LARES, Laser Relativity Satellite:
Towards a One Percent Measurement of Frame Dragging by LAGEOS, LAGEOS 2, LARES and GRACE

by **Ignazio Ciufolini** (Univ. Salento)

presented by **Rolf Koenig** (GFZ)

A. Paolozzi*, E. Pavlis*, R. Koenig*, J. Ries*, R. Matzner*, G. Sindoni*, H. Neumayer*

*Sapienza Un. Rome,
*Maryland Un.,
*GFZ-German Research Centre for Geosciences-Potsdam,
*Un. Texas Austin

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Content

BRIEF INTRODUCTION ON FRAME-DRAGGING and GRAVITOMAGNETISM

EXPERIMENTS

*** The 2004-2007 measurements using the GRACE Earth's gravity models and the LAGEOS satellites**

*** LARES: 2011**

DRAGGING OF INERTIAL FRAMES

(*FRAME-DRAGGING* as Einstein named it in 1913)

The “local inertial frames” are freely falling frames were, locally, we do not “feel” the gravitational field, examples: an elevator in free fall, a freely orbiting spacecraft.

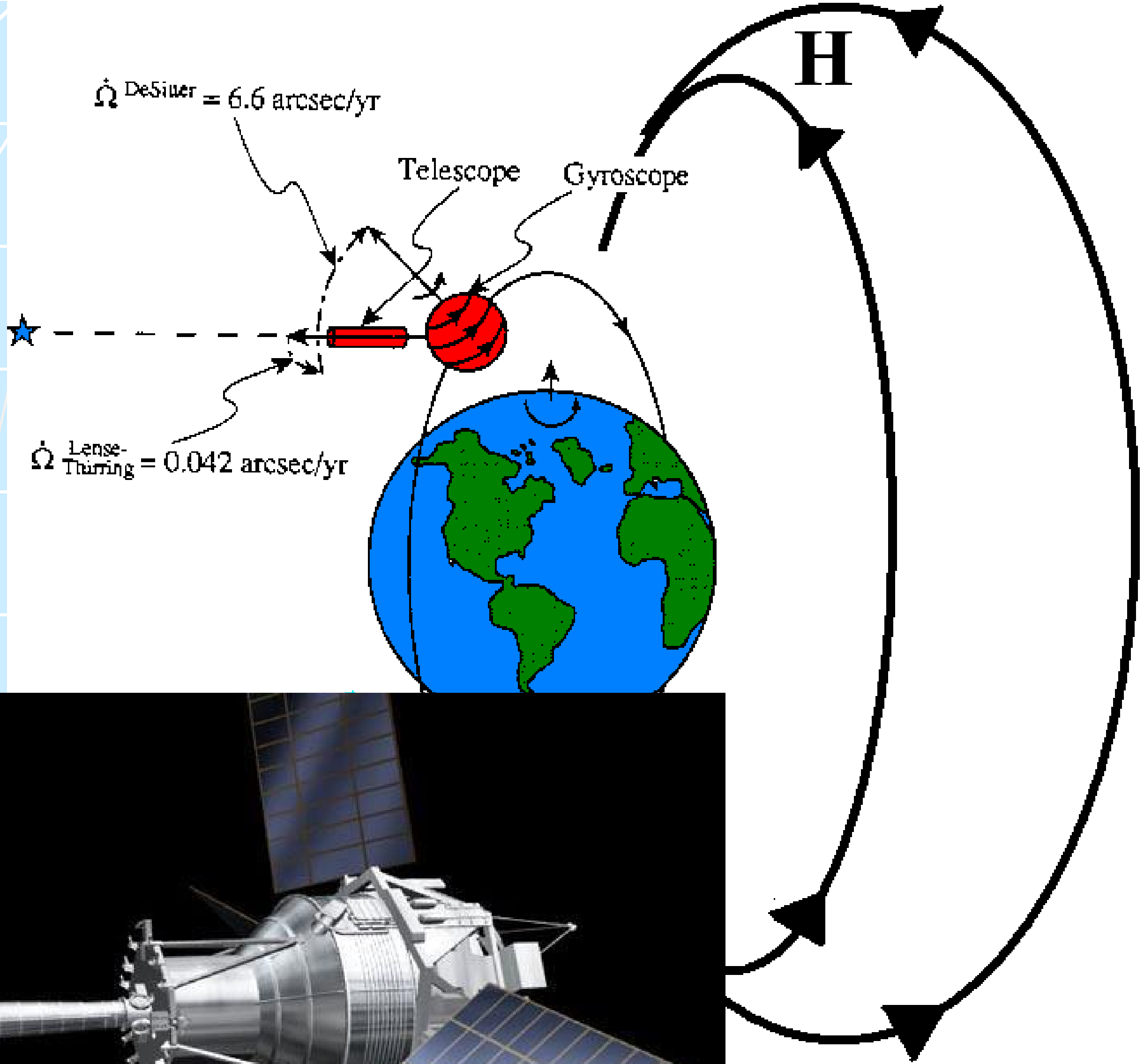
In General Relativity the axes of the local inertial frames are determined by gyroscopes and the gyroscopes are dragged by mass-energy currents, e.g., by the Earth rotation.

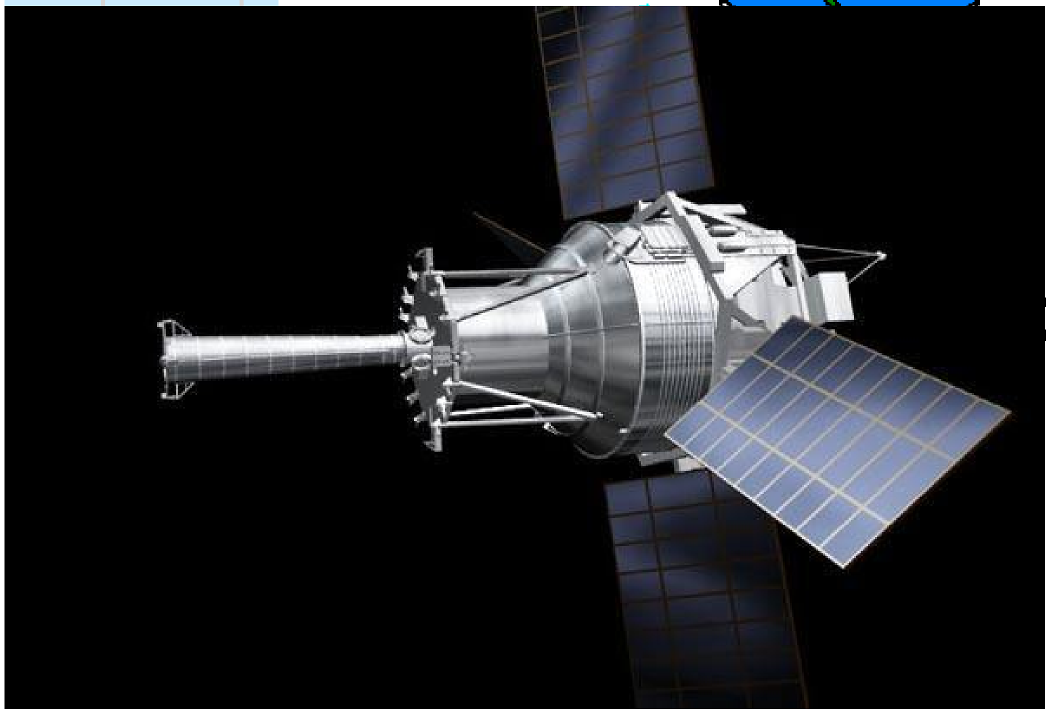
Thirring 1918
Braginsky, Caves and Thorne 1977
Thorne 1986
I.C. 1994-2001

GRAVITOMAGNETISM: frame-dragging is also called gravitomagnetism for its *formal* analogy with electrodynamics

