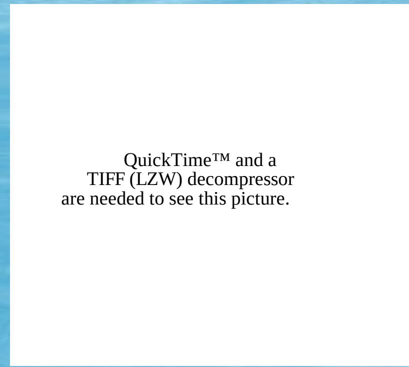
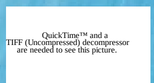
Recent Results from SLR Experiments in Fundamental Physics:



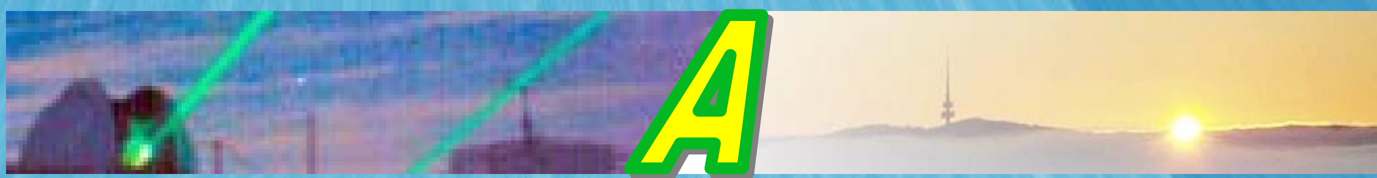
Frame-dragging observed with Satellite Laser Ranging

Errico**s** C. Pavlis, JCET/UMBC - NASA Goddard 698, (epavlis@UMBC.edu)

Ignazio Ciufolini, Università degli Studi di Lecce, Lecce, Italy



Rolf König, GeoForschungsZentrum (GFZ), Potsdam, Germany

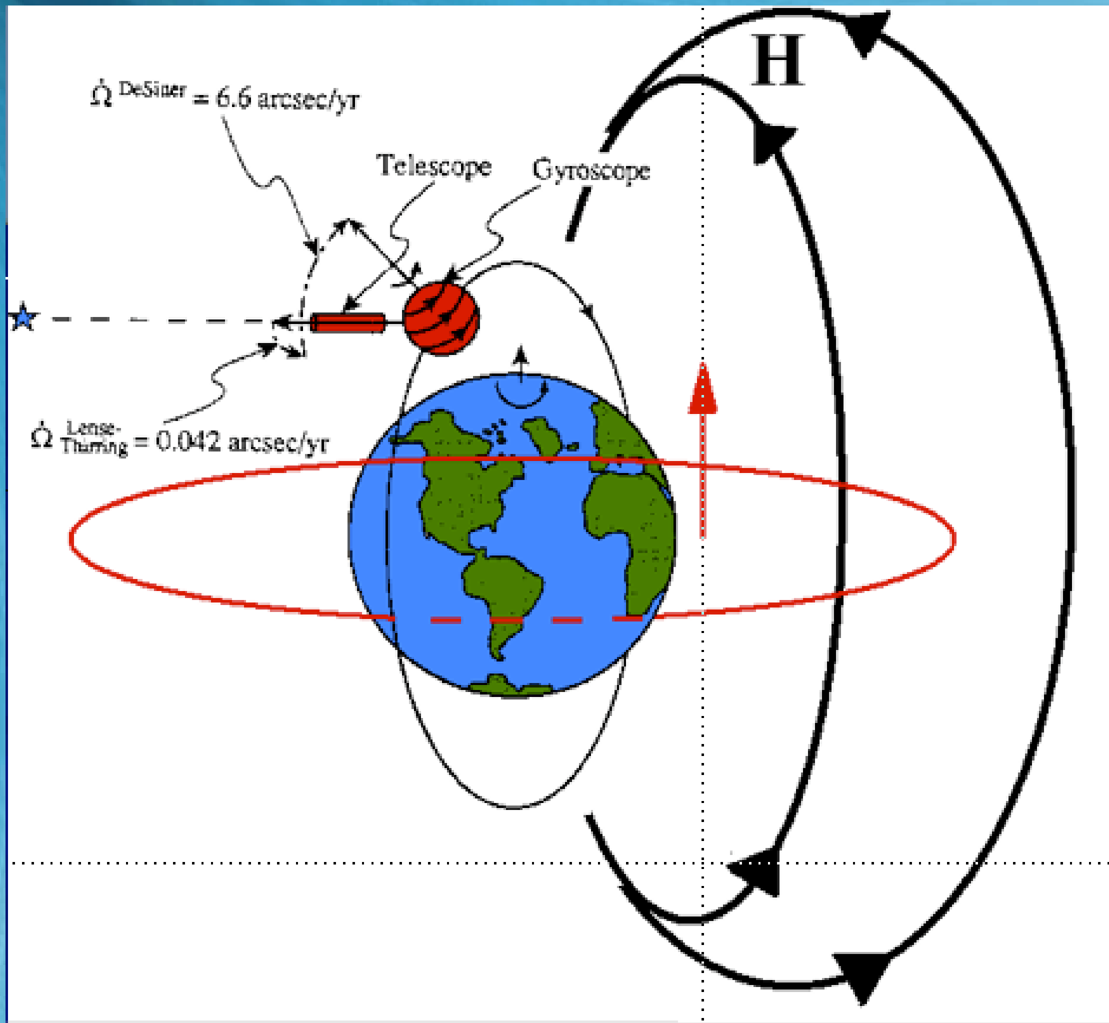


15th International Laser Ranging Workshop
"Extending the Range"
15-20 October 2006, Canberra, Australia

