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

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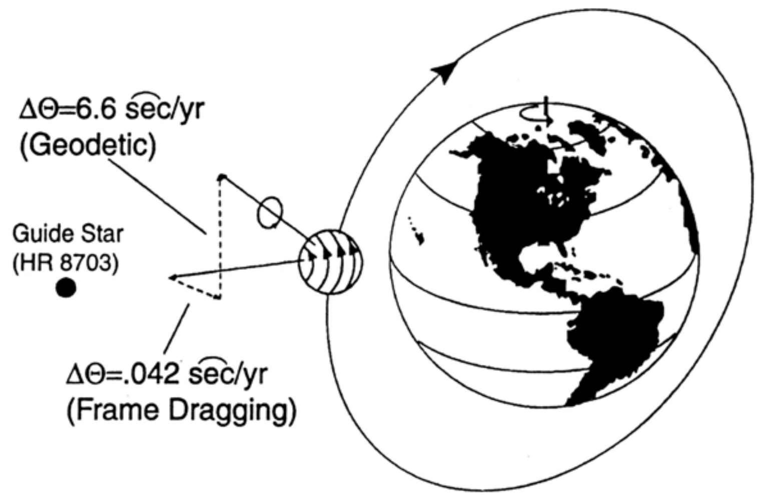
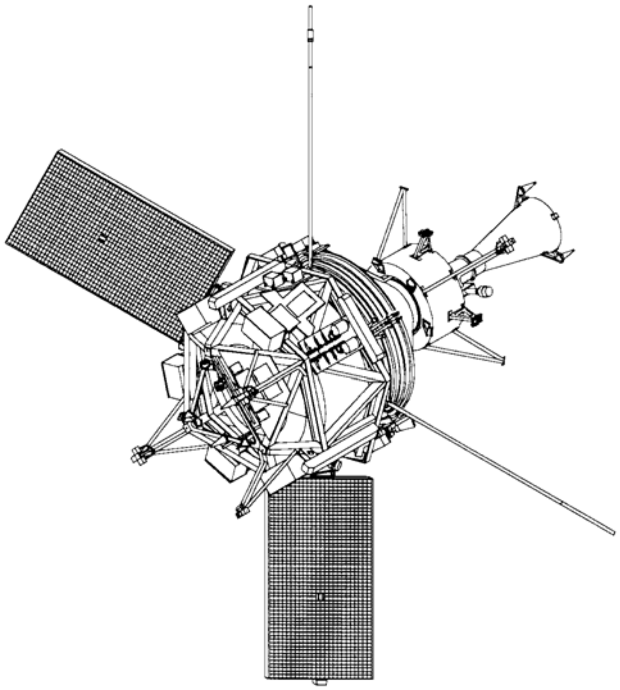
Introduction

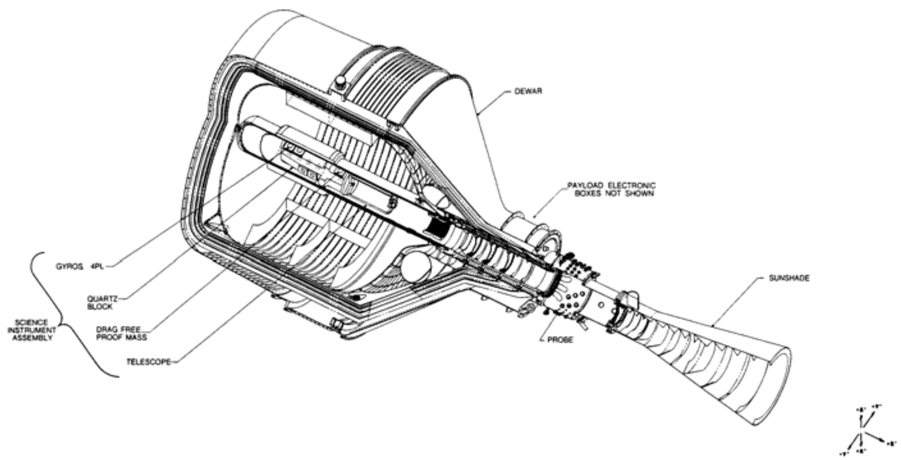
- The General Relativity prediction of the Lense-Thirring precession of an orbit due to ‘frame dragging’ has not been confirmed with the level of confidence required for a test of this importance.
- Previous analyses are limited by optimistic and unprovable assumptions regarding the magnitude and correlation of the errors in the low degree geopotential harmonics.
- The joint NASA-DLR GRACE (Gravity Recovery and Climate Experiment) mission is successfully gathering data, and dramatically improved gravity fields have already been determined.
- We examine the expected improvements in the Lense-Thirring experiment using SLR data to Lageos-1 and Lageos-2 and gravity field models from GRACE.