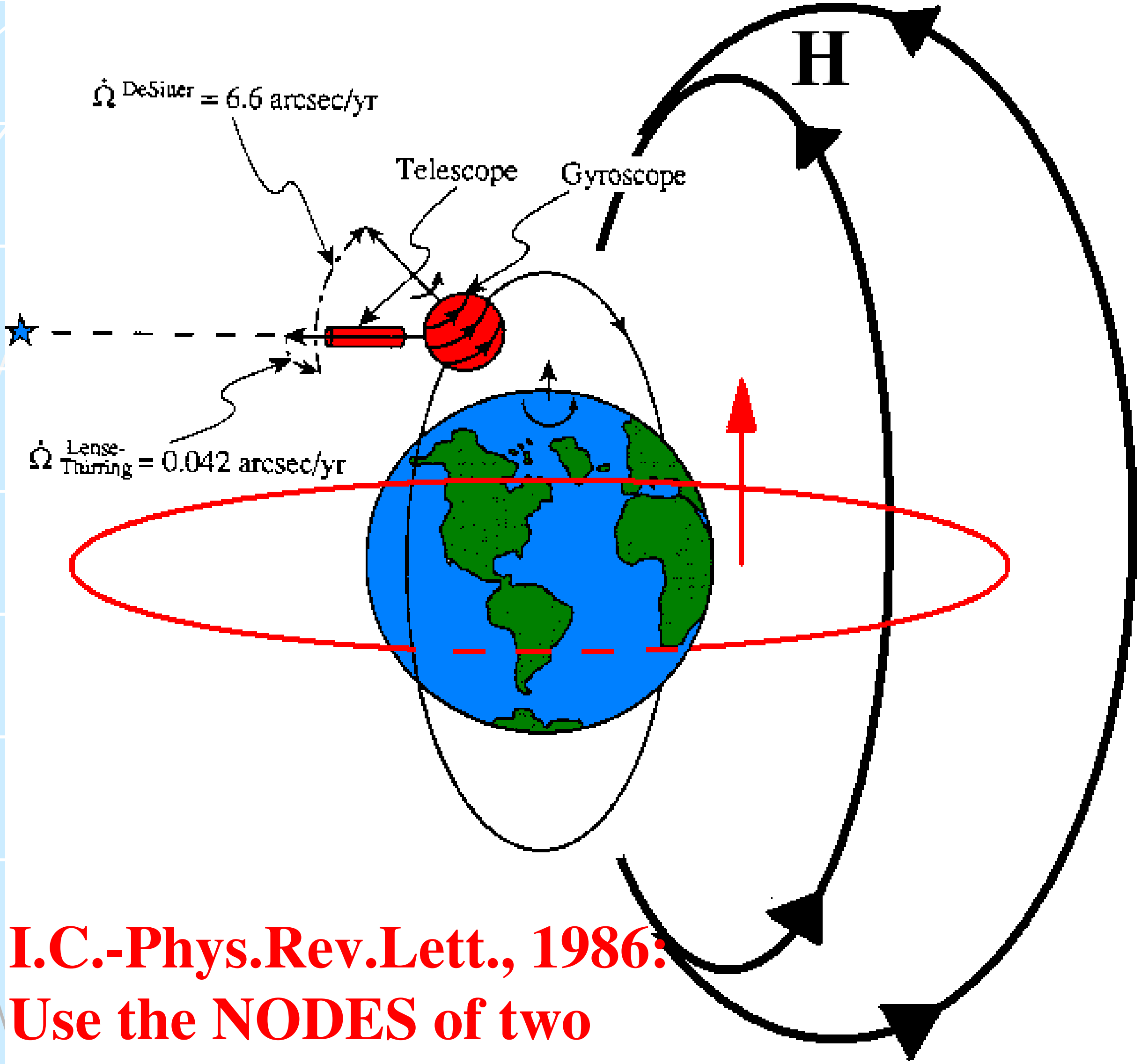
- In electrodynamics a magnetic needle is changing its orientation because of the magnetic field
- and the magnetic field is generated by electric currents.

- In General Relativity a gyroscope is changing its orientation (frame-dragging) because of the gravitomagnetic field and the gravitomagnetic field is generated by mass currents, such as the Earth rotation (Earth angular momentum).





GRAVITY PROBE B



I.C.-Phys.Rev.Lett., 1986:
Use the NODES of two LAGEOS satellites; the orbital plane of these satellites is a huge gyroscope affected by frame-dragging. This is called the Lense-Thirring effect

Measurement of the Lense-Thirring Drag on High-Altitude, Laser-Ranged Artificial Satellites

Ignazio Ciufolini

Center for Theoretical Physics, Center for Relativity, and Physics Department, University of Texas, Austin, Texas 78712

(Received 16 October 1984; revised manuscript received 19 April 1985)

We describe a new method of measuring the Lense-Thirring relativistic nodal drag using LAGEOS together with another similar high-altitude, laser-ranged satellite with appropriately chosen orbital parameters. We propose, for this purpose, that a future satellite such as LAGEOS II have an inclination supplementary to that of LAGEOS. The experiment proposed here would provide a method for experimental verification of the general relativistic formulation of Mach's principle and measurement of the gravitomagnetic field.

PACS numbers: 04.80.+z

In special and general relativity there are several precession phenomena associated with the angular momentum vector of a body. If a test particle is orbiting a rotating central body, the plane of the orbit of the particle is dragged by the intrinsic angular momentum J of the central body, in agreement with the general relativistic formulation of Mach's principle.[1]

In the weak-field and slow-motion limit the nodal lines are dragged in the sense of rotation, at a rate given by[2]

$$\dot{\Omega} = [2/a^3(1-e^2)^{3/2}]J, \tag{1}$$

where a is the semimajor axis of the orbit, e is the eccentricity of the orbit, and geometrized units are used, i.e., $G=c=1$. This phenomenon is the Lense-Thirring effect, from the names of its discoverers in 1918.[2]

In addition to this there are other precession phenomena associated with the intrinsic angular momentum or spin $\mathbf{S}$ of an orbiting particle. In the weak-field and slow-motion limit the vector $\mathbf{S}$ precesses at a rate given by[1] $d\mathbf{S}/d\tau = \dot{\mathbf{\Omega}} \times \mathbf{S}$ where

$$\dot{\mathbf{\Omega}} \equiv -\tfrac{1}{2}\mathbf{v}\times\mathbf{a} + \tfrac{3}{2}\mathbf{v}\times\nabla U + \frac{1}{r^3}\left[-\mathbf{J} + \frac{3(\mathbf{J}\cdot\mathbf{r})\mathbf{r}}{r^2}\right], \tag{2}$$

where $\mathbf{v}$ is the particle velocity, $\mathbf{a} \equiv d\mathbf{v}/d\tau - \nabla U$ is its nongravitational acceleration, $\mathbf{r}$ is its position vector, τ is its proper time, and U is the Newtonian potential.

The first term of this equation is the Thomas precession.[3] It is a special relativistic effect due to the noncommutativity of nonaligned Lorentz transformations. It may also be viewed as a coupling between the particle velocity $\mathbf{v}$ and the nongravitational forces acting on it.

The second (de Sitter[4]–Fokker[5]) term is general relativistic, arising even for a nonrotating source, from the parallel transport of a direction defined by $\mathbf{S}$; it may be viewed as spin precession due to the coupling between the particle velocity $\mathbf{v}$ and the static $-g_{\alpha\beta,0}=0$ and $g_{i0}=0$—part of the space-time geometry.

The third (Schiff[6]) term gives the general relativistic precession of the particle spin $\mathbf{S}$ caused by the intrinsic angular momentum $\mathbf{J}$ of the central body—$g_{i0}\neq 0$.

We also mention the precession of the periapsis of an orbiting test particle due to the angular momentum of the central body. This tiny shift of the perihelion of Mercury due to the rotation of the Sun was calculated by de Sitter in 1916.[7]

All these effects are quite small for an artificial satellite orbiting the Earth.

We propose here to measure the Lense-Thirring dragging by measuring the nodal precession of laser-ranged Earth satellites. We shall show that two satellites would be required; we propose that LAGEOS[8–10] together with a second satellite LAGEOS X with opposite inclination (i.e., with $I^X = 180° - I$, where $I \simeq 109.94°$ is the orbital inclination of LAGEOS) would provide the needed accuracy.