Outline

- Brief theoretical introduction
- Lense-Thirring Measurement: How?
- Orbital Perturbations
- Gravitational (Earth) Model Evolution
- Our measurement of Lense-Thirring Effect
- Results & Future plans

Gravitomagnetism



GR effects on a gyroscope orbiting around a planet (e.g. Earth)

Gravitomagnetism

A typical test particle can be a satellite orbiting around a planet (e.g., Earth)

The gravitomagnetic "force" is smaller than the gravitational monopole, so we can use the tools of celestial mechanics and consider this "force" as a ***perturbation*** of Keplerian motion

Orbital Theory

Putting the gravitomagnetic "force" into the perturbation equations, and integrating them to first order, we get the formulae for the secular rate of node and perigee:

$$
\begin{cases}
\dot{\Omega}^{L-T} = \dfrac{2GJ}{c^2 a^3 (1-e^2)^{3/2}} \\[2ex]
\dot{\omega}^{L-T} = \dfrac{-6GJ}{c^2 a^3 (1-e^2)^{3/2}} \cos I
\end{cases}
$$

Discovered by J. Lense and H. Thirring in 1918.

1986 Proposal at Univ. of Texas, Austin

Lense-Thirring Measurement: How?

We want to measure Earth gravitomagnetism with artificial satellites tracked by SATELLITE LASER RANGING **(SLR)**

- Source of field: Earth (with angular momentum)
- Test particle: satellite (e.g. LAGEOS, LAGEOS II, *LARES*,…)
- Measure: two-way range (with laser)

The Targets ("Particles")

We analyzed range data from the two satellites
LAGEOS and **LAGEOS II**

These satellites are used in geodesy and geophysics for:

- Crustal movements (tectonic motions)
- Pole motion and Earth rotation (Reference Frame Definition)
- Temporal changes of Earth's gravity field (long wavelength!)

And they can also be used as test particles, i.e.:

PROBES OF GENERAL RELATIVITY

Perturbations

Gravitational:

- Even zonal harmonic coefficients J_{2n} of the geopotential (static part)
- Odd zonal harmonic coefficients J_{2n+1} (static part)
- Non zonal harmonic coefficients (Tesseral and Sectorial)
- Solid and ocean Earth tides and other temporal variations of Earth gravity field
- Solar, lunar and planetary perturbations
- de Sitter precession
- Other general relativistic effects
- Deviations from geodesic motion

Non-gravitational:

- Solar radiation pressure
- Earth albedo
- Anisotropic emission of thermal radiation due to Sun visible radiation (Yarkovsky-Schach effect)
- Anisotropic emission of thermal radiation due to Earth infrared radiation (Yarkovsky-Rubincam effect)
- Neutral and charged particle drag
- Earth magnetic field

Perturbations

Gravitational perturbations:

- Even zonal harmonic coefficients J_{2n} of the geopotential (static part)
- Odd zonal harmonic coefficients J_{2n+1} (static part)
- Non zonal harmonic coefficients (Tesseral and Sectorial)
- Solid and ocean Earth tides and other temporal variations of Earth gravity field
- Solar, lunar and planetary perturbations
- de Sitter precession
- Other general relativistic effects
- Deviations from geodesic motion

$\delta\mu^{\text{even zonals}} \leq 3\text{-}4\%\ \mu^{GR}$

$\delta\mu^{\text{odd zonals}} \leq 10^{-3}\ \mu^{GR}$

$\delta\mu^{\text{tides}} \leq 1\%\ \mu^{GR}$

$\delta\mu^{\text{other}\ \ldots} \leq 10^{-3}\ \mu^{GR}$

Perturbations

Non-gravitational perturbations:

- Solar radiation pressure
- Earth albedo
- Anisotropic emission of thermal radiation due to Sun visible radiation (Yarkovsky-Schach effect)
- Anisotropic emission of thermal radiation due to Earth infrared radiation (Yarkovsky-Rubincam effect)
- Neutral and charged particle drag
- Earth magnetic field

$\delta\mu^{\text{solar rad.}} \leq 10^{-3}\ \mu^{GR}$

$\delta\mu^{\text{albedo}} \leq 1\%\ \mu^{GR}$

$\delta\mu^{Y\text{-}S} \leq 1\%\ \mu^{GR}$

$\delta\mu^{Y\text{-}R} \leq 1\%\ \mu^{GR}$

$\delta\mu^{\text{Drag-like}} \leq 10^{-3}\ \mu^{GR}$

Gravitational Model Evolution

During the last two decades, a lot of work was done on modeling the gravity field from satellite perturbations, altimetry and surface gravimetry, resulting in a series of geopotential models: JGM-2, JGM-3, **EGM96 (360x360)**, …

High accuracy and resolution models though were only recently obtained as a direct consequence of dedicated missions such as **CHAMP** and **GRACE:**

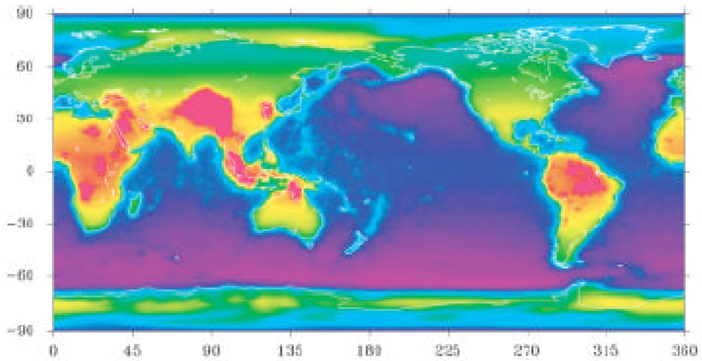
- EIGEN02S (*120x120,+140*)
- GGM01S (*120x120, **95***)
- EIGEN-GRACE02S (*150x150, **120***)
- GGM02S (*160x160, **120***)
- EIGEN-GRACE03 (*180x180*)
- EIGEN-GRACE04 (*360x360)*