Gravity Probe-B

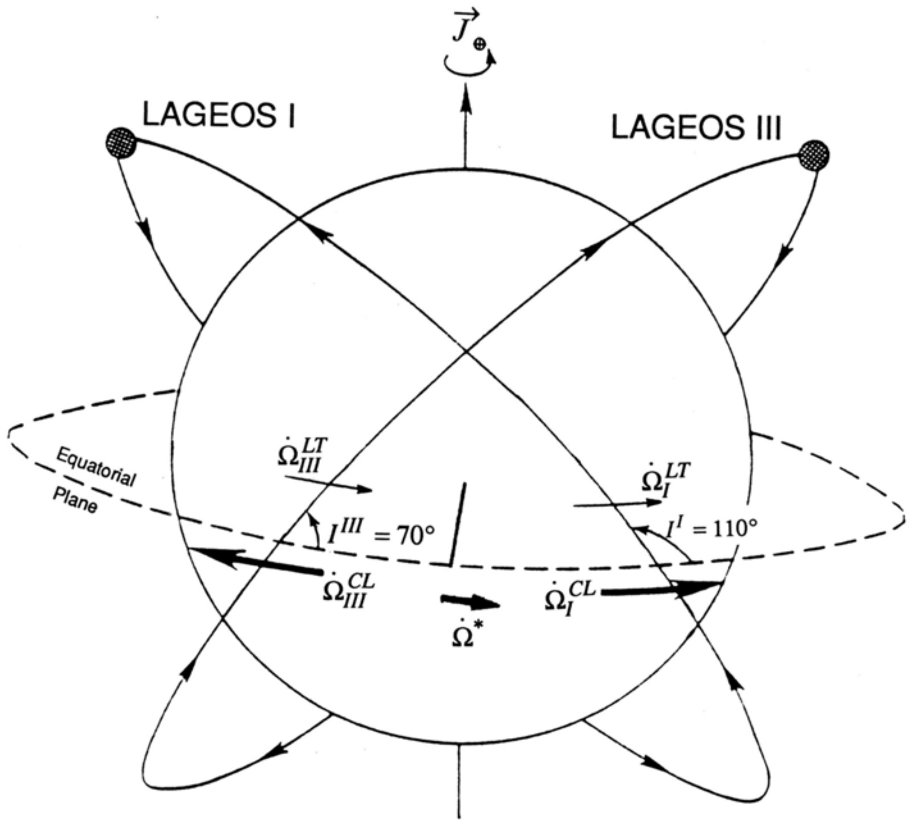
- GP-B relativity experiment on track for launch next year; expected to verify frame dragging of an ultra-precise gyro to better than 1%







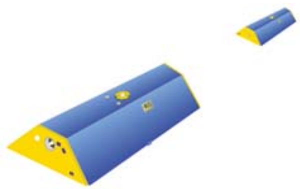
Proposed Dual-Satellite Lense-Thirring Experiment (LAGEOS-3)



Object of measurement:

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

LAGEOS-2 at GSFC



Dual-Satellite Lense-Thirring Experiments (Lageos-3, LARES)

	L-1/L-3 1989 [1]	L-1/L-3 1997 [2]	L-2/L3 1997 [2]
Geopotential (including tides, seasonal)	5%	1%	2%
Earth radiation pressure	1%	1%	1%
Uncertainty in other relativistic effects	1%	1%	1%
Thermal forces [3]	3%	3%	6%
Even zonal geopotential [4]	3%	1%	1%
Random and stochastic errors	5%	2%	2%
RSS error	8%	4%	7%