The major part of the nodal precession of an Earth satellite is a classical effect due to deviations from spherical symmetry of the Earth's gravity field—quadrupole and higher mass moments.[11] These deviations from sphericity are measured by the expansion of the potential $U(r)$ in spherical harmonics. From this expansion of $U(r)$ follows[11] the formula for the classical precession of the nodal lines of an Earth satellite:

$$\dot{\Omega}_{\text{class}} \simeq -\frac{3}{2}n\left(\frac{R_\oplus}{a}\right)^2 \frac{\cos I}{(1-e^2)^2}\left\{J_2 + J_4\left[\frac{5}{8}\left(\frac{R_\oplus}{a}\right)^2 (7\sin^2 I - 4)\frac{1+\frac{3}{2}e^2}{(1-e^2)^2}\right] + \dots\right\}, \tag{3}$$

IC, PRL 1986:
Use of the nodes of two laser-ranged Satellites to measure the Lense-Thirring effect in order to eliminate the error due to the even zonal harmonics

International Journal of Modern Physics A, Vol. 4, No. 13 (1989) 3083–3145

A COMPREHENSIVE INTRODUCTION TO THE LAGEOS GRAVITOMAGNETIC EXPERIMENT: FROM THE IMPORTANCE OF THE GRAVITOMAGNETIC FIELD IN PHYSICS TO PRELIMINARY ERROR ANALYSIS AND ERROR BUDGET

IGNAZIO CIUFOLINI

CNR-Istituto di Fisica dello Spazio Interplanetario, Via G. Galilei-CP 27-00044 Frascati, Italy

and

Center for Space Research, The University of Texas at Austin, Austin, Texas 78712, USA

Received 3 May 1988
Revised 7 October 1988

The existence of the gravitomagnetic field, generated by mass currents according to Einstein geometrodynamics, has never been proved. The author of this paper, after a discussion of the importance of the gravitomagnetic field in physics, describes the experiment that he proposed in 1984 to measure this field using LAGEOS (Laser geodynamics satellite) together with another non-polar, laser-ranged satellite with the same orbital parameters as LAGEOS but a supplementary inclination.

The author then studies the main perturbations and measurement uncertainties that may affect the measurement of the Lense-Thirring drag. He concludes that, over the period of the node of ~ 3 years, the maximum error, using two nonpolar laser ranged satellites with supplementary inclinations, should not be larger than ~ 10% of the gravitomagnetic effect to be measured.

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IC IJMPA 1989: Analysis of the orbital perturbations affecting the nodes of LAGEOS-type satellites

(1) Use two LAGEOS satellites with supplementary inclinations

OR:

Use n satellites of LAGEOS-type to measure the first n-1 even zonal harmonics: J_2, J_4, … and the Lense-Thirring effect

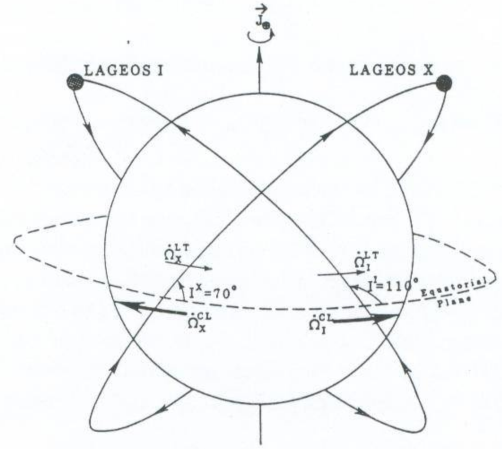


Fig. 5. The LAGEOS and LAGEOS *X* orbits and their classical and gravitomagnetic nodal precessions. A new[17] configuration to measure the Lense-Thirring effect.

For J_2, this corresponds, from formula (3.2), to an uncertainty in the nodal precession of 450 milliarcsec/year, and similarly for higher J_{2n} coefficients. Therefore, the uncertainty in $\dot{\Omega}^{\text{Class}}_{\text{Lageos}}$ is more than ten times larger than the Lense-Thirring precession.

A solution would be to orbit several high-altitude, laser-ranged satellites, similar to LAGEOS, to measure J_2, J_4, J_6, etc., and one satellite to measure $\dot{\Omega}^{\text{Lense-Thirring}}$.

Another solution would be to orbit polar satellites; in fact, from formula (3.2), for polar satellites, since $I = 90°$, $\dot{\Omega}^{\text{Class}}$ is equal to zero. As mentioned before, Yilmaz proposed the use of polar satellites in 1959.[40,41] In 1976, Van Patten and Everitt[46,47] proposed an experiment with two drag-free, guided, counter-rotating, polar satellites to avoid inclination measurement errors.

A new solution[15,16,17,21,22,23] would be to orbit a second satellite, of LAGEOS type, with the same semimajor axis, the same eccentricity, but the inclination supplementary to that of LAGEOS (see Fig. 5). Therefore, "LAGEOS X" should have the following orbital parameters:

$$I^X \cong \pi - I^I \cong 70°\,, \qquad a^X \cong a^I\,, \qquad e^X \cong e^I\,. \tag{3.3}$$

With this choice, since the classical precession $\dot{\Omega}^{\text{Class}}$ is linearly proportional to $\cos I$, $\dot{\Omega}^{\text{Class}}$ would be equal and opposite for the two satellites:

$$\dot{\Omega}^{\text{Class}}_X = -\dot{\Omega}^{\text{Class}}_I\,. \tag{3.4}$$

By contrast, since the Lense-Thirring precession $\dot{\Omega}^{\text{Lense-Thirring}}$ is independent of the inclination (Eq. (3.1)), $\dot{\Omega}^{\text{Lense-Thirring}}$ will be the same in magnitude and sign for both satellites:

On a new method to measure the gravitomagnetic field using two orbiting satellites

I. CIUFOLINI
IFSI-CNR - Frascati, Italy
Dipartimento Aerospaziale, Università di Roma «La Sapienza» - Roma, Italy

(ricevuto il 20 Settembre 1996; approvato il 15 Novembre 1996)

Summary. — We describe a new method to obtain the first direct measurement of the Lense-Thirring effect, or dragging of inertial frames, and the first direct detection of the gravitomagnetic field. This method is based on the observations of the orbits of the laser-ranged satellites LAGEOS and LAGEOS II. By this new approach one achieves a measurement of the gravitomagnetic field with accuracy of about 25%, or less, of the Lense-Thirring effect in general relativity.

PACS 11.90 – Other topics in general field and particle theory.
PACS 04.80.Cc – Experimental test of gravitational theories.

1. – The gravitomagnetic field, its invariant characterization and past attempts to measure it

Einstein's theory of general relativity [1, 2] predicts the occurrence of a «new» field generated by mass-energy currents, not present in classical Galilei-Newton mechanics. This field is called the gravitomagnetic field for its analogies with the magnetic field in electrodynamics.