GeoForschungsZentrum Potsdam, Germany
Center for Space Research, Univ. of Texas, Austin

Gravitational Model Evolution

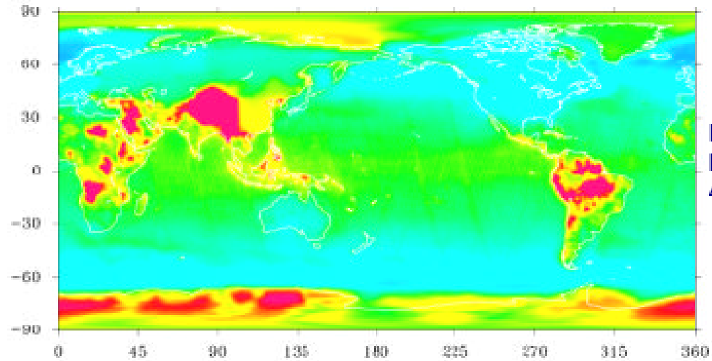
Geoid errors from GRACE are much more uniform and without land/sea discrimination

Predicted geoid height errors for EGM96*



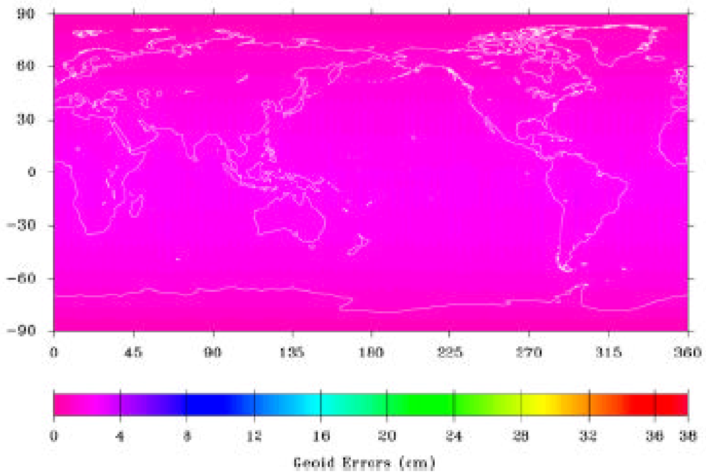
Errors as large as 50 cm

Predicted gravity anomaly errors for EGM96*



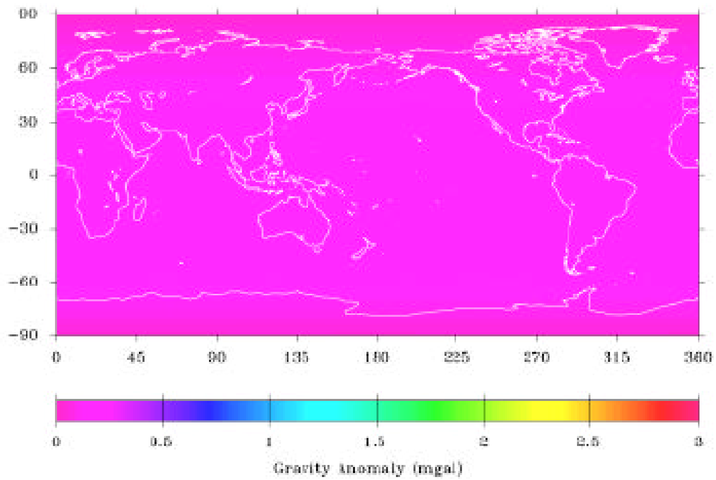
Errors as large as 4 mgal

Predicted geoid height errors for GGM01S*



Errors less than 2 cm

Predicted gravity anomaly errors for GGM01S*



Errors less than 0.2 mgal

* at ~300 km resolution (degree/order 70)

Our measurement of L-T Effect

Perturbations due to current uncertainties in ***J_2*** are greater than the L-T effect, i.e., we are not able to model Earth gravity with the accuracy needed to extract the gravitomagnetic precession.

But thanks to *Ignazio Ciufolini* there ***is*** a method to overcome this problem, using the LAGEOS and LAGEOS II nodes (although not exactly in "butterfly" configuration), in a ***linear combination***!