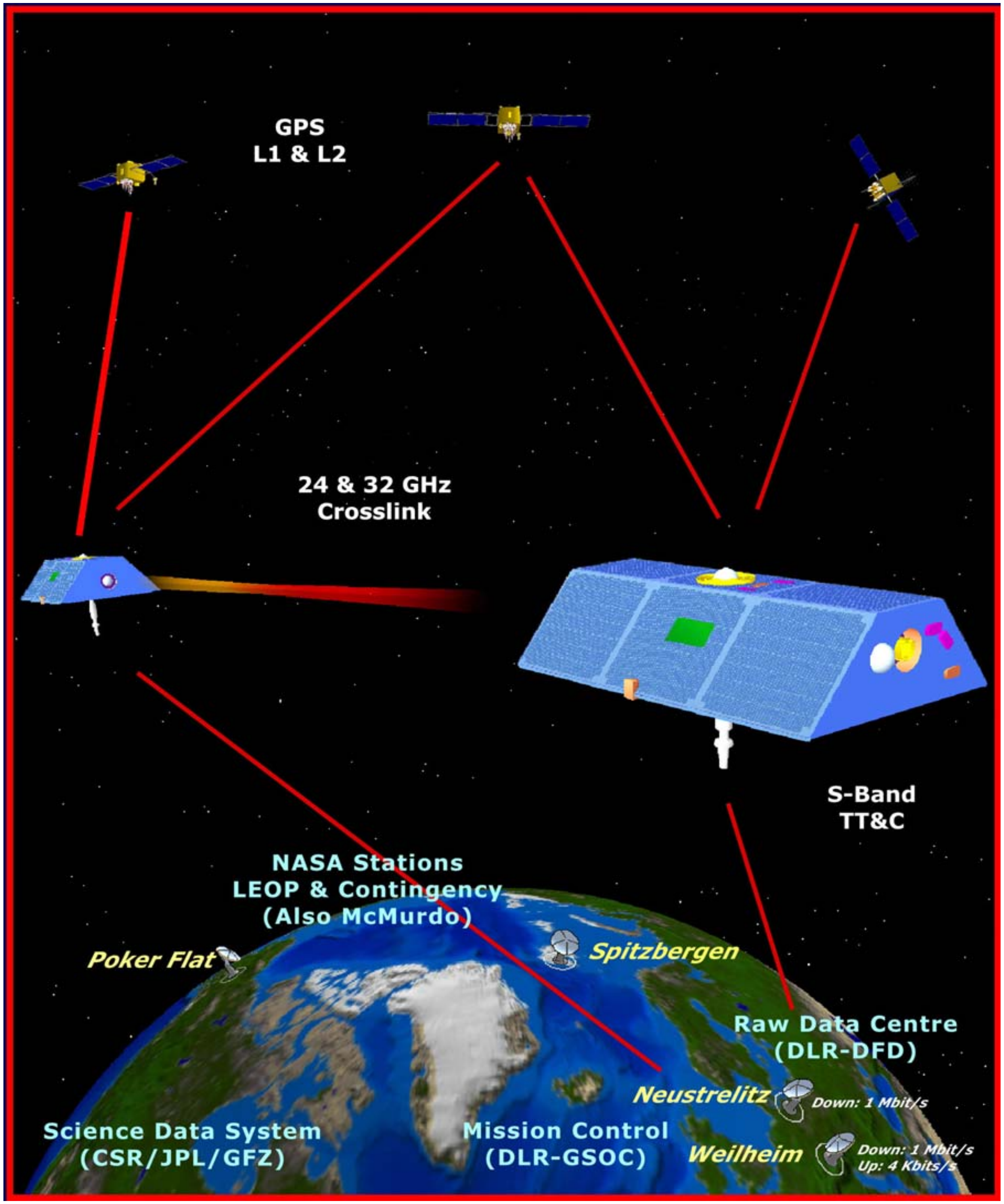
Notes:
1) GEM-T1 gravity/tide models
2) JGM-3 gravity/tide models (results are similar for EGM-96)
3) Reduction of thermal forces with LARES may improve overall result to ~3%
4) Assuming less than 0.1 degree inclination injection error

Recent Analyses

- Ciufolini *et al.* (Science, 1998) found the LT effect confirmed with SLR tracking to Lageos-1 and 2 to 20% level
  - Used Lageos-1 node-rate, Lageos-2 node-rate and Lageos-2 perigee rate to determine LT effect, along with J2 and J4. Needed only to consider EGM96 errors in J6, J8, etc.
- Method used was innovative but there are significant uncertainties in the assumptions used for the error assessment, especially regarding the contribution of the zonals (Ries *et al.* 1998).
  - Use of Lageos-2 perigee to eliminate J4 introduces the effect of a number of non-gravitational forces for which the models (and their errors) are uncertain
  - Use of very favorable negative correlation between zonals (the result of inadequate separation of the zonals in the gravity solution) to reduce the error from approximately 50% to 13%
  - Realistically, there is no reason to expect that the errors in EGM96 are static and representative of the errors during the LT experiment

Gravity Covariance Concerns

- While there may be various views about this, any experiment based on current gravity models will be plagued with uncertainties regarding the error analysis
  - A more solid foundation is necessary for a confident verification of GR
- What we need is a gravity model so accurate that contributions from errors in the zonals are insignificant
  - Removes need to use Lageos-2 perigee rate to eliminate J4; much cleaner signal in node-rates
  - No assumption about correlations needed to reduce contribution of gravity



GRACE Mission

Science Goals

High resolution, mean & time variable gravity field mapping for Earth System Science applications.