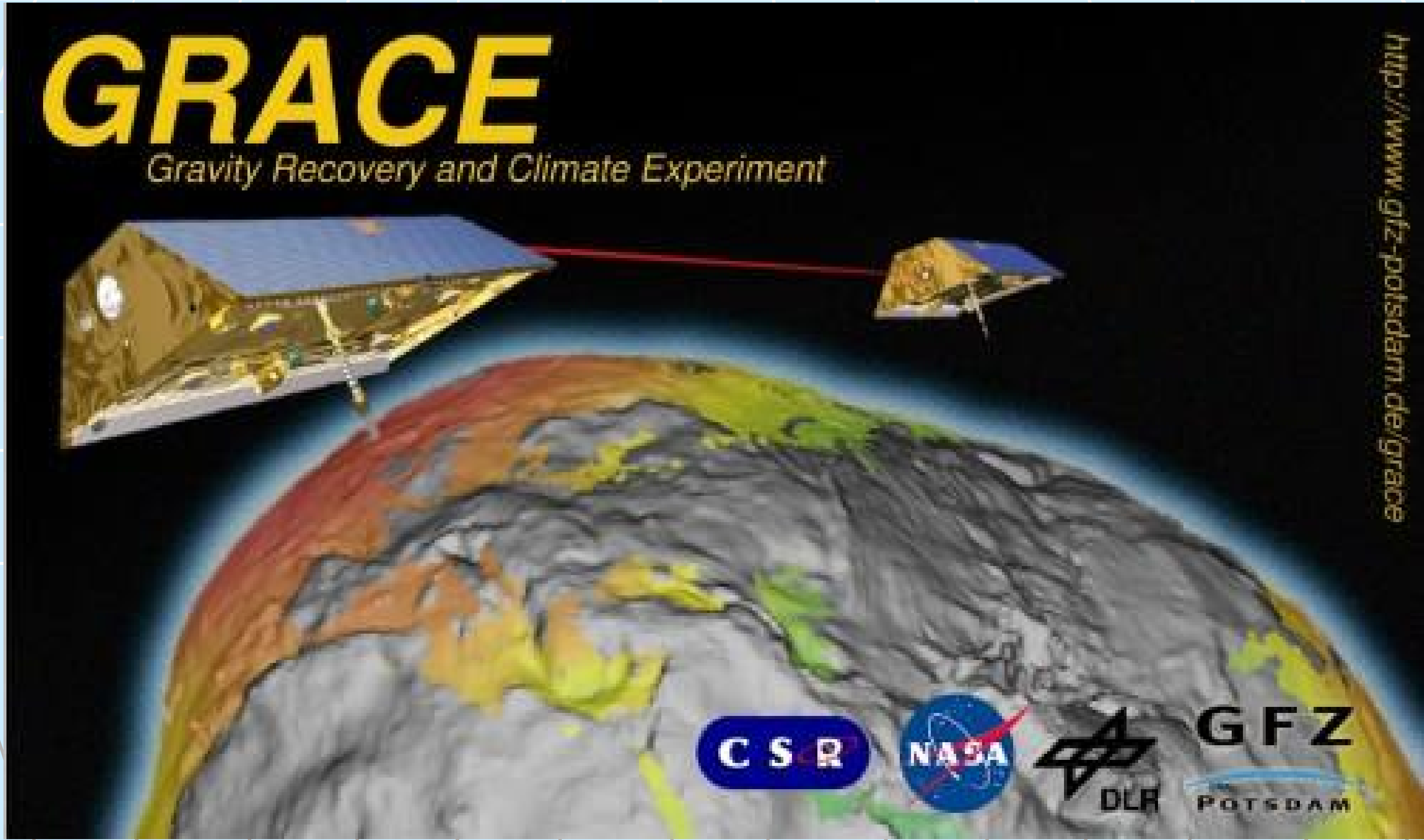
In general relativity, for a stationary mass-energy current distribution $\varrho_m \boldsymbol{v}$, in the weak-field and slow-motion limit, one can write [2] the Einstein equation in the Lorentz gauge: $\Delta \boldsymbol{h} \cong 16\pi\varrho_m \boldsymbol{v}$, where $\boldsymbol{h} \equiv (h_{01}, h_{02}, h_{03})$ are the $(0i)$-components of the metric tensor; $\boldsymbol{h}$ is called the gravitomagnetic potential. For a localized, stationary mass-energy distribution, in the weak-field and slow-motion limit, we can then write: $\boldsymbol{h} \cong -2((\boldsymbol{J} \times \boldsymbol{x})/r^3)$, where $\boldsymbol{J}$ is the angular momentum of the central body. In general relativity, one can also define [2] a gravitomagnetic field $\boldsymbol{H}$ given by $\boldsymbol{H} = \nabla \times \boldsymbol{h}$.

The Lense-Thirring effect is a consequence of the gravitomagnetic field and consists of a tiny perturbation of the orbital elements of a test particle due to the angular momentum of the central body. To characterize the gravitomagnetic field generated by the angular momentum of a body, and the Lense-Thirring effect, and distinguish it from other relativistic phenomena, such as the de Sitter effect, due to the

IC NCA 1996:
use the node of LAGEOS and the node of LAGEOS II to measure the Lense-Thirring effect

However, in 1996 the two nodes were not enough to measure the Lense-Thirring effect because of the uncertainties in the Earth gravity field

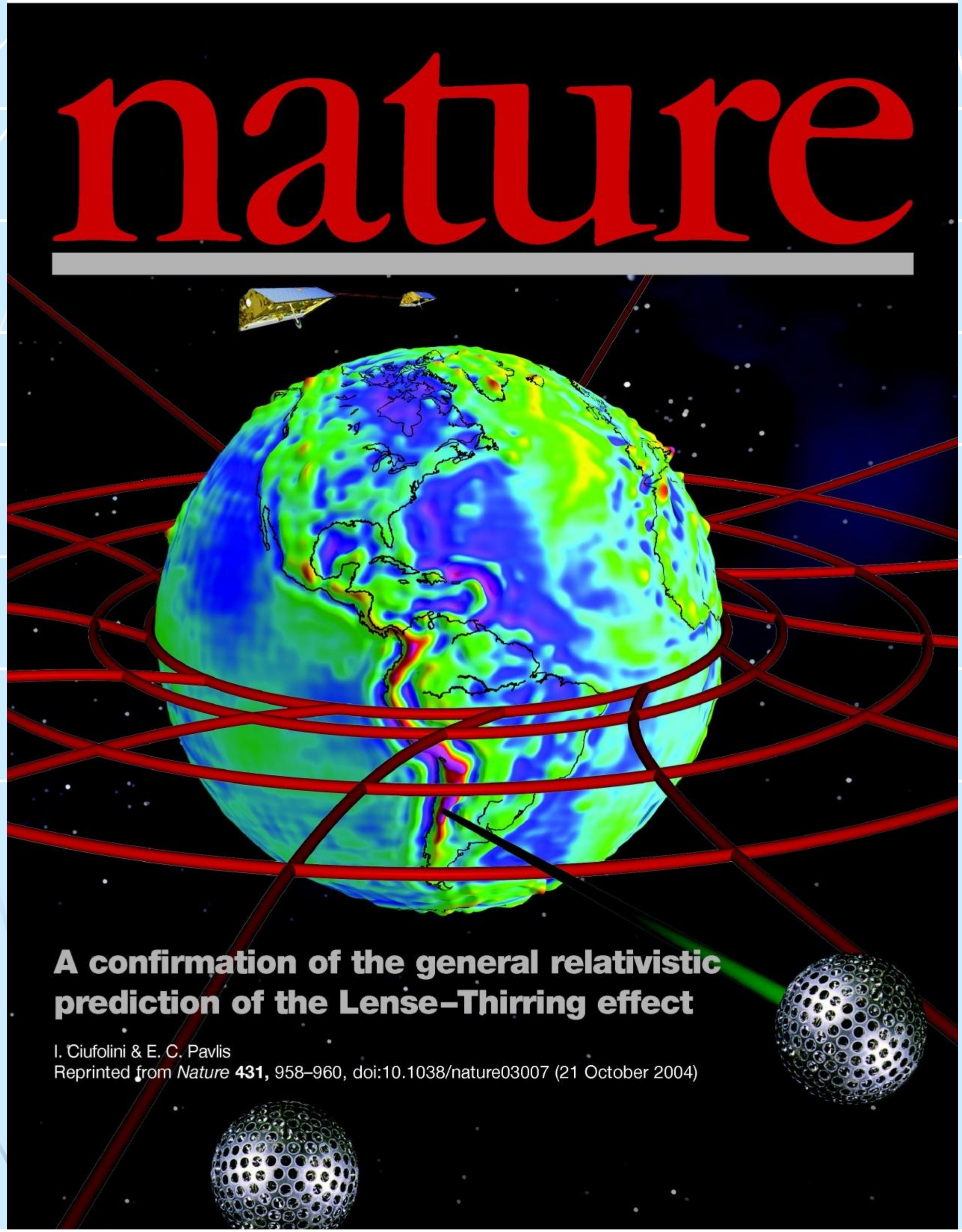
2002



Use of GRACE to test Lense-Thirring at a few percent level:
J. Ries et al. 2003 (1999),E. Pavlis 2002 (2000)

EIGEN-GRACE02S Model and Uncertainties

Even zonals lm	Value · 10^{-6}	Uncertainty	Uncertainty on node I, relative to the frame-dragging effect	Uncertainty on Node II, relative to the frame-dragging effect	Uncertainty on perigee II, relative to the frame-dragging effect
20	– 484.16519788	$0.53 \bullet 10^{-10}$	$1.59\ \Omega_{LT}$	$2.86\ \Omega_{LT}$	$1.17\ \omega_{LT}$
40	0.53999294	$0.39 \bullet 10^{-11}$	$0.058\ \Omega_{LT}$	$0.02\ \Omega_{LT}$	$0.082\ \omega_{LT}$
60	–.14993038	$0.20 \bullet 10^{-11}$	$0.0076\ \Omega_{LT}$	$0.012\ \Omega_{LT}$	$0.0041\ \omega_{LT}$
80	0.04948789	$0.15 \bullet 10^{-11}$	$0.00045\ \Omega_{LT}$	$0.0021\ \Omega_{LT}$	$0.0051\ \omega_{LT}$
10,0	0.05332122	$0.21 \bullet 10^{-11}$	$0.00042\ \Omega_{LT}$	$0.00074\ \Omega_{LT}$	$0.0023\ \omega_{LT}$



The result was published in Nature Letters in 2004.