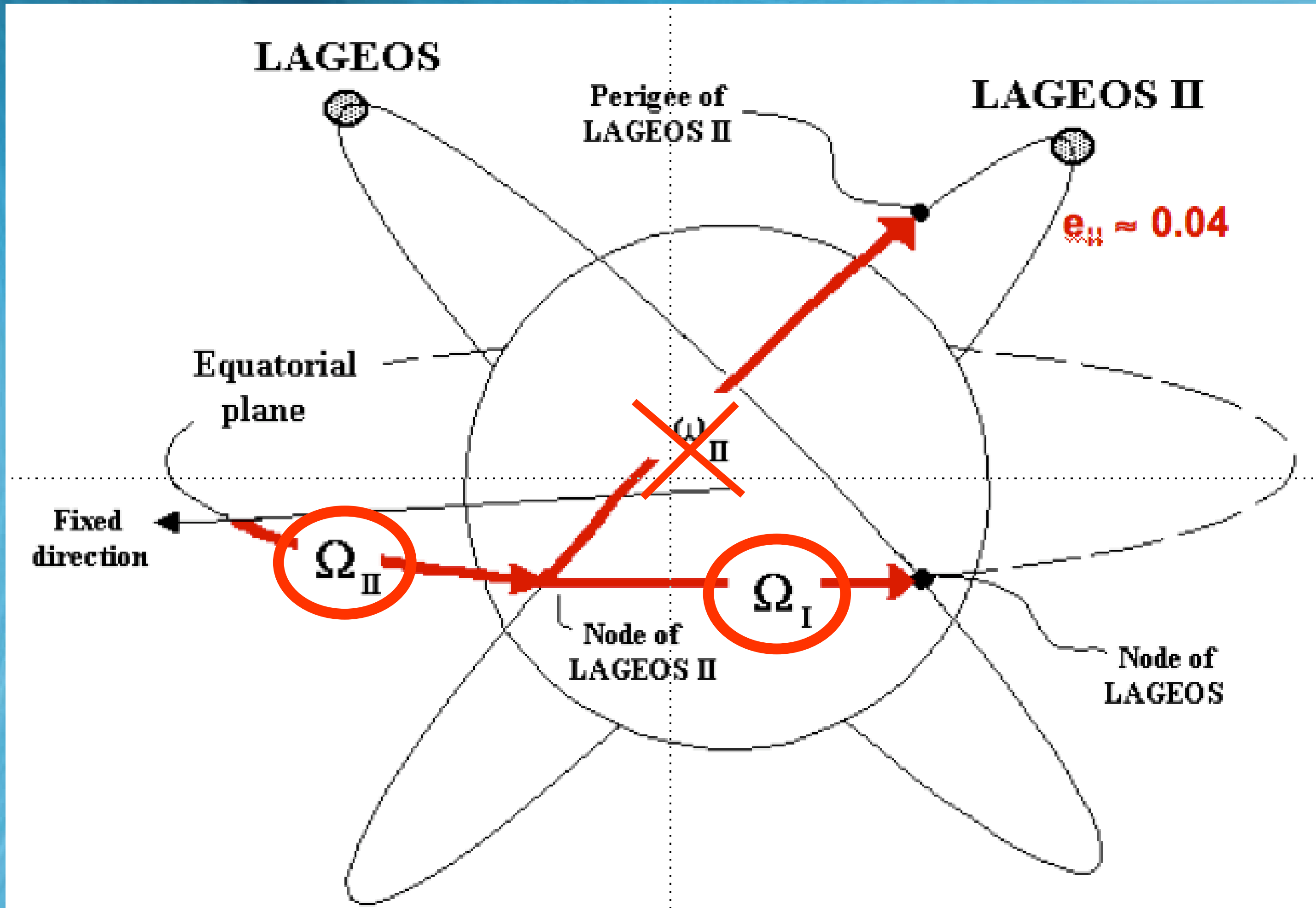
Our measurement of L-T Effect

The observed Keplerian elements have uncertainties that represent unknown errors and therefore are not modeled.

In our procedure of fit of experimental data, $\delta\dot{\Omega}^{class}$ and $\delta\dot{\omega}^{class}$ add up to μ (the unknown intensity of the L-T effect) to form the total difference between model and experimental data: the RESIDUAL

RESIDUAL = Computed value (Newtonian $\boldsymbol{\mu \equiv 0}$) – Observed value (True $\boldsymbol{\mu}$)

Our measurement of L-T Effect



The older scheme, used in our 1998 analysis reported in [*Science*, 1998], is now simplified, **removing the LAGEOS II perigee**

Our measurement of L-T Effect

This "observation" is the general one, the one we used in our 1998 analysis reported in [*Science*, 1998], when the available Earth models were not of the quality we have today (thanks to GRACE!), and we were forced to eliminate both, the errors due to J_2 and J_4.

With the improved Earth models from GRACE, we were able to accept the error due to J_4 and still stay within our error budget. This allowed us to eliminate the use of the LAGEOS II perigee, which was a source of additional errors (due to the nature of perigee perturbations), perform our experiment using only the nodal residuals of the two satellites, using a slightly modified "observation equation":

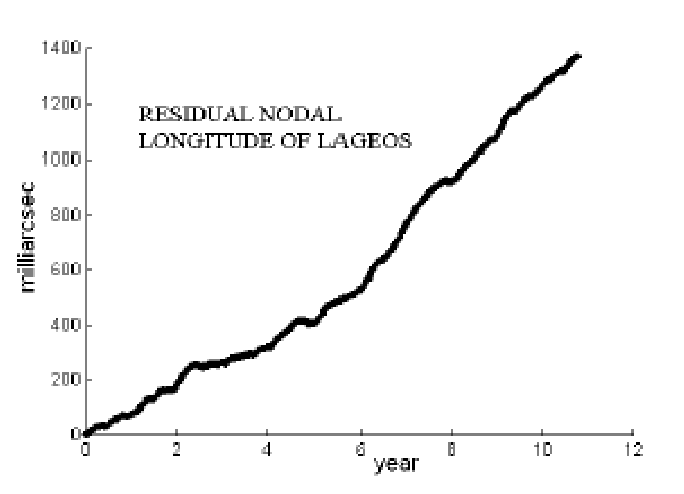
$$\delta\dot{\Omega}_I + k\,\delta\dot{\Omega}_{II} = 48.2\mu + other\,errors \quad [mas/y]$$

This formula gives us the magnitude of L-T effect from the observed residuals of the two ***nodes only***.