Mission Systems

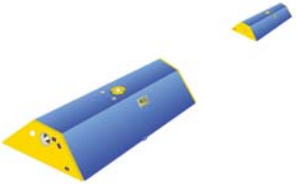
Instruments

- HAIRS (JPL/SSL/APL)
- SuperSTAR (ONERA)
- Star Cameras (DTU)
- GPS Receiver (JPL)

Satellite (JPL/DSS)
Launcher (DLR/Eurockot)
Operations (DLR/GSOC)
Science (CSR/JPL/GFZ)

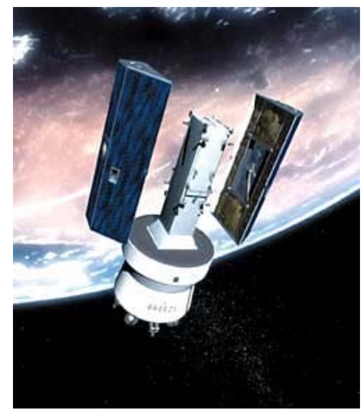
Orbit

Launched: March 17, 2002
Initial Altitude: 500 km
Inclination: 89 deg
Eccentricity: ~0.001
Separation Distance: ~220 km
Lifetime: 5 years
Non-Repeat Ground Track, Earth Pointed, 3-Axis Stable