We measured frame-dragging to be 99 % of its General Relativity prediction with an error of about 10 %.

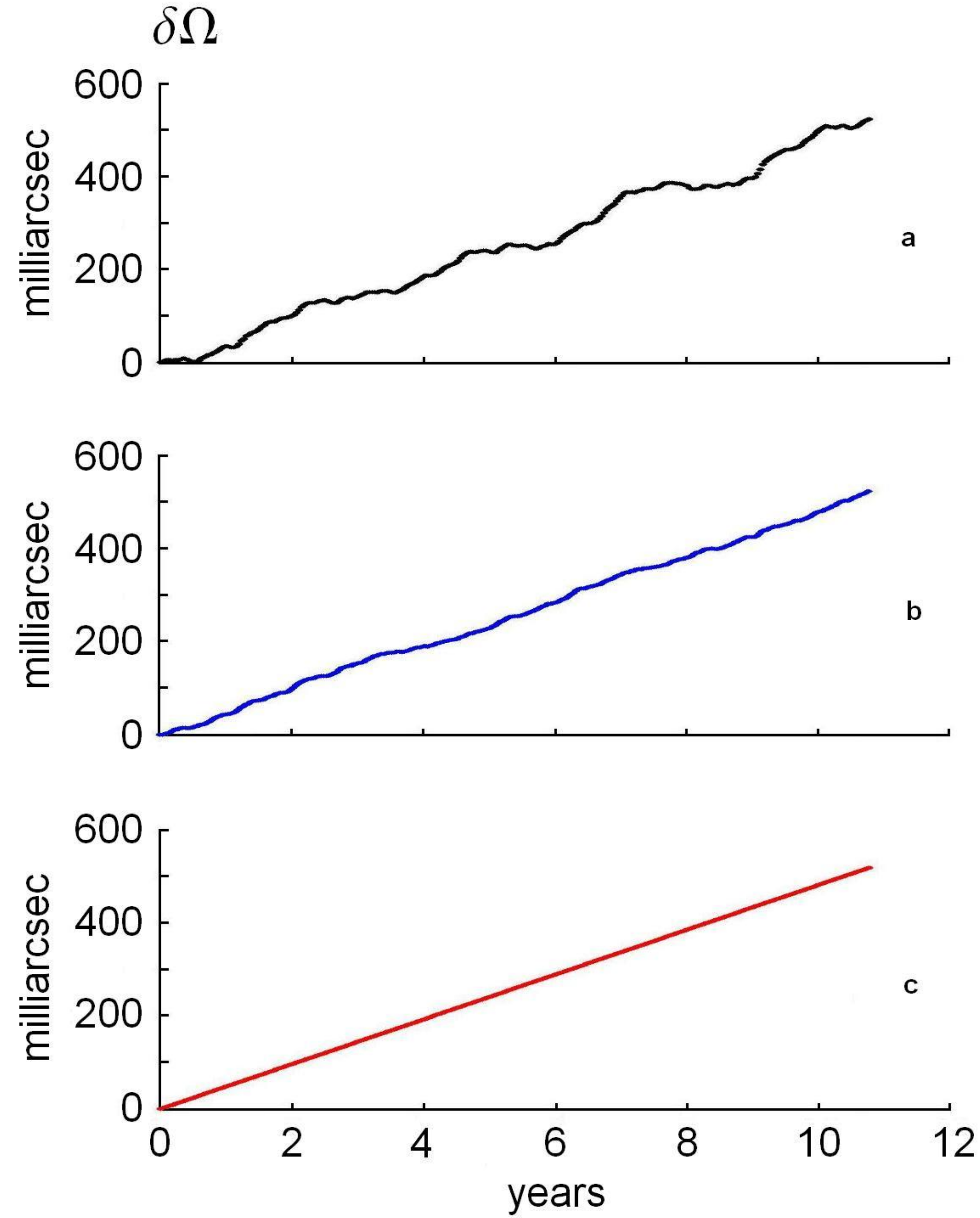


Figure 2

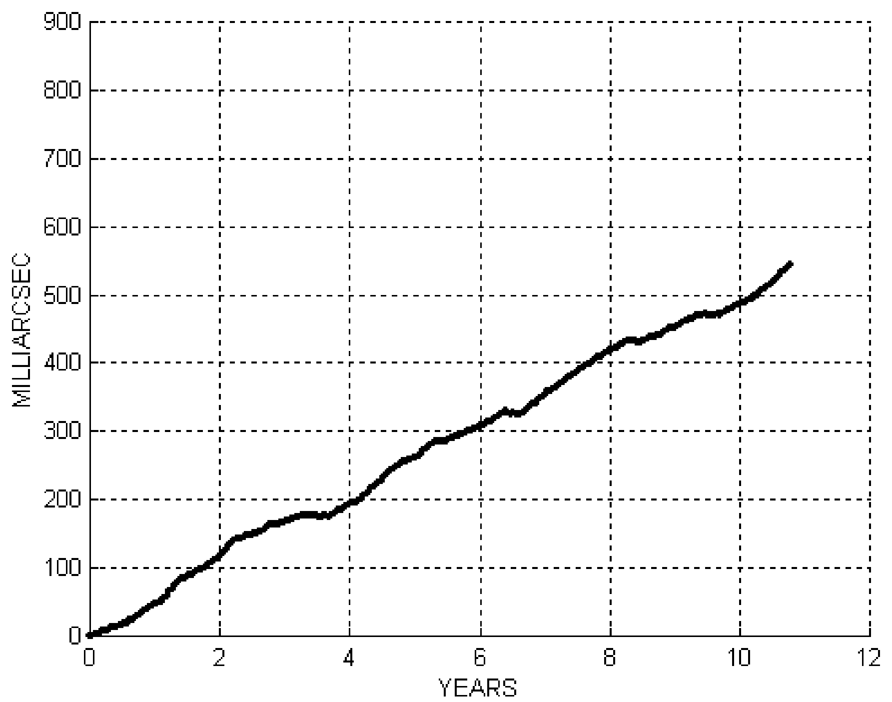
Observed value of Lense-Thirring effect using The combination of the LAGEOS nodes.

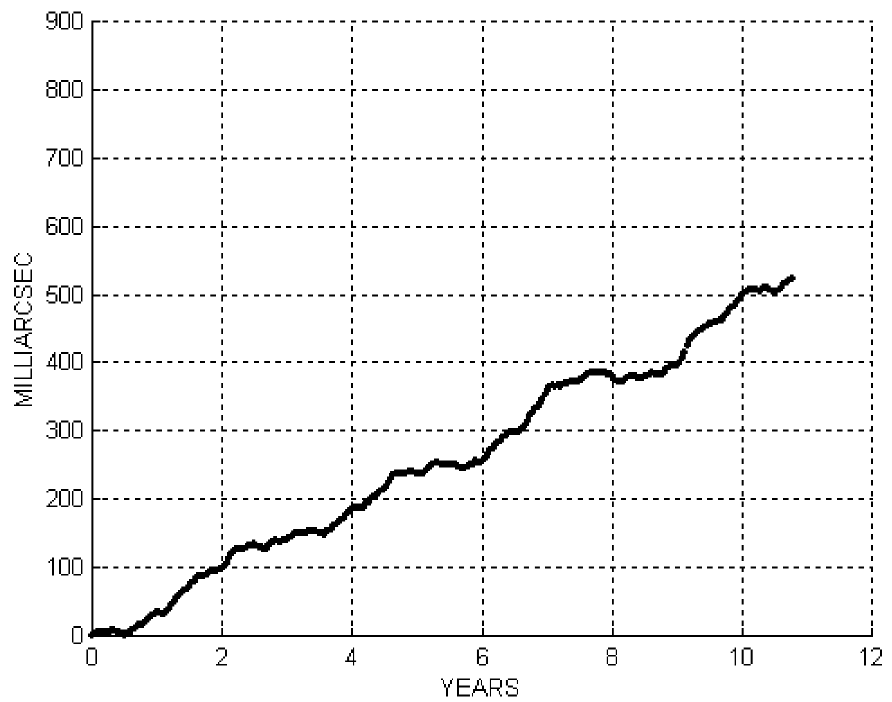
Observed value of Lense-Thirring effect = 99% of the general relativistic prediction. Fit of linear trend plus 6 known frequencies

General relativistic Prediction = 48.2 mas/yr

I.C. & E.Pavlis, Letters to NATURE, 431, 958, 2004.