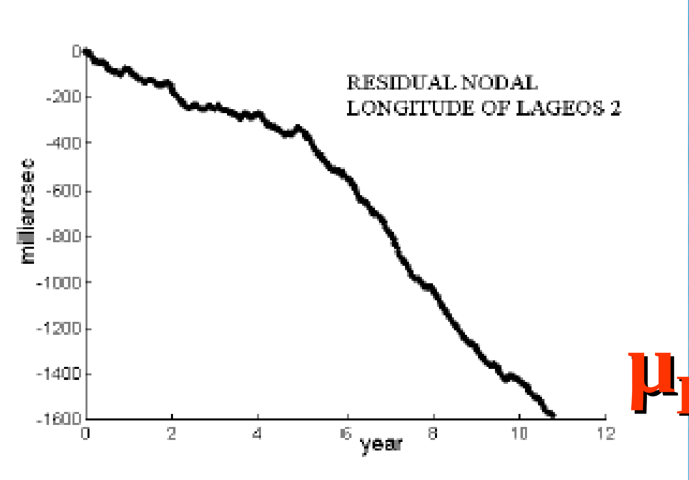
2004 L-T Results

- Orbital analysis of the 1993 to 2004 LAGEOS and LAGEOS 2 SLR data from the ILRS tracking network
- 14-day arc fits, modeling everything we know, except for the L-T acceleration
- Formation of residual series of the nodes from successive arcs
- Integration of the residual series and fit for μ

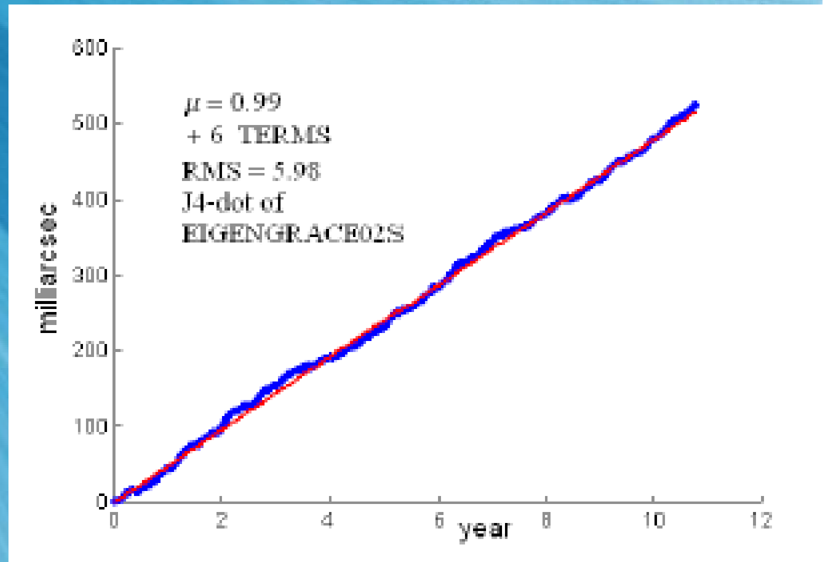
2004 L-T Results



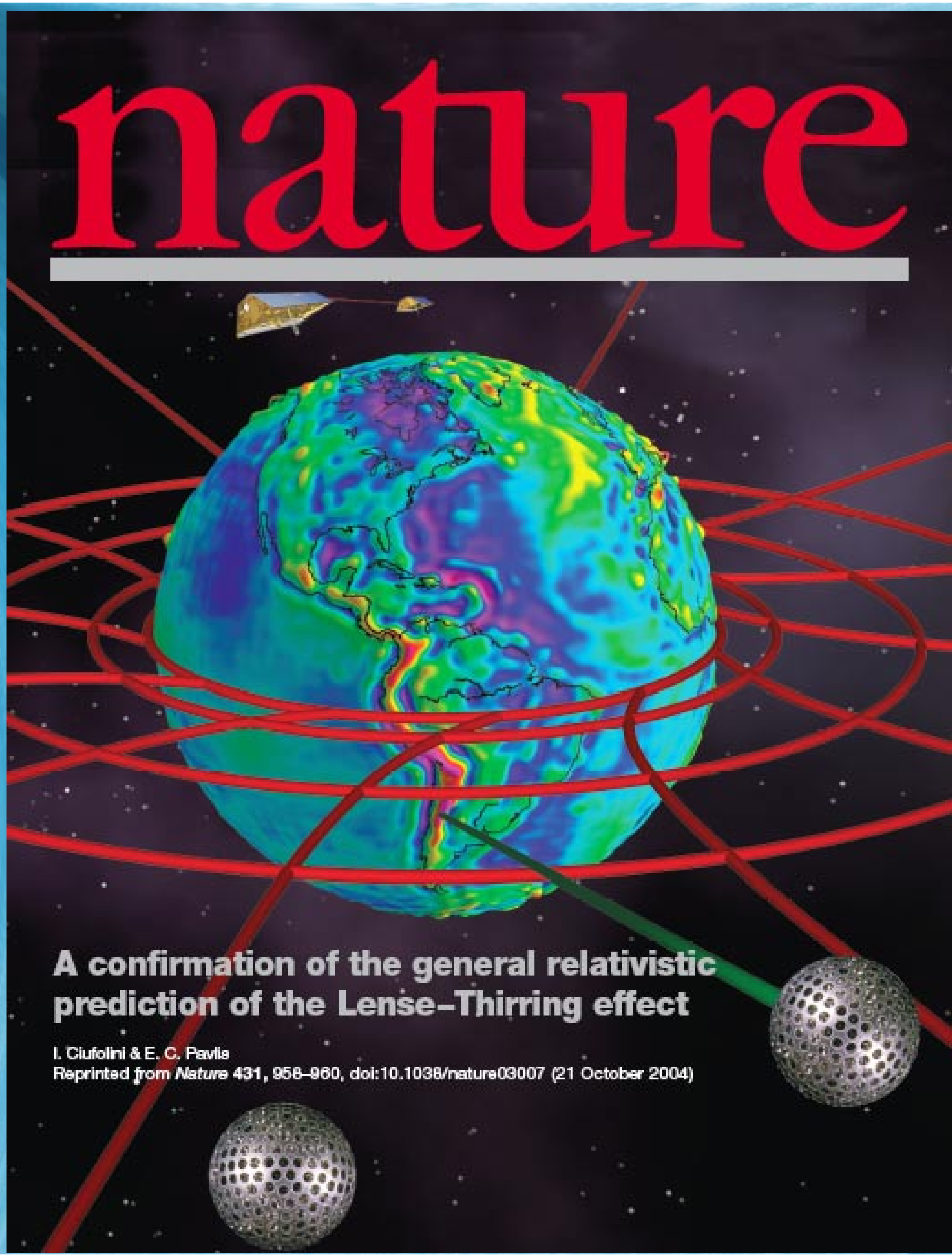
$$\delta\dot{\Omega}_I + 0.545\delta\dot{\Omega}_{II} = 48.2\mu$$



