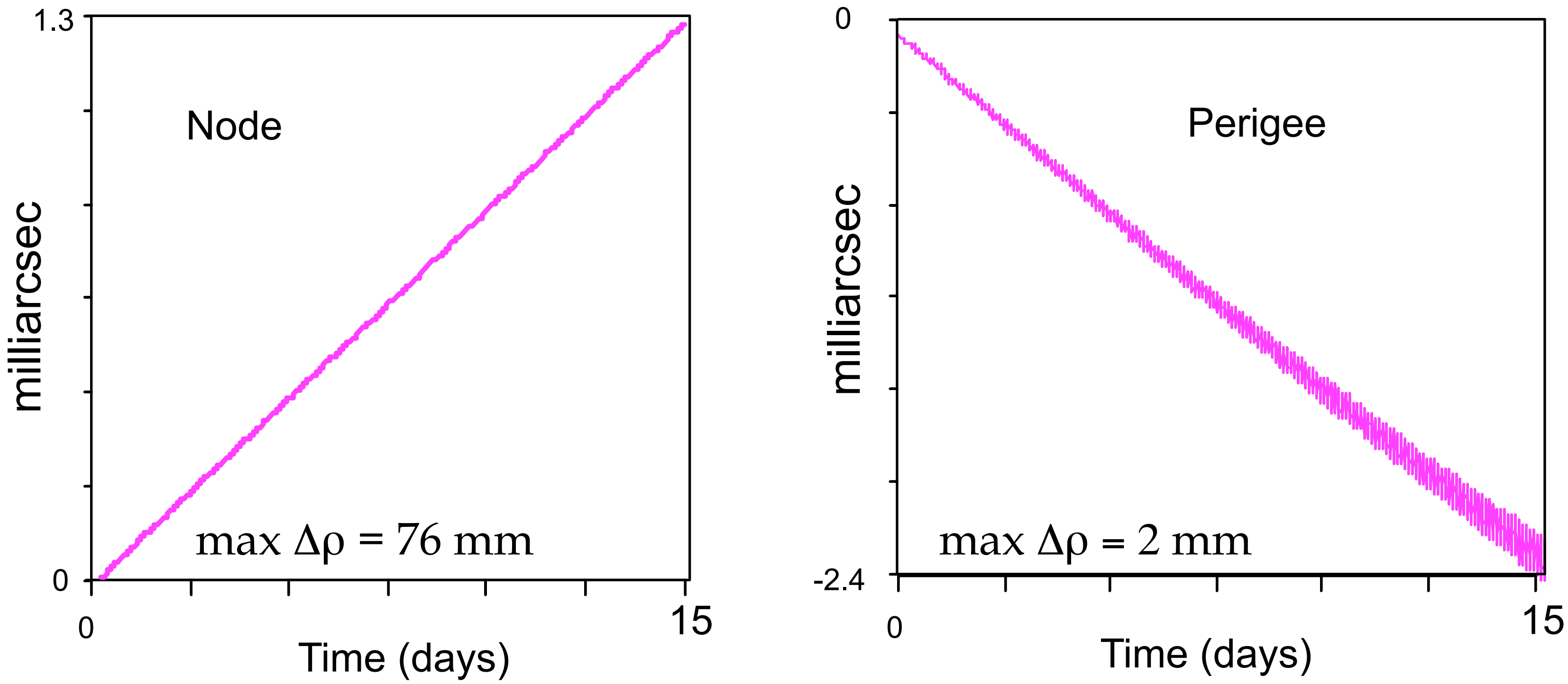
Spinning Mass

- Most observable effect on a satellite orbit is the Lense-Thirring precession of the ascending node

$$\dot{\Omega} = \frac{2G}{c^2 a^3} \frac{J}{(1-e^2)^{\frac{3}{2}}}$$ ≈ 31 marcsec/yr for LAGEOS

Lense-Thirring Effect on Node and Perigee

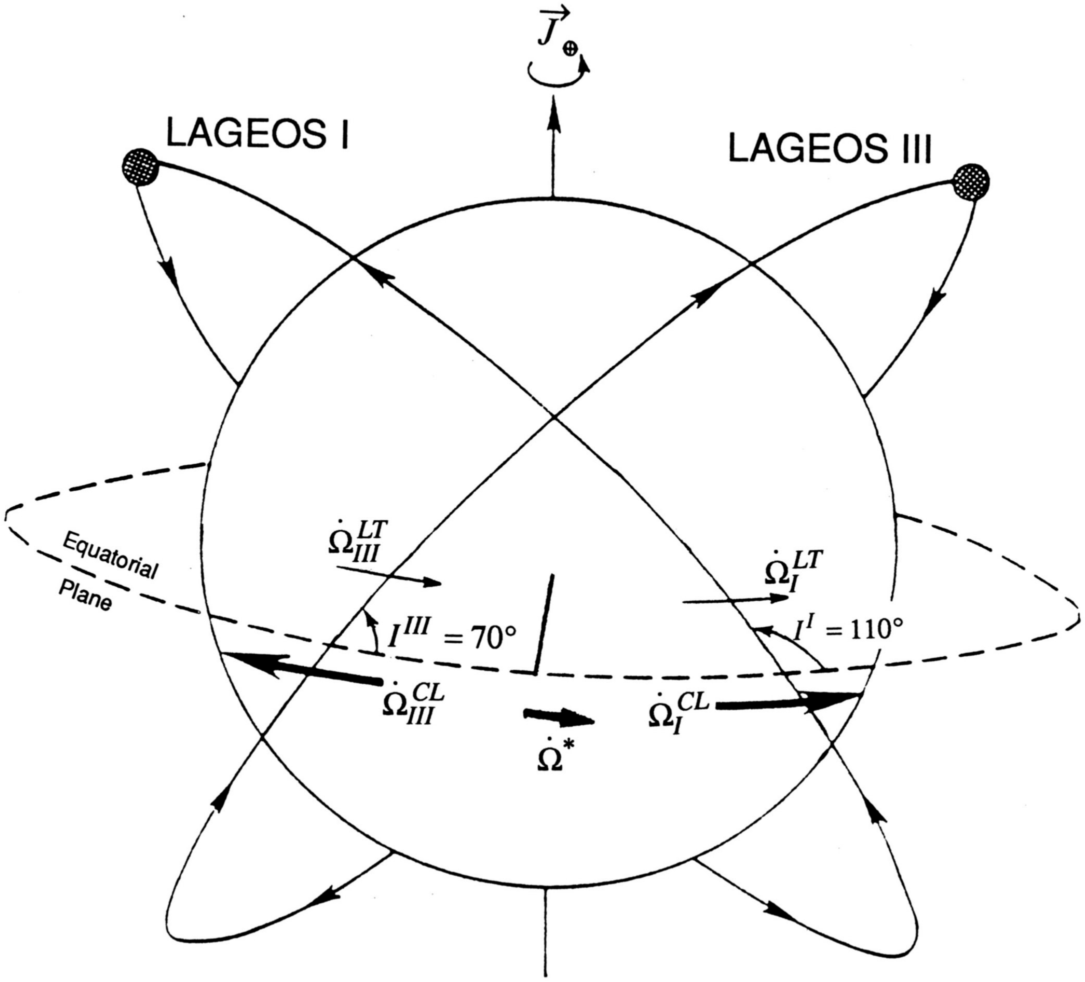
Effect of Lense-Thirring precession on Node and Perigee of LAGEOS-2 over 15 days