NEW 2006-2007 ANALYSIS OF THE LAGEOS ORBITS USING THE GFZ ORBITAL ESTIMATOR **EPOS**

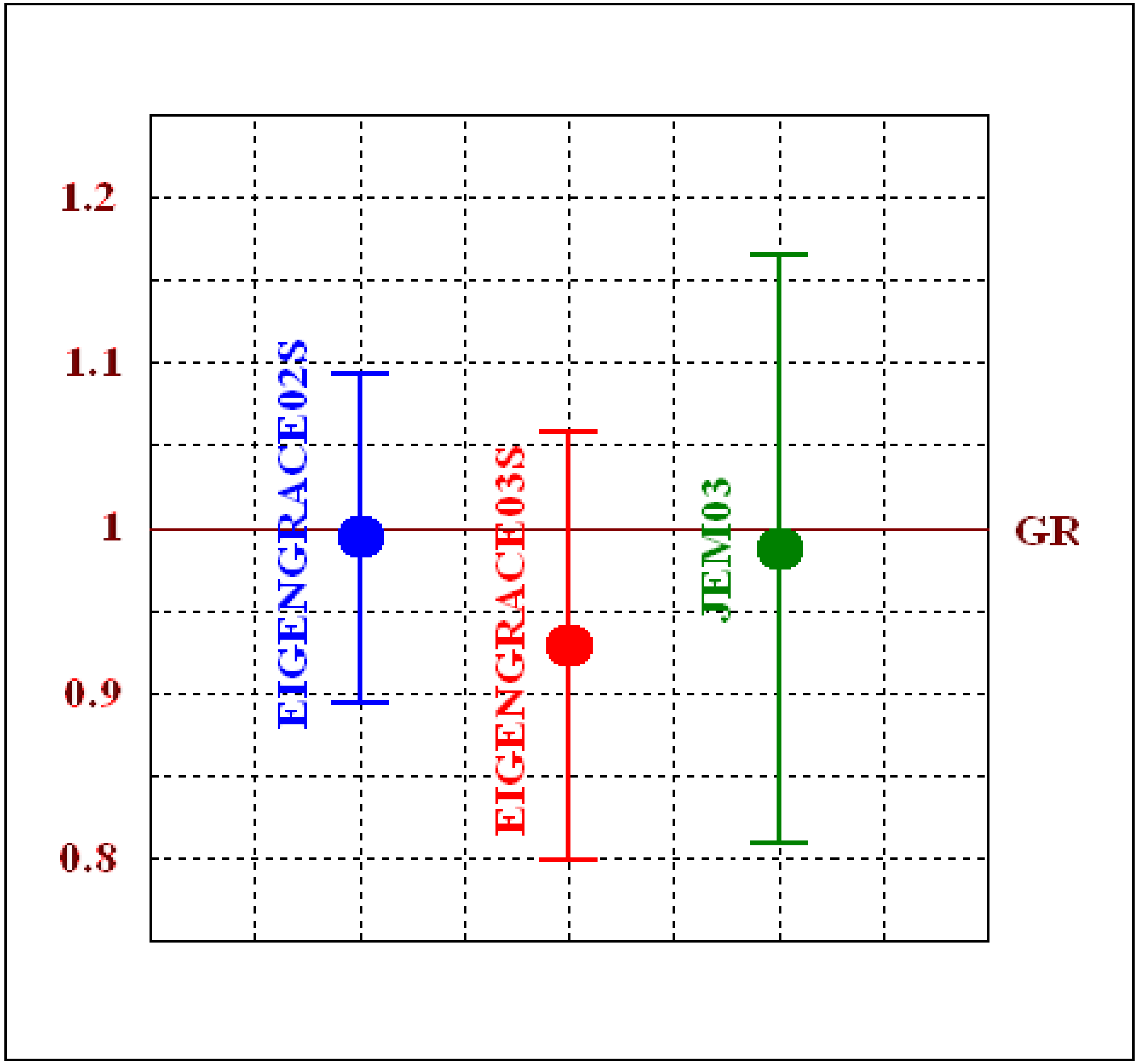




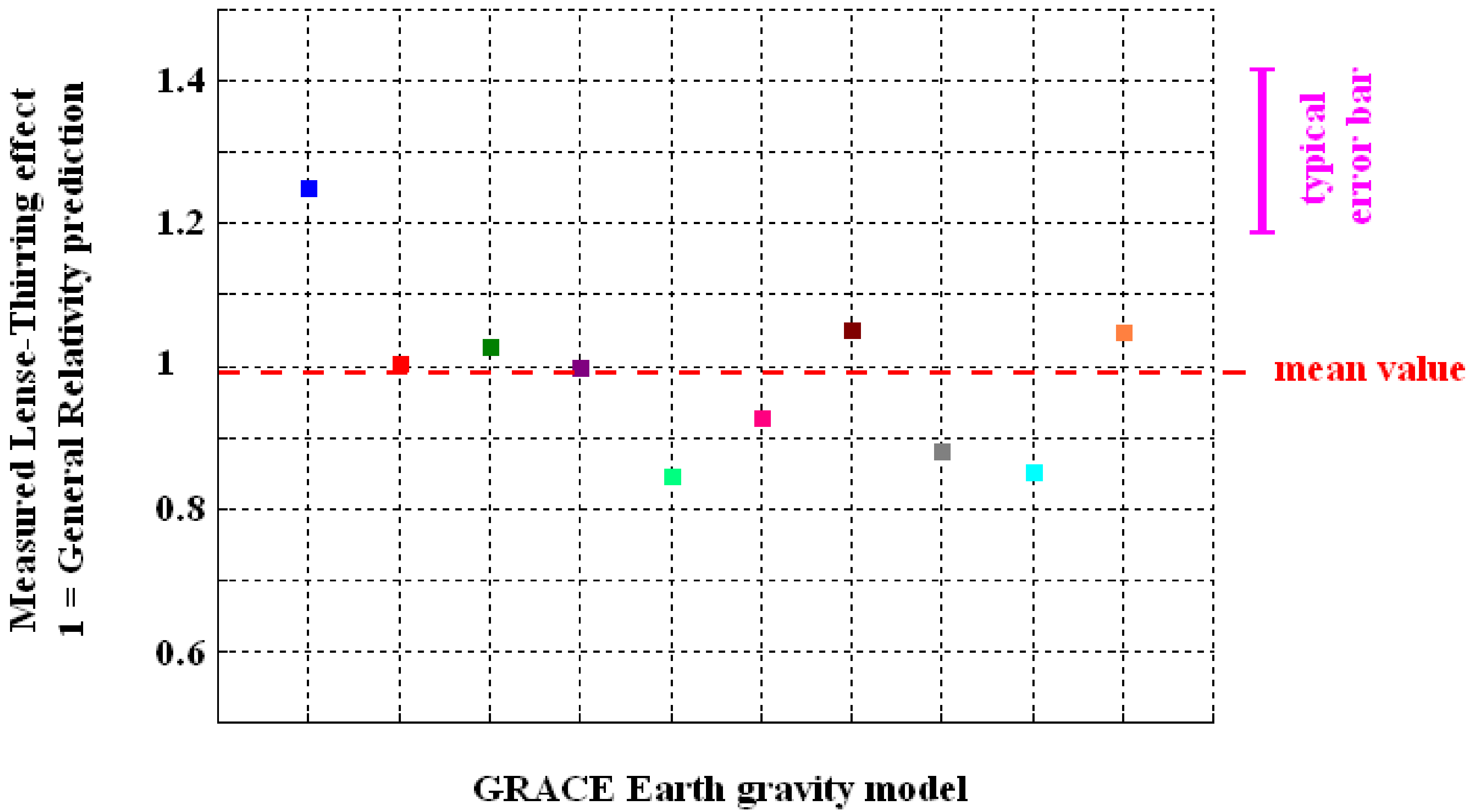
*by adding the geodetic precession of the orbital plane of an Earth satellite in the EPOS orbital estimator.