EIGEN-GRACE02S



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


nature
A confirmation of the general relativistic prediction of the Lense–Thirring effect
I. Ciufolini & E. C. Pavlis
Reprinted from *Nature* 431, 958–960, doi:10.1038/nature03007 (21 October 2004)

2004 L-T Results

- Reliability of the result and a robust estimate of its confidence interval is necessary, in order to accept it.

- Our error analysis, and further investigations taking into account even more recent Earth models from GRACE (GGM02S, EIGEN-GRACE04, etc.), lead us to an error estimate which is at best 5% and not worse than 10%.

Beyond the 2004 L-T Results

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New Astronomy 11 (2006) 527–550

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Determination of frame-dragging using Earth gravity models from CHAMP and GRACE

I. Ciufolini [a,*], E.C. Pavlis [b], R. Peron [c]

[a] *Dipartimento di Ingegneria dell'Innovazione, Università di Lecce and INFN Sezione di Lecce, Via Monteroni, 73100 Lecce, Italy*
[b] *Joint Center for Earth Systems Technology (JCET/UMBC), University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA*
[c] *Dipartimento di Fisica, Università di Lecce and INFN Sezione di Lecce, Via Arnesano, 73100 Lecce, Italy*

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Communicated by G. Setti

Beyond the 2004 L-T Results

- Improve error budget of the technique
- Repeat the analysis with more models
- Consider new models from other groups
- Validate the analysis with results from an independent s/w package
- Collaborate with groups repeating independently the analysis using our technique

Beyond the 2004 L-T Results

- As of this year we have initiated a collaboration with the **GFZ** group in Potsdam, Germany, using their EPOSOC s/w

- On-going inter-comparison of results with **CSR** group at Univ. of Texas, Austin (J. Ries and R. Eanes) using the UTOPIA s/w, with the goal to generate a joint publication with results from existing models, but primarily, with their definitive GRACE model to be released in the next few months, the **GGM03**

2006 EPOSOC(GFZ) Results

EIGEN-GRACE02S

Secular + 6 freq. fitted - Geodetic precession

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

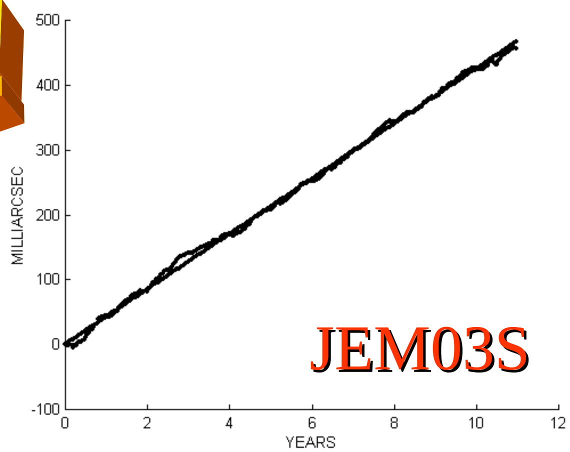
Raw residuals

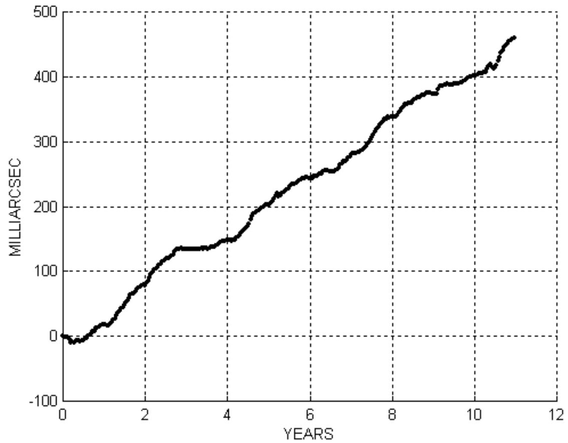
$\mu = 1.03$

RMS = 7.4 mas

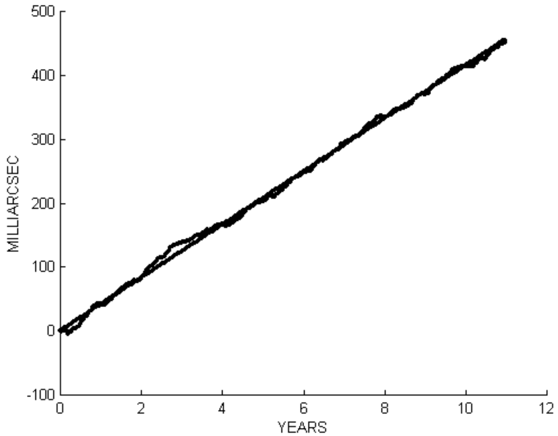
New Results

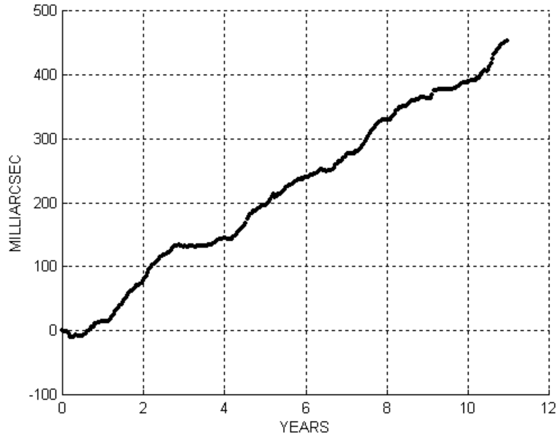
New !