LAGEOS-1 eccentricity is smaller, reducing signal further

Note that the magnitude of the signal to be observed was not a problem; the systematic errors were just larger and dominated the signal of interest

Dual-Satellite Lense-Thirring Experiment (LAGEOS-3)



Object of measurement:

$$\dot{\Omega}^{*} = \tfrac{1}{2}\left(\dot{\Omega}^{I} + \dot{\Omega}^{III}\right)$$

LAGEOS-1 alone is insufficient because the LT precession cannot be separated from much larger precession due to the even zonal harmonics (simply not known accurately enough)

In 1986, it was proposed by I. Ciufolini (a UT physics student) to launch an identical satellite into orbit with same altitude as LAGEOS-1 but with opposite inclination

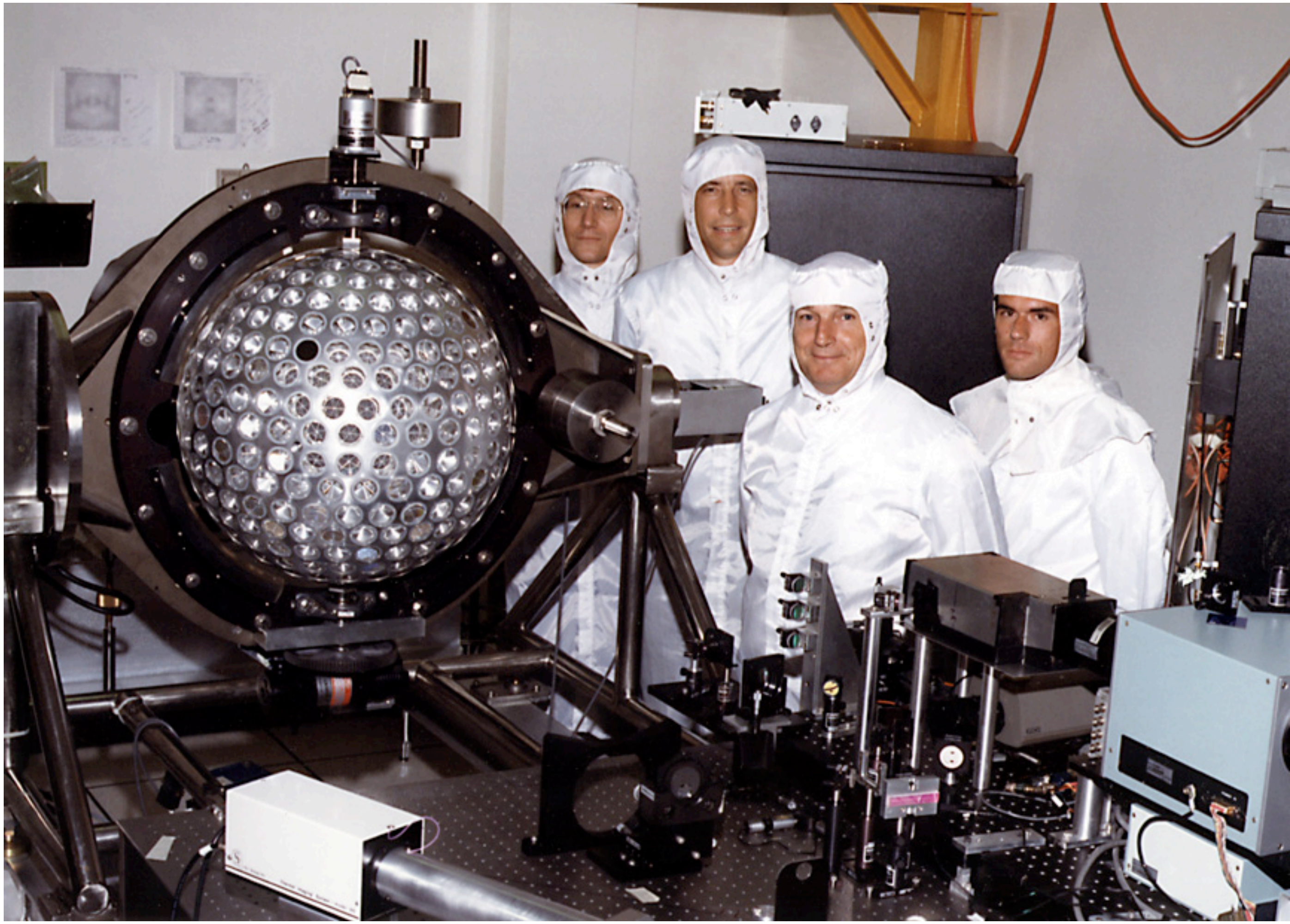
This would cancel out effect of errors in all even zonal harmonics on the orbit node rates

1989 study funded by NASA determined experimental accuracy of better than 10%, but mission ultimately rejected

Why Not Use LAGEOS-2?

During this time, LAGEOS-2 was being prepared for launch

However, the orbit inclination chosen (52.6°) was not suitable (at the time) because the gravity model errors were too large



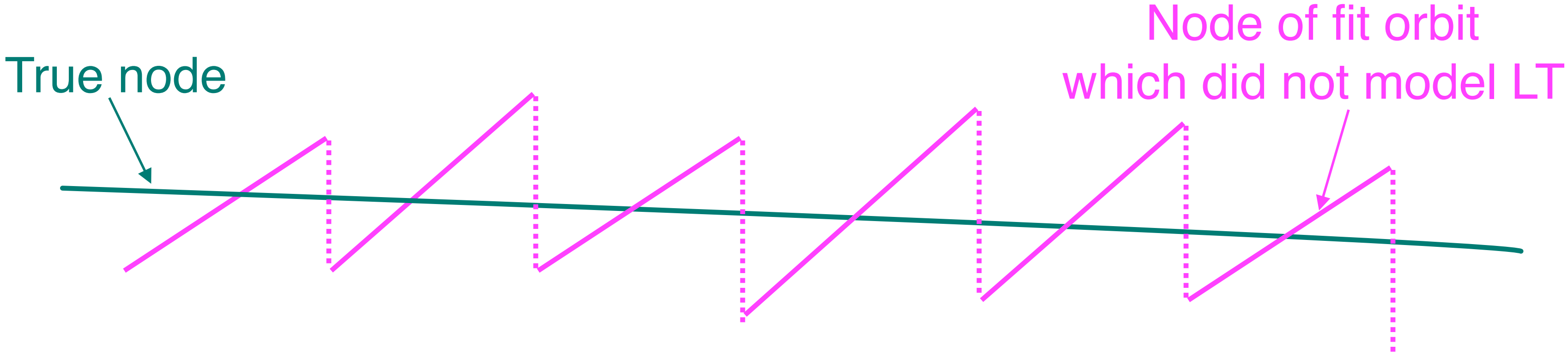
LAGEOS-2 at NASA/GSFC for optical testing
(left to right: J. Ries, R. Eanes, B. Tapley and M. Watkins)

Early Results using LAGEOS-1 and -2

- Ciufolini et al. (Science, 1998) claimed the LT effect confirmed with SLR tracking to LAGEOS-1 and -2 to 20% level using EGM96
  - Used LAGEOS-1 node-rate, LAGEOS-2 node-rate and LAGEOS-2 perigee rate to determine LT effect, eliminating errors in J2 and J4.
- Method used was novel but there were significant issues
  - Use of LAGEOS-2 perigee to eliminate J4 introduced the (uncertain) effect of a number of non-gravitational in-plane forces
  - Relying on very favorable negative correlation between zonals (the result of inadequate separation of the zonals in the gravity solution) to reduce the error estimate from approximately 50% to 13%
  - Uncertain 'calibration' of EGM96 covariance; difficult to independently validate sigmas
  - There is no reason to expect that the errors in EGM96 are static and representative of the errors during the LT experiment
  - LAGEOS satellites used twice (in gravity field estimate and then again in LT experiment)