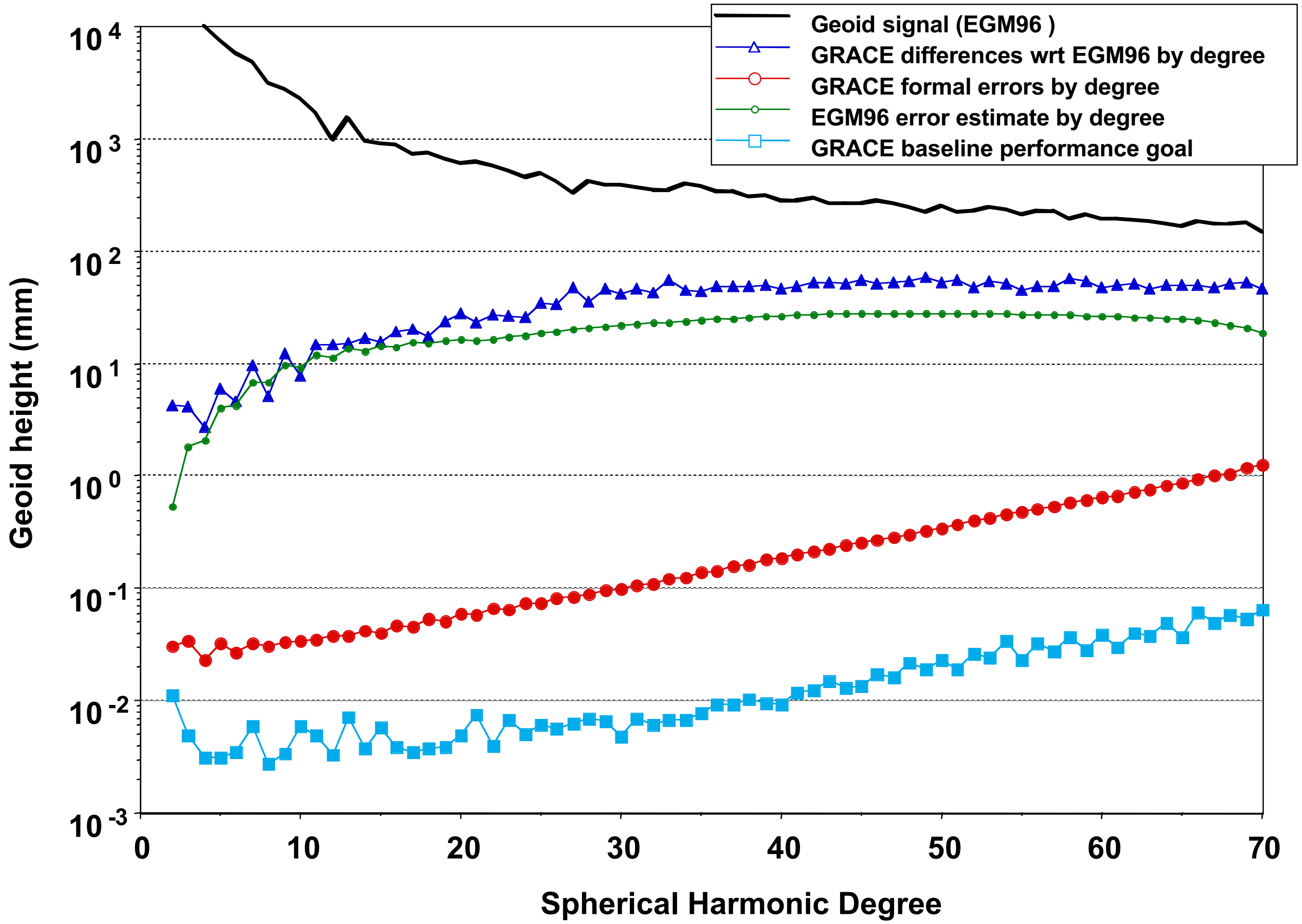


GRACE Mission Status

- **Mission is in Commissioning Phase**
- **Flight Segment Status**
  - Satellites continue collecting all science data
    - All instruments in their nominal operational modes
  - Flight procedures & software stable
    - Attitude Control System now refined for all coarse modes
    - IPU S/W upload imminent; will improve science data quality
  - Remaining tasks in Commissioning Phase
    - K-Band Boresight Calibrations
  - Loss of some redundancy on GRACE-1
    - 1 of 2 USO
    - 1 of 2 redundant sides of accelerometer control unit
    - Gyro failure (not used for Science)
- **Ground Operations (Oberpfaffenhofen, Germany)**
  - GSOC successfully operating twin satellites in a multi-mission environment
  - Over 99% data safely recovered from satellites (science & housekeeping)



Current Gravity Model Improvement

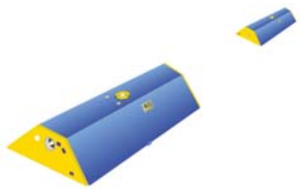


Data not yet fitting to the noise level, thus the formal errors are higher than the baseline

Current errors likely to be above the formal errors

Estimated LT Detection Accuracy

- Considering current formal errors to be representative of what GRACE is likely to achieve, LT should be detectable with a few percent uncertainty
  - Experiment would then be limited by other contributions such as the surface force models and ocean tides (which will average down over the 5-year mission)
  - Confidence in the gravity model error predictions is an important part of GRACE calibration/validation activities