mu = **0.883114962661653**
rateperyear = **42.4861007987136**
rms = **5.98330842061449**





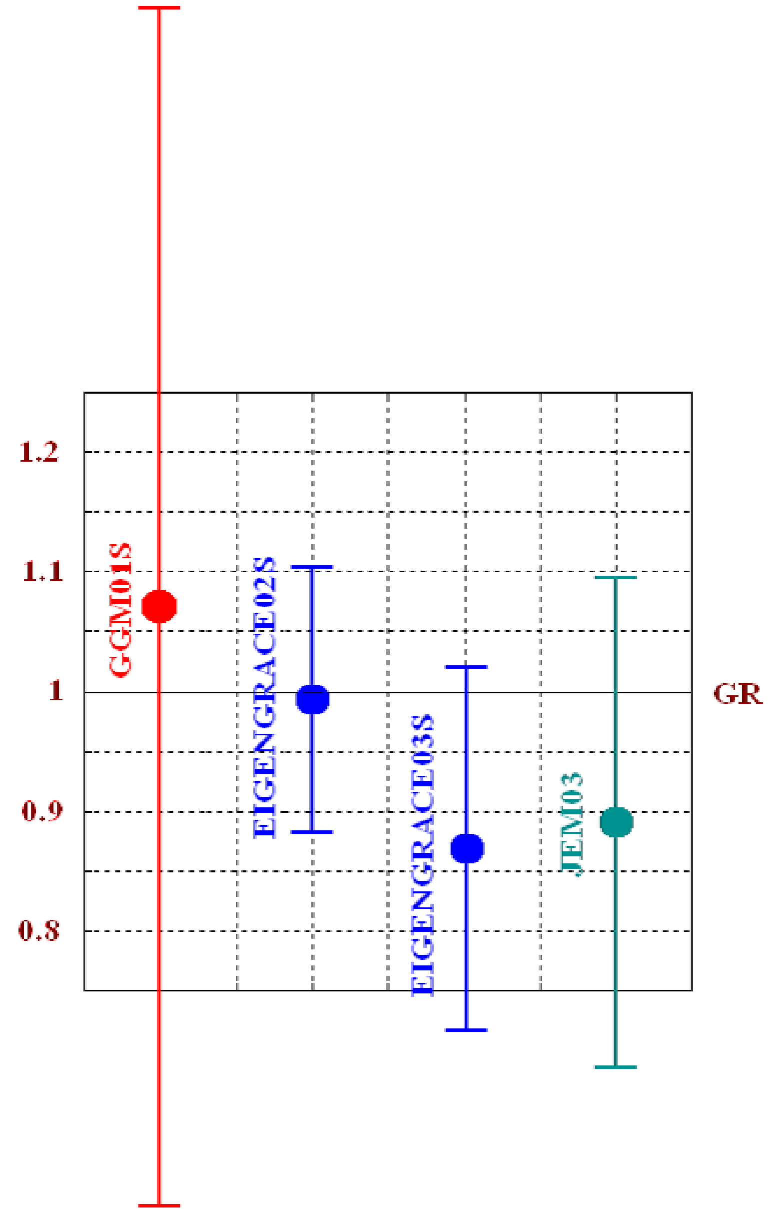
mu = **0.862729824124275**
rateperyear = **41.5053847115527**
rms = **6.07186951510152**

EIGEN-GRACE03S

New Gravity Model Results

- Finalized the analysis of the models shown at right, using both s/w, ours Geodyn (NASA Goddard), and EPOSOC of GFZ, with the collaboration of the team of Dr. Rolf König.

- The new results are consistent with GR and indicate the agreement of independent s/w and analysis teams.