Ciufolini's Novel Analysis Method

- Integration of end-point overlaps of short-arcs (7-15 days) is assumed to preserve effect of mismodeling LT (reasonable for secular signals)



- Linear combination of two nodes (LAGEOS-1 and -2) to produce "J_2-free" LT signal

$$\delta\dot{\Omega}_I + 0.545\,\delta\dot{\Omega}_{II} = 48.2\mu \qquad \mu_{GR}=1.00$$

- In 1998 analysis, a different linear combination was used to include LAGEOS-2 perigee and remove J_4 as well

Prospects for an Improved Lense-Thirring Test with SLR and the GRACE Gravity Mission

Presentation at October 2002 ILRS workshop…

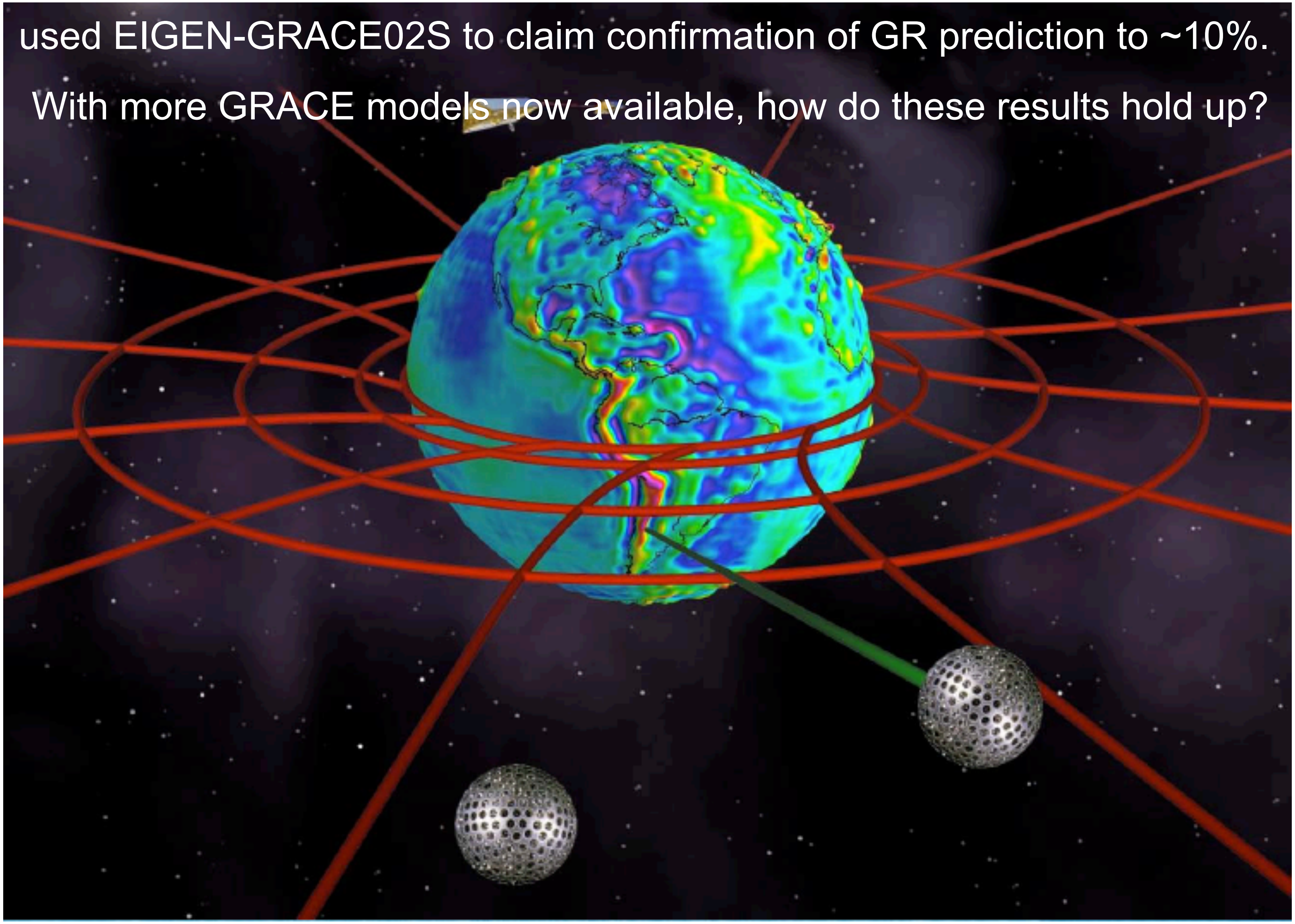
“Considering current formal errors to be representative of what GRACE is likely to achieve, LT should be detectable with a few percent uncertainty” using just the node signals

The uncertainties associated with perigee are avoided, as is using the LAGEOS satellites for both the gravity field and the LT estimates.