OLD 2004 ANALYSIS OF THE LAGEOS ORBITS USING THE NASA ORBITAL ESTIMATOR **GEODYN**

Comparison of Lense-Thirring effect measured using different Earth gravity field models



Each point corresponds to a different GRACE Earth gravity model



In 2008 Ries et al. presented independent results for the measurement of frame.draggging by spin using LAGEOS, LAGEOS 2 and the GRACE Earth's gravity models.

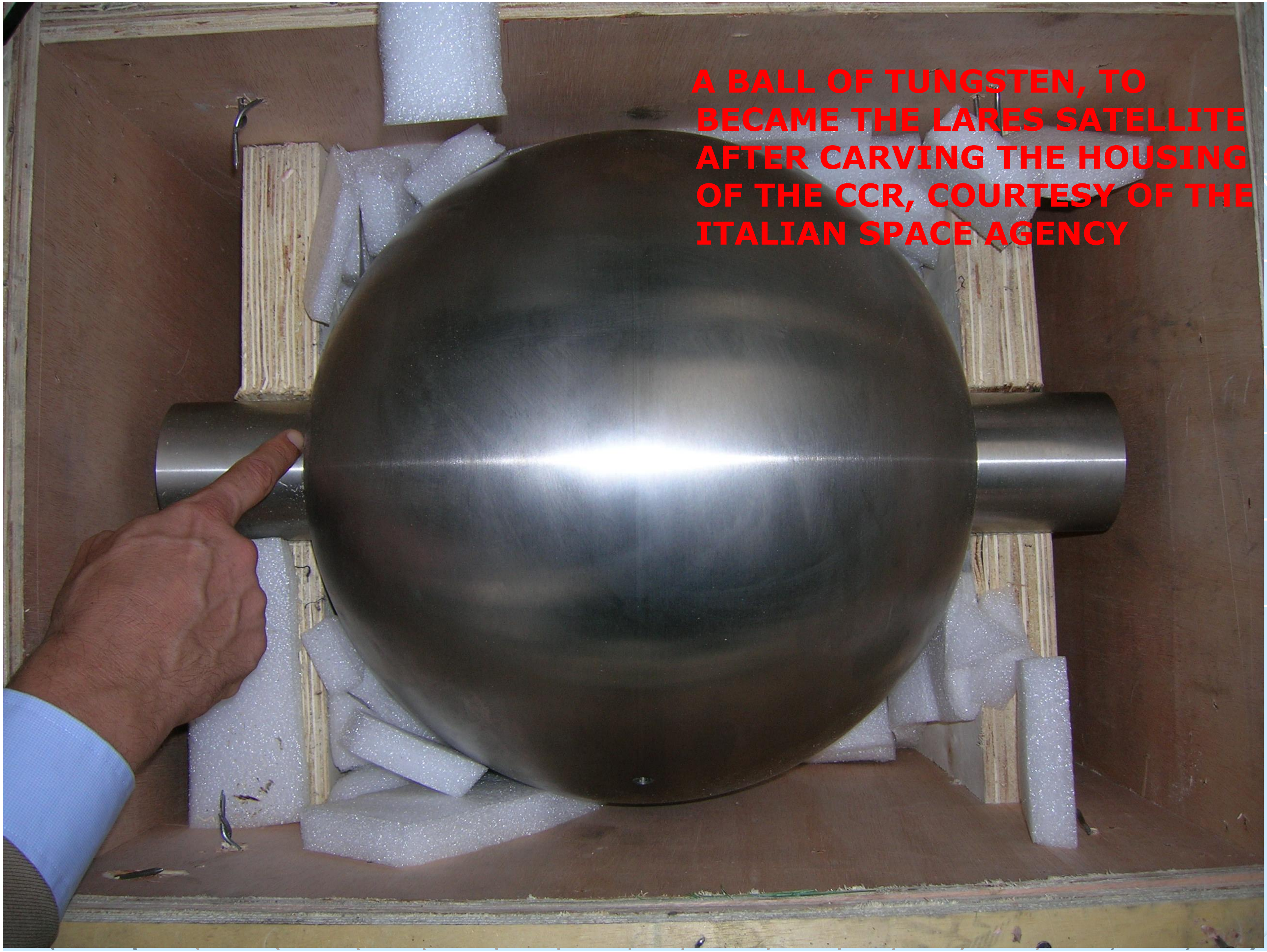
John Ries (UT Austin) error budget is of about 12 %.

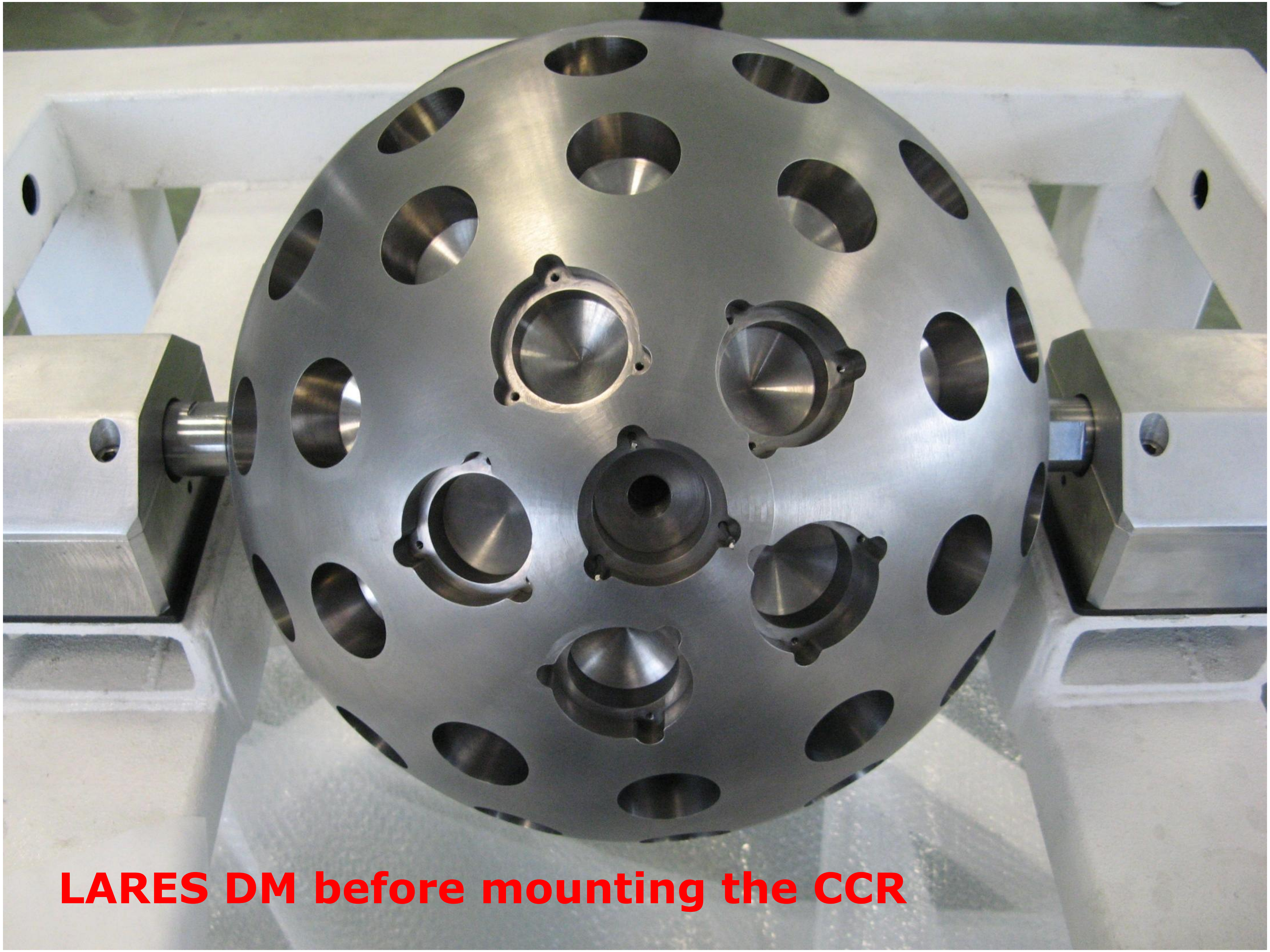
LARES
(LAser RElativity Satellite)
Italian Space Agency