Satellite Orbit Comparisons

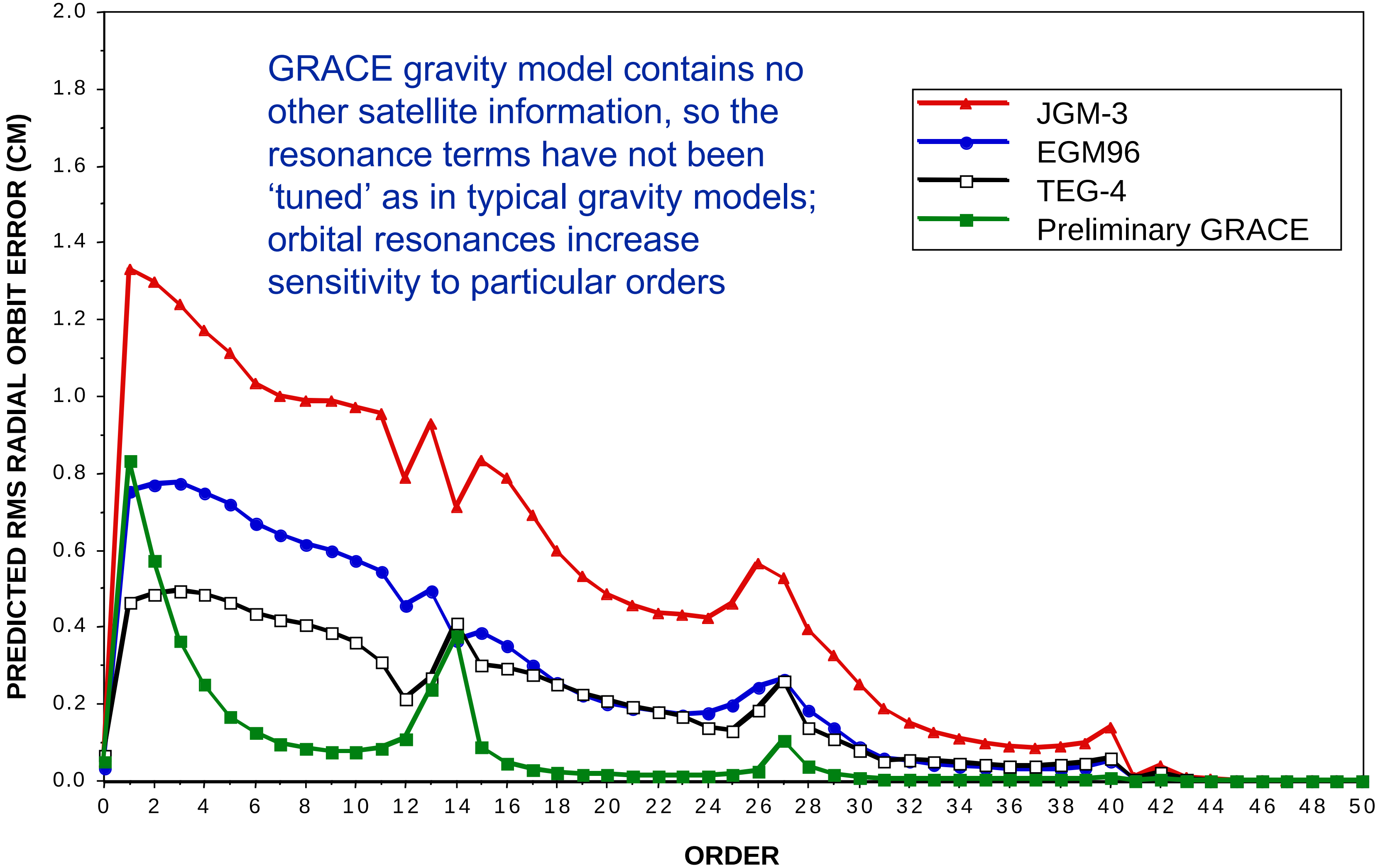
Gravity Model	Starlette (cm)	Stella (cm)	Lageos-1, Lageos-2 (cm)	GEOS-3 (cm)	GFZ-1 (cm)	ERS-2 (cm)	T/P (cm)	Westpac (cm)	CHAMP GPS DD (cm)	CHAMP SLR (cm)
JGM-3	4.3	6.5	0.72, 0.75	7.9	41	8.4	5.68	4.6	5.7	41
EGM96	3.7	6.4	0.78, 0.76	8.3	37	7.9	5.74	6.6	6.3	38
GRIM5C1	3.2	2.8	0.71, 0.72	6.7	23	6.6	5.65	6.0	4.5	38
TEG4	2.9	2.8	0.78, 0.74	8.6	26	6.6	5.71	5.2	1.3	7
GRACE	3.5	5.2	1.24, 1.32	6.6	20	6.8	5.67	6.0	1.2	7

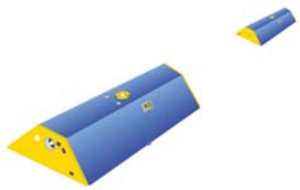
- Laser range rms for Starlette, Stella, Lageos 1/2, GEOS-3, GFZ-1; 3-6 day arcs with daily drag coefficients, 1/rev empirical alongtrack and crosstrack estimated (alongtrack only for Lageos-1/2) (Lageos-1/2 arcs span May 2002)
- Altimeter crossover RMS for T/P, ERS-2 ; 5-day arcs for ERS-2, 10-day arc length for T/P; 1/rev alongtrack and crosstrack estimated
- Double-differenced GPS phase for CHAMP (SLR data not used in orbit solution); 1-day arcs with 90 minute drag coefficients, 3-hour 1/rev alongtrack and crosstrack estimated

GRACE-only solution is based only on GRACE data gathered during April/May/August 2002

Note that GRACE solution has no other satellite information; orbit fits are limited by ‘untuned’ resonances

Starlette Orbit Error Prediction from Covariance





Summary

- A less optimistic error assessment of current results is closer to 50–100%, which is too large for a confident detection of frame-dragging
- A confident test of General Relativity has to rest on verifiable error assertions
- LAGEOS-3 would be best satellite-based experiment, but combining GRACE gravity determination with existing satellites should provide a confident and unambiguous detection of the frame dragging effect at the few percent level