Prospects were good IF gravity field solutions met expectations

GRACE launched in March 2002

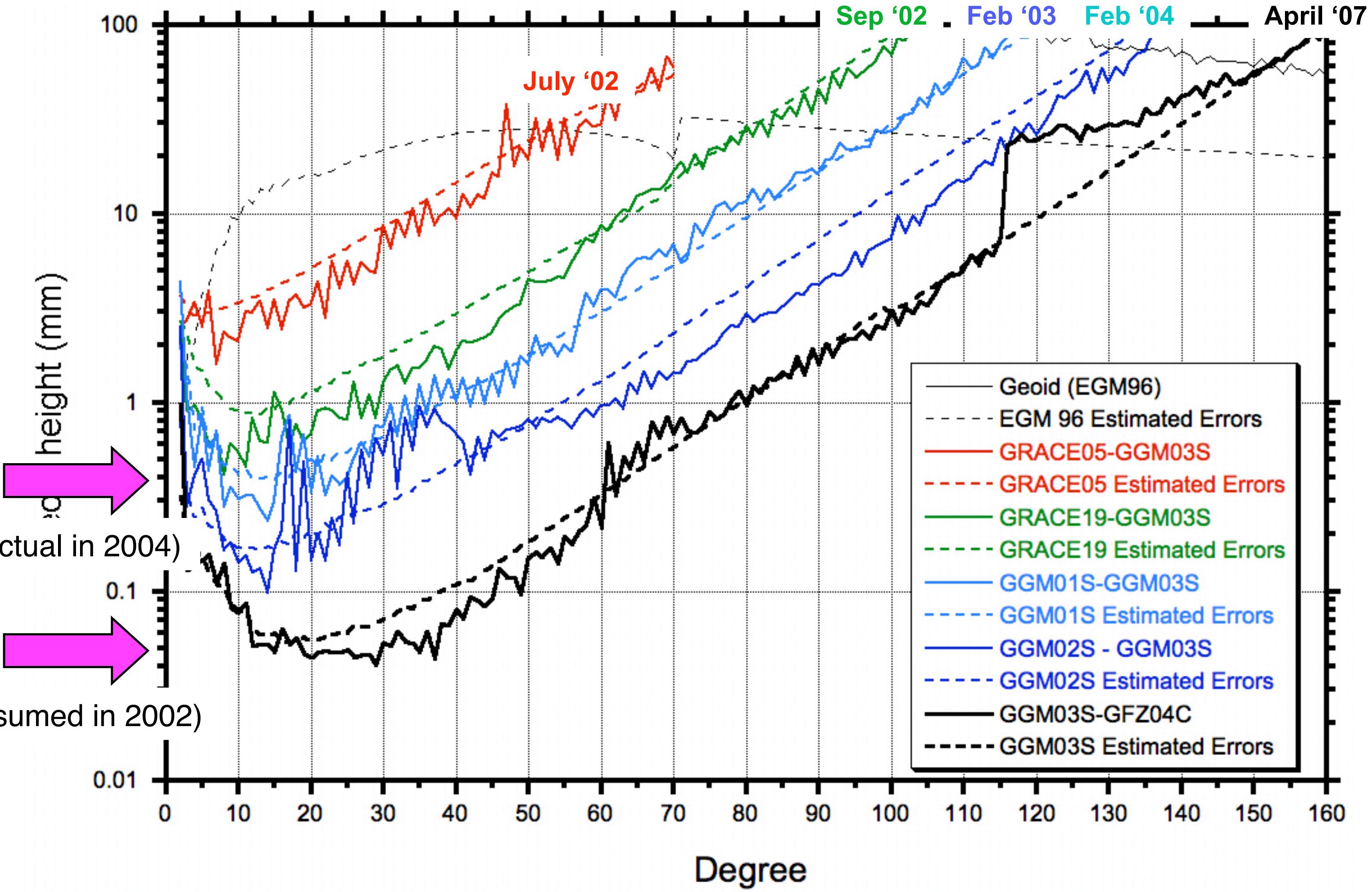
Ciufolini and Pavlis, Nature, 2004



used EIGEN-GRACE02S to claim confirmation of GR prediction to ~10%.

With more GRACE models now available, how do these results hold up?

Progress in GRACE Gravity Models

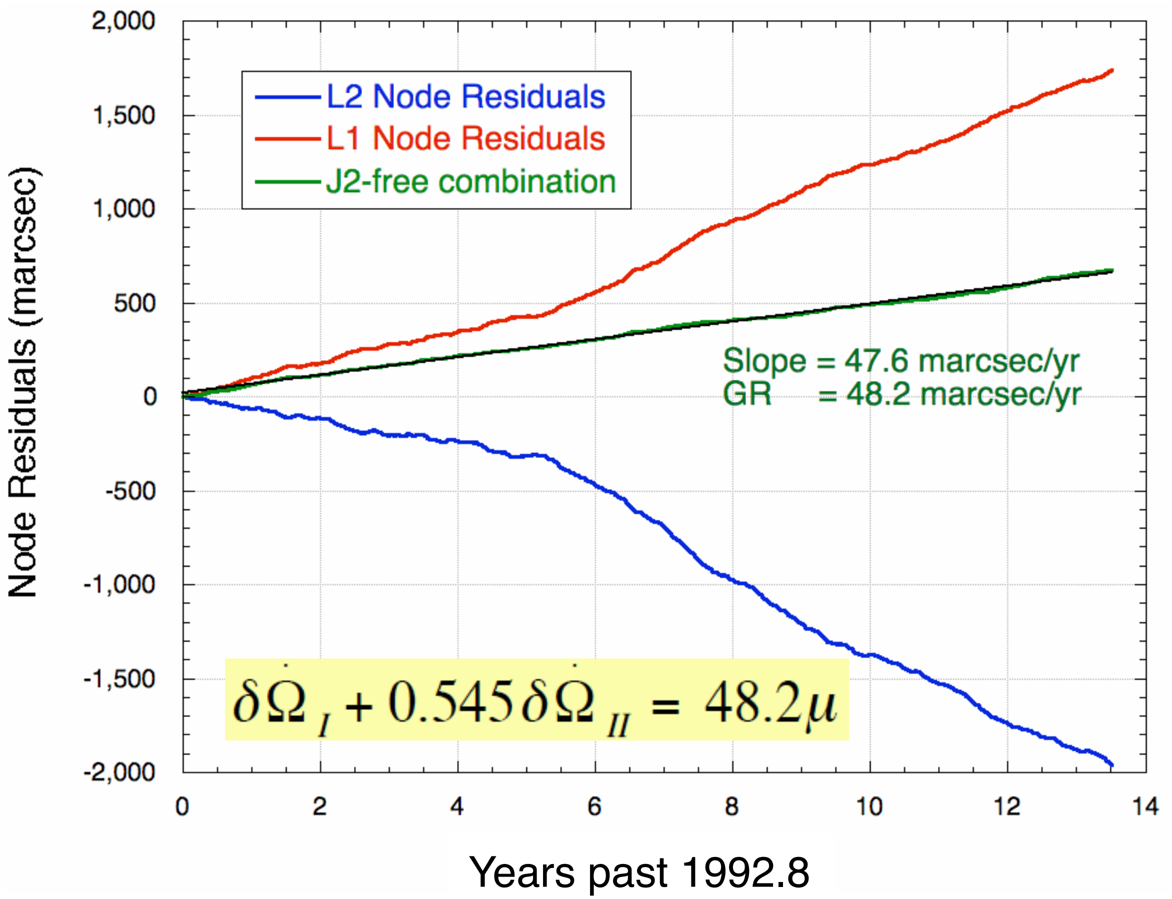


(actual in 2004)

(assumed in 2002)

Better GRACE Gravity Fields Available

- Using a more recent CSR gravity solution (GIF22a based on 12 months of GRACE data) and 13.5 years of SLR data, we recovered GR value of LT precession to ~1%
- Looks good but how reliable are these results?
- We can now look at multiple GRACE solutions and determine a more confident experiment uncertainty