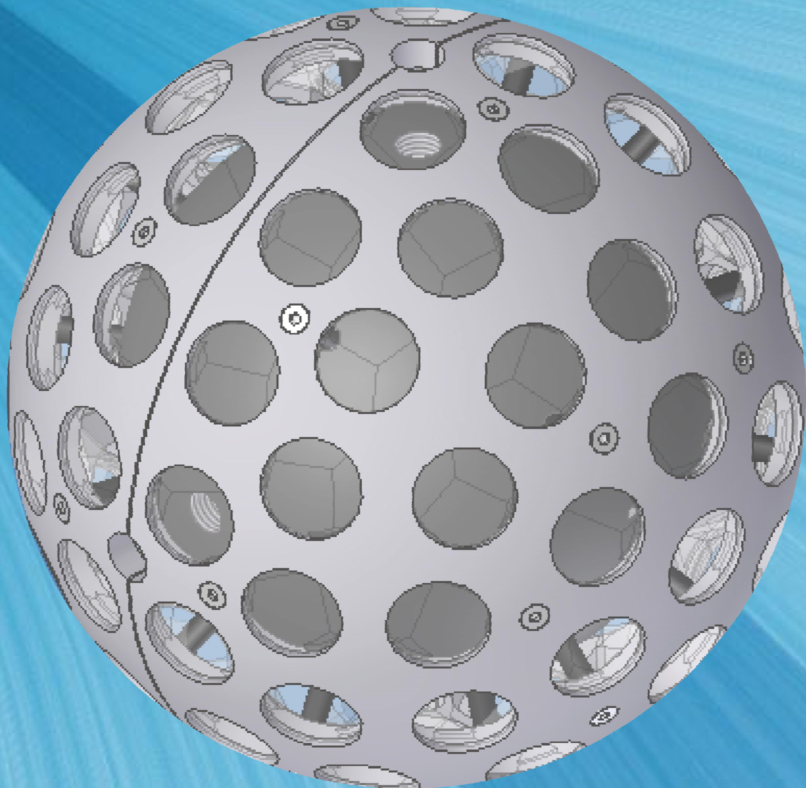


The Future

- GRACE-based gravity models with increased accuracy, soon to be released
- LAGEOS in chaotic spin, LAGEOS II slowing down (impacts LARES design)
- New targets required with better design and a complete set of accurate measurements done prior to launch!
- Lighter design possible, due to new CCR options and even further improvement in future gravity models

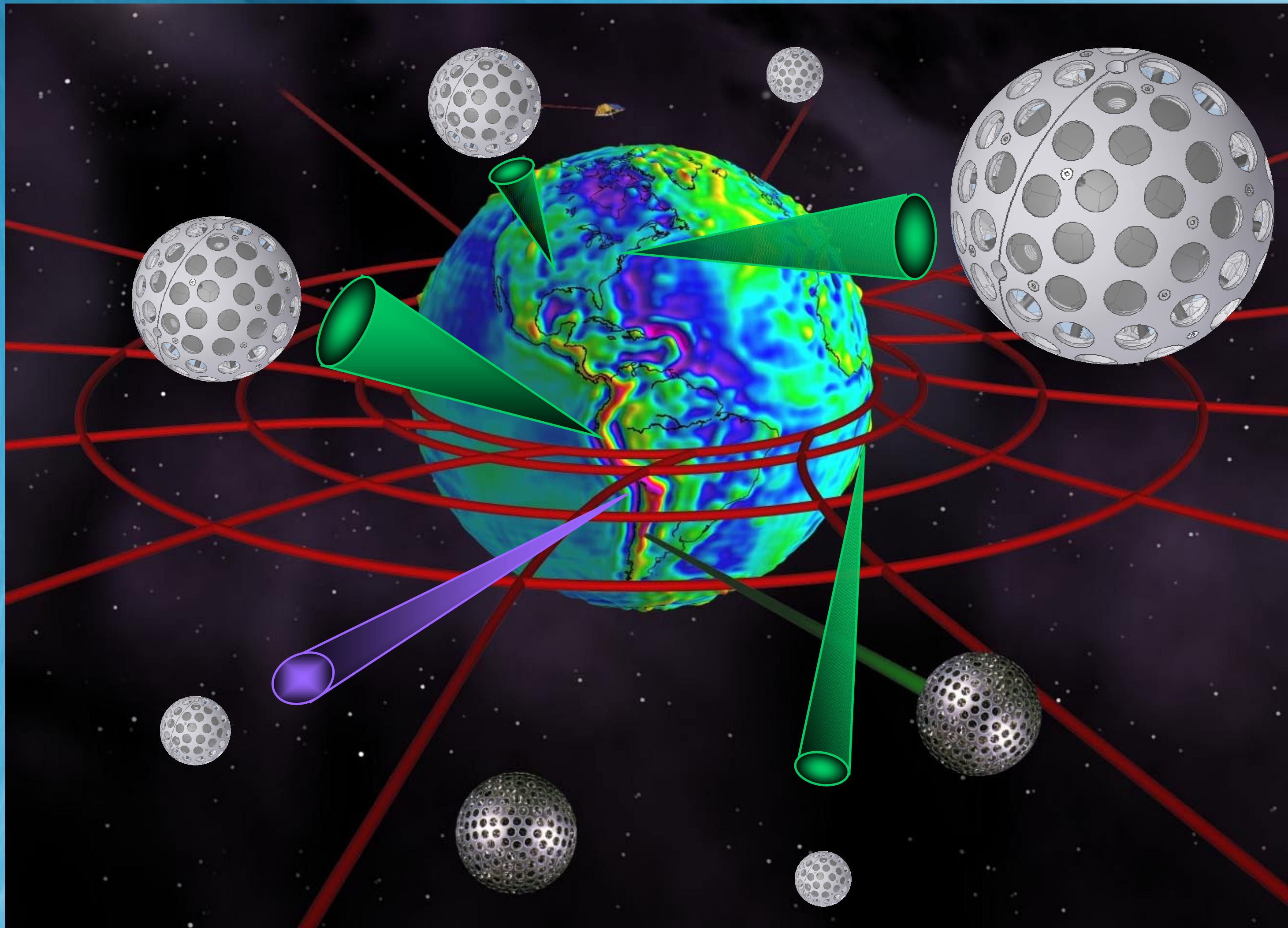
The Future

- Design & Launch LARES
- Mechanical, Thermal and Optical characterization of LARES at LNF/INFN
- LARES' contribution to geodesy will also be significant and valuable in many research areas.




LARES
LARES
Prototipo LARES
SSCR-LNF-INFN
21/02/2006
Prog.:
T.Napolitano
Appr.:
M.A. Franceschi
Vista dall'alto
Scala: 1:1
Vista isometrica
Scala: 1:1
Prototipo LARES
SSCR-LNF-INFN
01/03/2006
Sfera Interna
Prog.:
T.Napolitano
Appr.:
M.A. Franceschi

A Future SLR Constellation



Thank You!