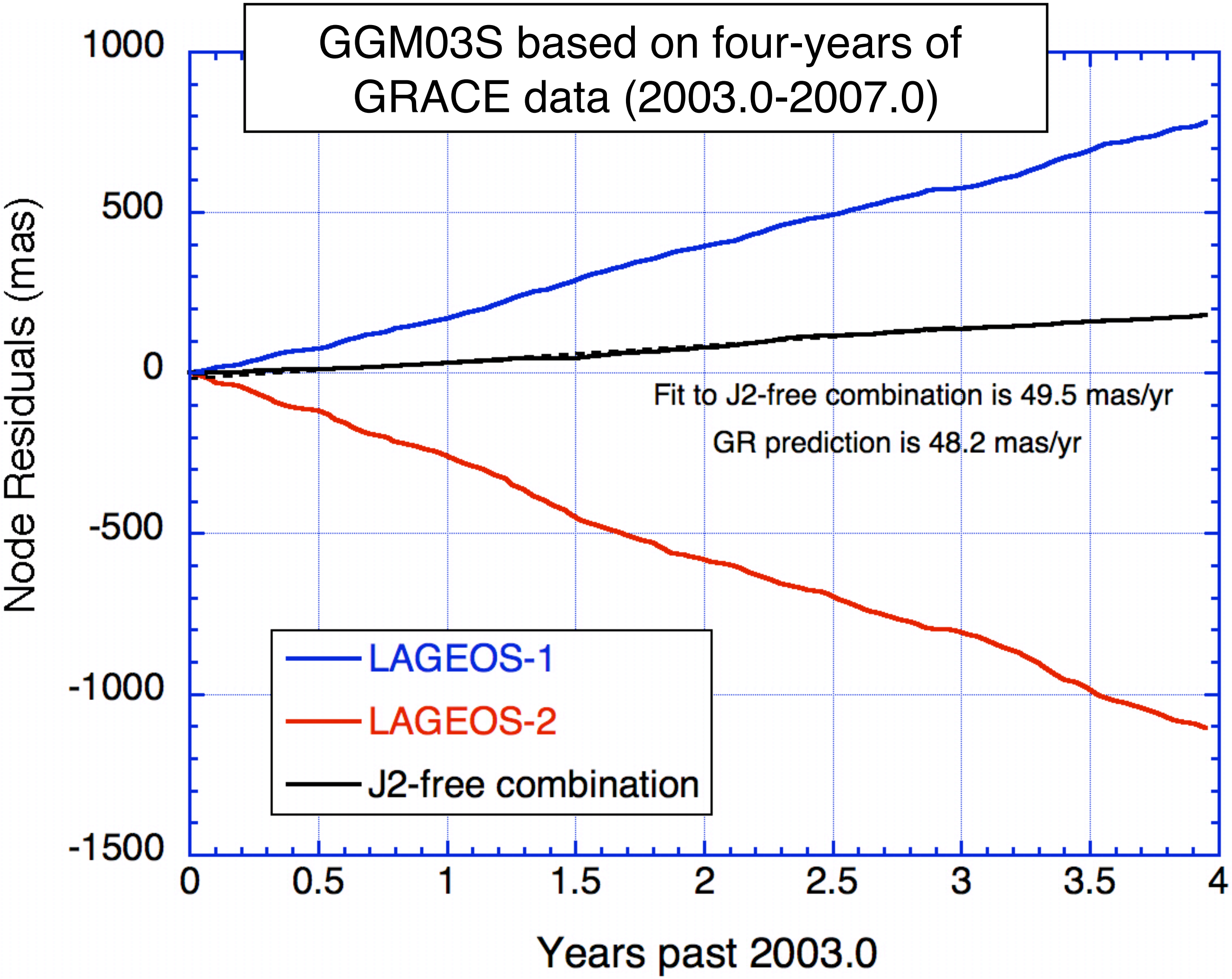
$$\delta\dot{\Omega}_{I} + 0.545\,\delta\dot{\Omega}_{II} = 48.2\mu$$

Note how large changes in the node series (due to significant changes in J2) cancel out in J2-free combination

LT Experiment over GRACE Mission only

An important concern in the error is the mapping of the even zonals from the mean epoch of the GRACE data to the mean epoch of the SLR data

To avoid this, we tried an experiment using just the 4 years used for GGM03S



Solution uncertainty increases due to shortness of time series;
4 years seems to be about the minimum

Gravity Model Uncertainty and LT Error

LT Results for Recent GRACE gravity models

Gravity model	Year	LT signal / GR	C40	C40 Sigma	C60	C60 Sigma
EIGEN-GRACE02S	2004.1	1.25	5.40007101E-07	3.9E-12	-1.49930405E-07	2.0E-12
GGM02S	2004.6	1.01	5.39975648E-07	8.3E-12	-1.49939959E-07	4.5E-12
EIGEN-CG03C	2005.3	1.03	5.39987470E-07	3.8E-12	-1.49955461E-07	1.8E-12
GIF22a	2005.7	0.99	5.39989338E-07	1.5E-13	-1.49953540E-07	1.0E-13
JEM04G	2005.9	0.84	5.39970358E-07	1.2E-13	-1.49967559E-07	9.1E-14
EIGEN-GL04C	2006.3	0.93	5.39973449E-07	4.5E-12	-1.49953685E-07	2.0E-12
JEM01-RL03B	2006.9	1.05	5.39992625E-07	8.5E-14	-1.49956879E-07	6.2E-14
GGM03S	2007.5	0.88	5.39972911E-07	4.6E-12	-1.49959620E-07	1.6E-12
ITG-GRACE03S	2007.8	0.85	5.39965868E-07	3.8E-13	-1.49953913E-07	1.7E-13
EIGEN-GL05C	2008.5	1.04	5.39988199E-07	3.5E-12	-1.49953616E-07	1.4E-12
GGM03S (2003-2007 only)	2007.5	1.03	5.39972911E-07	4.6E-12	-1.49959620E-07	1.6E-12
Mean		0.99	5.39982297E-07		-1.49952464E-07	
StDev		0.12	1.3E-11		1.0E-11	

Our results for the same gravity field (EIGEN-GRACE02S) differ by 26%; suspect mapping of zonals to appropriate epoch, although other modeling differences may also be present

Error estimates assigned to C40 and C60 appear to be generally optimistic; a test of relativity requires robust (conservative) error estimates

Other ‘sanity’ tests to validate analysis method

GGM02S (model LT)	0.01	(differs by exactly 1.0 as expected)
GGM02S (no GP)	1.58	(Geodesic precession ~57% of LT)
GGM02S (no rates for J3,J4,J6)	1.02	(quadratic from rates is negligible)

Estimated Error Budget for LT Test

Error Source	% of LT
Scatter due to method (linear fit w/wo tidal lines)	1
Solar radiation pressure, Earth albedo, thermal reradiation effects	3
Zonal rates (quadratic effect; after mapping to mean epoch) *	1
C40 (estimated from scatter of GRACE gravity models) **	10
C60 (estimated from scatter of GRACE gravity models) **	5
C40-dot (20% uncertainty in mapping to mean epoch) ***	3
C60-dot (50% uncertainty in mapping to mean epoch) ***	2
RSS (% of LT)	12

* Epoch of GRACE gravity models typically ~2004.0-2005.0; mean epoch of SLR data ~2000

** Assigned sigmas typically too small; used C40 scatter 1.3e-11, C60 scatter 1.0e-11

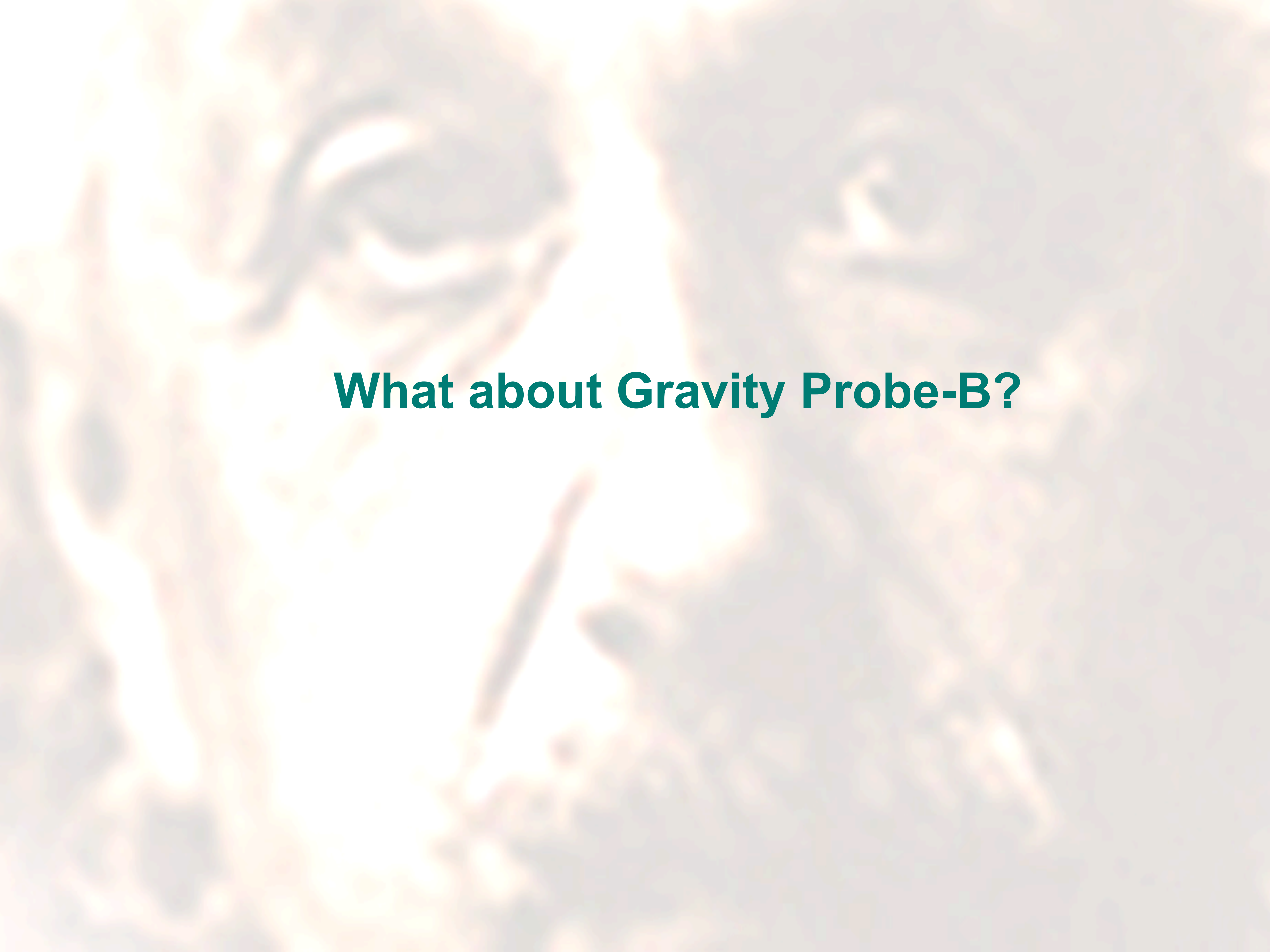
*** C40-dot uncertainty is estimated to be 20% of 4.7e-12/yr; 50% of 1.7e-12/yr for C60-dot

Resulting error estimate of 12% consistent with scatter of LT estimates (reduces to ~8% if EIGEN-GRACE02S is excluded)

However, effect of errors from mapping zonals to mean SLR epoch may be underestimated; zonal rates may be more uncertain than assumed here

SLR Confirms General Relativity

- Satellite laser tracking to LAGEOS-1 and -2 appears to confirm General Relativity’s prediction of the Lense-Thirring precession at the 8-12% level (1-sigma)
  - This is possible only with the dramatically improved geopotential models from the GRACE mission
  - Uncertainties in J4 and J6 (including rates) dominate current error budget, as expected
- Improvements in dynamical and measurement models help make it possible to achieve a reliable solution with only a few years of data
  - More years of GRACE data will provide a more accurate mean field and extend the interval for a Lense-Thirring test that does not require mapping zonals back to an earlier epoch

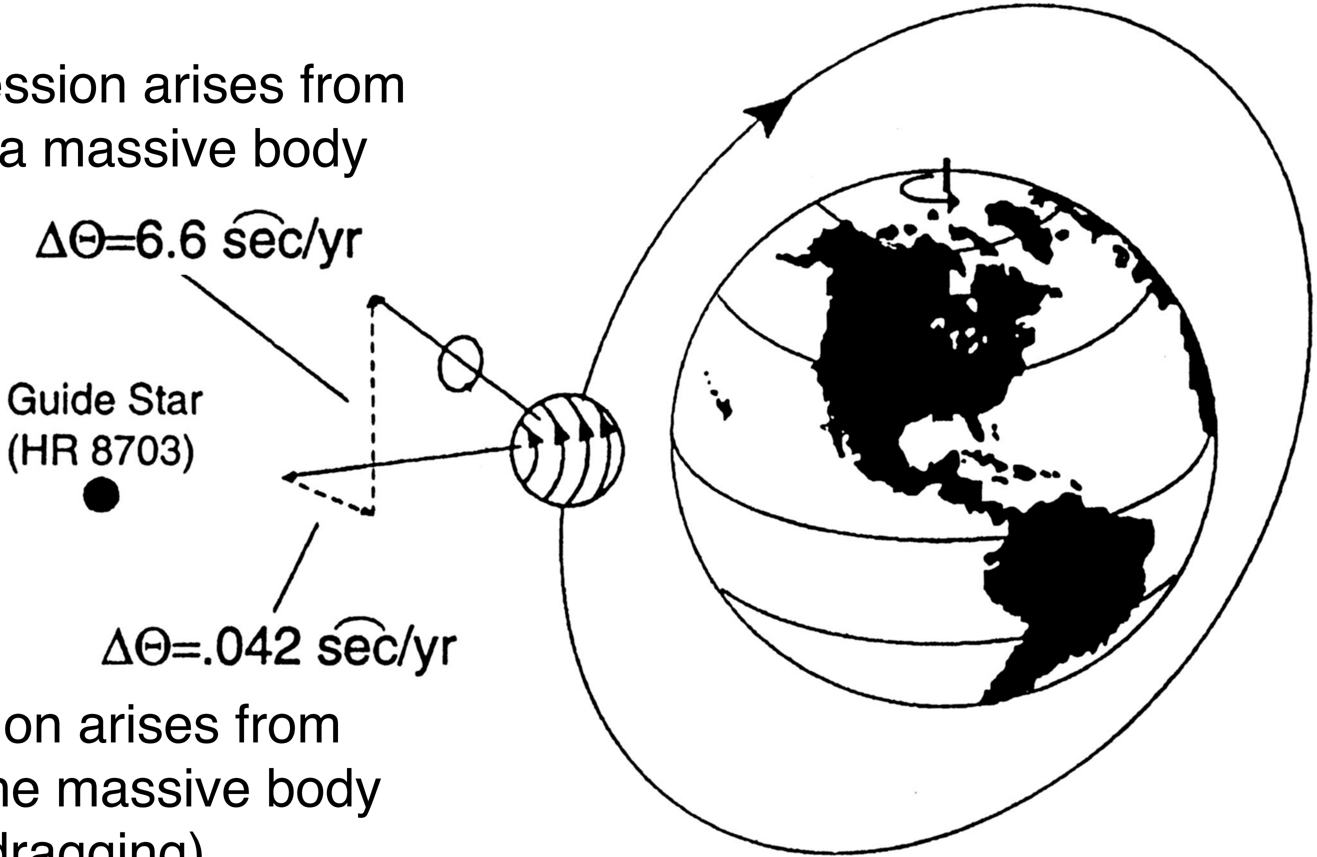


What about Gravity Probe-B?

Schiff Precession and Gravity Probe-B

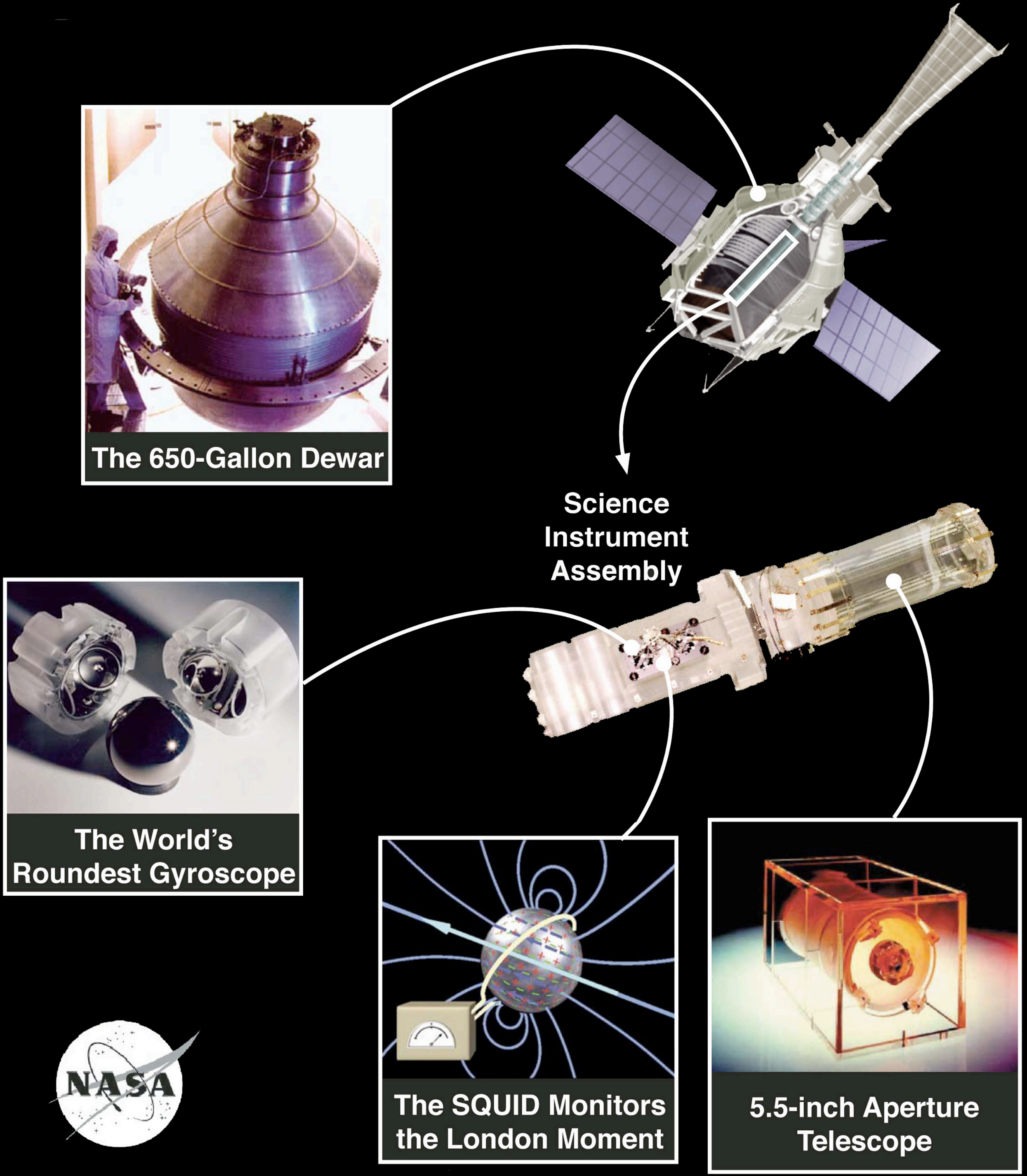
- Pugh (1959) and Schiff (1960) discovered that the gravitomagnetic effect would also affect the spin axis of an orbiting gyroscope (called the Schiff precession)

Geodetic precession arises from motion around a massive body



Schiff precession arises from the rotation of the massive body (frame-dragging)

Gravity Probe-B



Launched April 2004

17-month flight

Goal was to measure LT precession to 1%

Preliminary results released Spring 2007

Final results expected 2009

Zonal Harmonic Correlations

EGM96 correlations

	J2	J4	J6	J8
J4	-0.93			
J6	0.73	-0.80		
J8	-0.51	0.65	-0.89	
J10	0.16	-0.26	0.64	-0.83

Current GRACE correlations

	J2	J4	J6	J8
J4	-0.02			
J6	0.01	-0.23		
J8	0.00	-0.01	-0.29	
J10	0.00	0.00	-0.04	-0.31

GRACE Baseline correlations

	J2	J4	J6	J8
J4	-0.03			
J6	0.00	-0.24		
J8	-0.03	-0.02	-0.29	
J10	0.00	-0.00	-0.04	-0.31

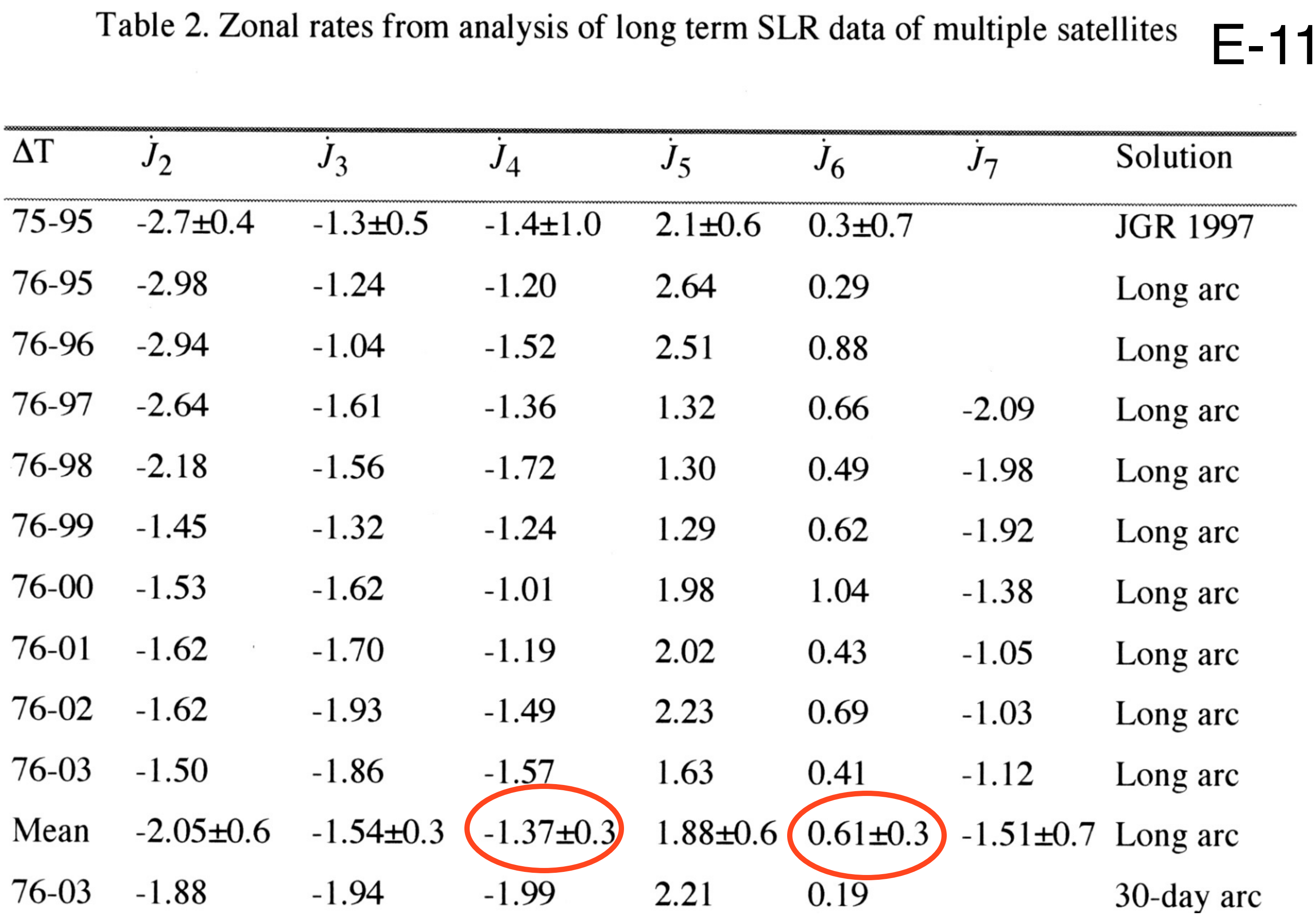
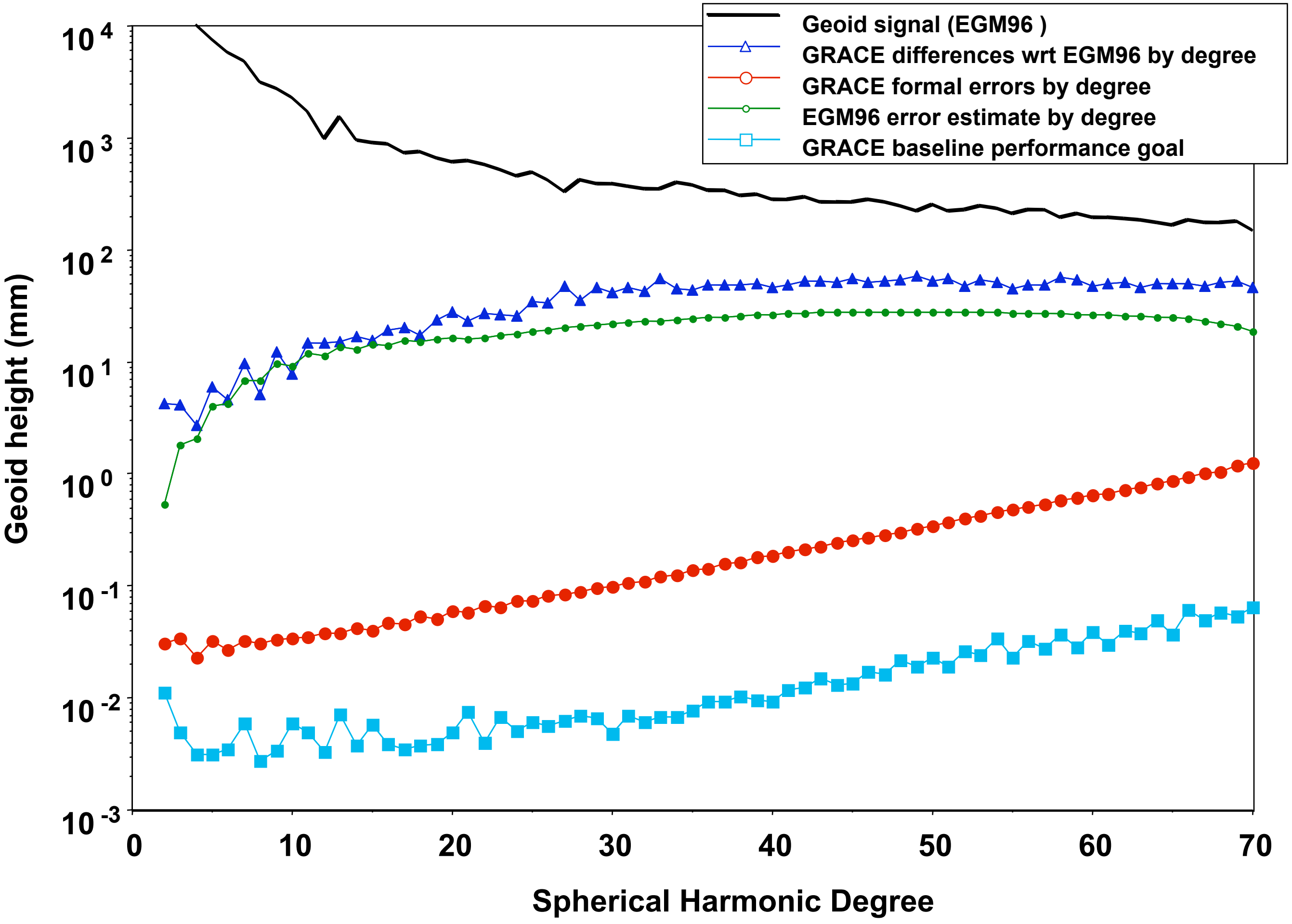


Table 2. Zonal rates from analysis of long term SLR data of multiple satellites

E-11/yr

ΔT	$\dot{J}_2$	$\dot{J}_3$	$\dot{J}_4$	$\dot{J}_5$	$\dot{J}_6$	$\dot{J}_7$	Solution
75-95	-2.7±0.4	-1.3±0.5	-1.4±1.0	2.1±0.6	0.3±0.7		JGR 1997
76-95	-2.98	-1.24	-1.20	2.64	0.29		Long arc
76-96	-2.94	-1.04	-1.52	2.51	0.88		Long arc
76-97	-2.64	-1.61	-1.36	1.32	0.66	-2.09	Long arc
76-98	-2.18	-1.56	-1.72	1.30	0.49	-1.98	Long arc
76-99	-1.45	-1.32	-1.24	1.29	0.62	-1.92	Long arc
76-00	-1.53	-1.62	-1.01	1.98	1.04	-1.38	Long arc
76-01	-1.62	-1.70	-1.19	2.02	0.43	-1.05	Long arc
76-02	-1.62	-1.93	-1.49	2.23	0.69	-1.03	Long arc
76-03	-1.50	-1.86	-1.57	1.63	0.41	-1.12	Long arc
Mean	-2.05±0.6	-1.54±0.3	-1.37±0.3	1.88±0.6	0.61±0.3	-1.51±0.7	Long arc
76-03	-1.88	-1.94	-1.99	2.21	0.19		30-day arc

GRACE Errors used for 2002 LT Assessment



Data not yet fitting to the noise level, thus the formal errors are higher than the baseline

Current errors likely to be above the formal errors

Dual-Satellite Lense-Thirring Experiment

- NASA funded a study, led by Byron Tapley, to determine expected performance
- Using six complete, blind mission simulations, an accuracy of 7-8% was predicted
- Results improve to few percent level if using better gravity models

L-3	L-1/[1] 1989	L-1/L-3	L-2/L3[2]
1997		**1997**	
Geopotential (including tides, seasonal)		**5%**	**1%2%**
Earth radiation pressure[3]		**1%1%**	**1%**
Uncertainty in other relativistic effects[4]		**1%**	**1%1%**
Thermal forces		**3%3%**	**6%**
Even zonal geopotential		**3%1%**	**1%**

Notes:
1) GEM-T1 gravity/tide models
2) JGM-3 gravity/tide models (results are similar for EGM-96)
3) Reduction of thermal forces could improve overall result to ~3% (alternative, LARES, was proposed)
4) Assuming less than 0.1 degree inclination injection error