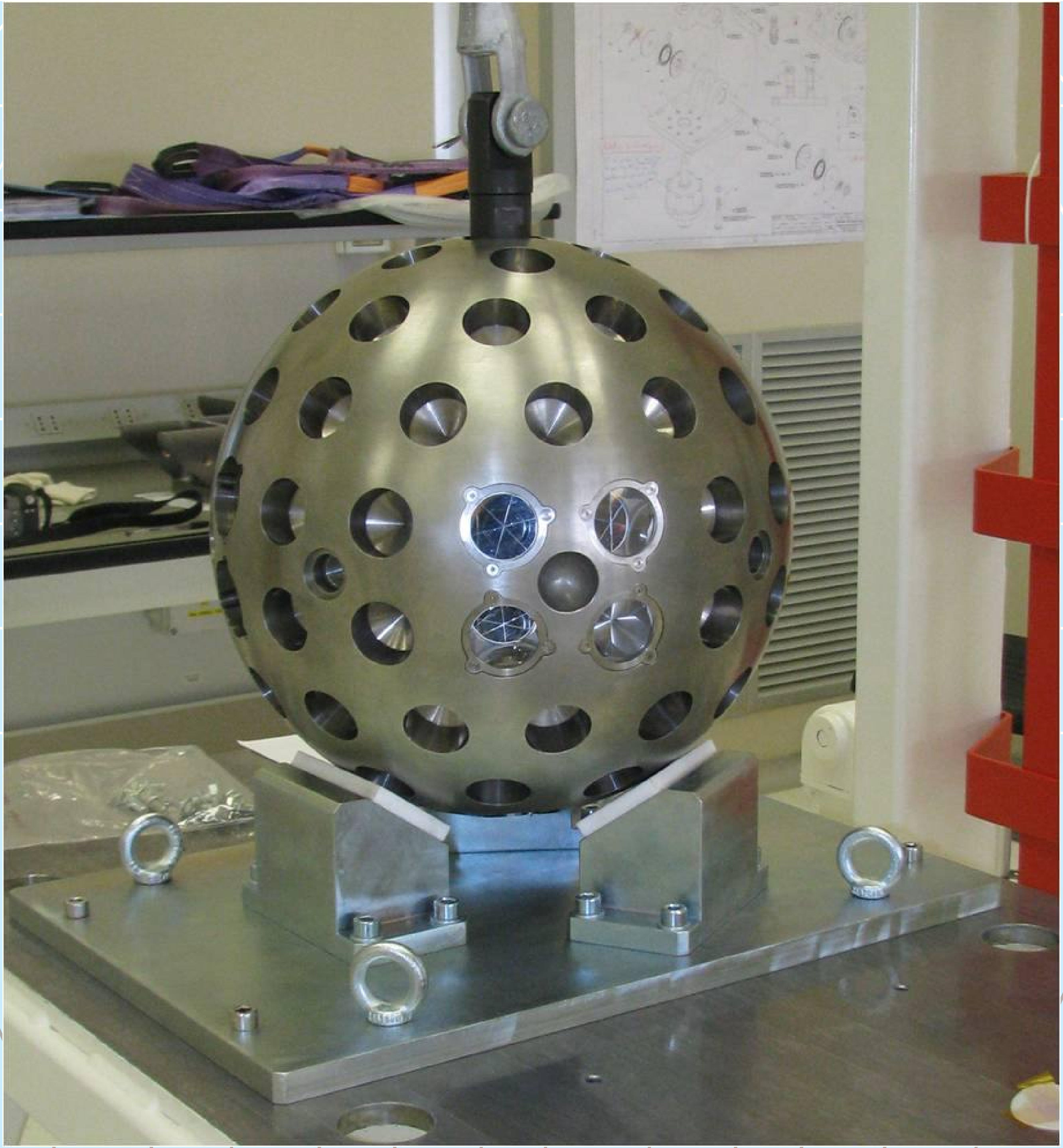
- Weight about 400 kg
- Radius about 18 cm
- Material Solid sphere of Tungsten alloy
- Semimajor axis about 7900 km
- Eccentricity nearly zero
- Inclination about 71.5 degrees
- Combined with LAGEOS and LAGEOS 2 data it would provide a confirmation of Einstein General Relativity, the measurement of frame-dragging with accuracy of a few percent.

LARES design by: Sapienza University of Rome (Antonio Paolozzi and his team)

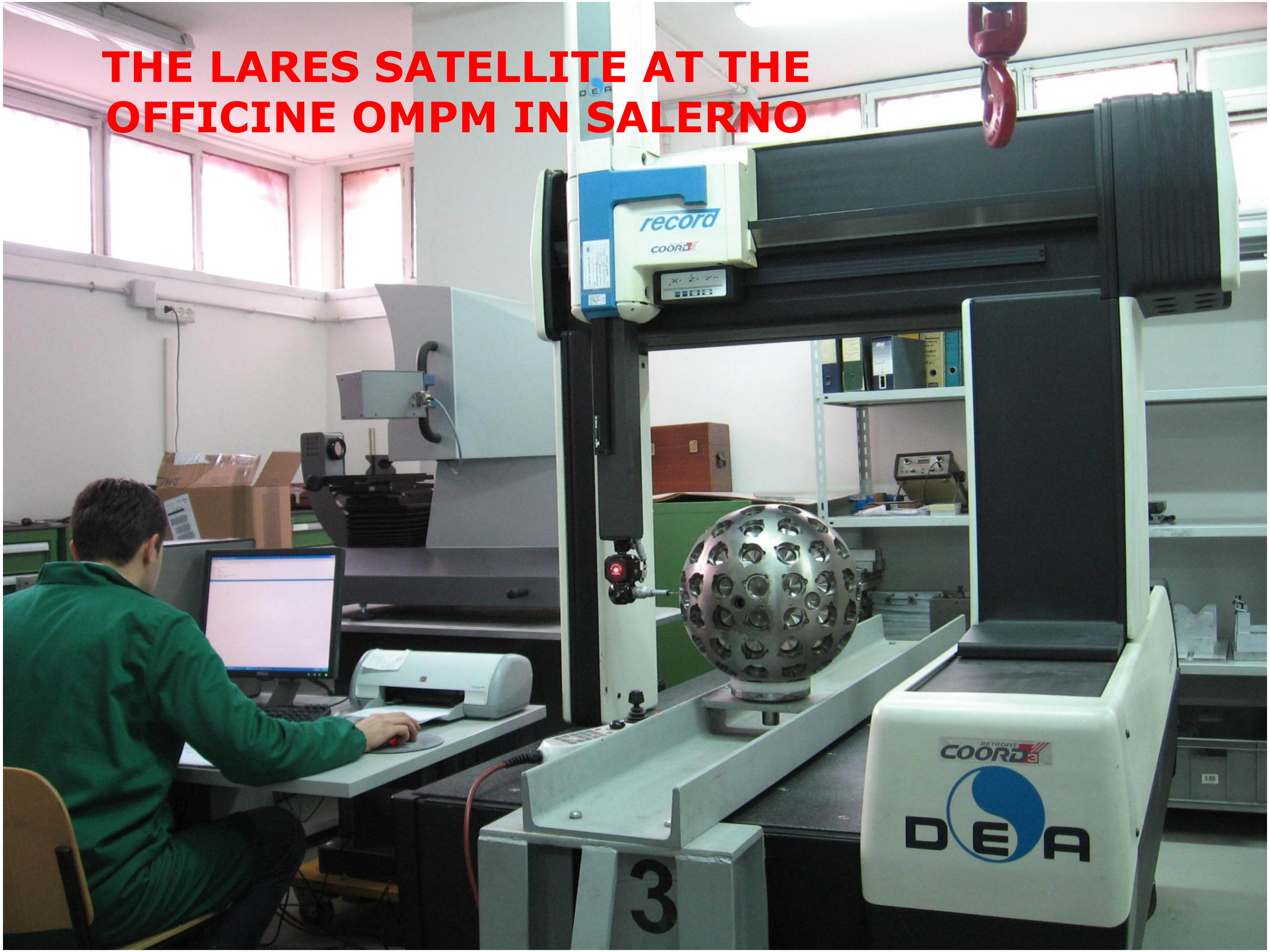

The new VEGA launcher
by the European Space Agency,
first launch planned at the end of 2011-beginning of 2012, with the LARES payload


A BALL OF TUNGSTEN, TO
BECAME THE LARES SATELLITE
AFTER CARVING THE HOUSING
OF THE CCR, COURTESY OF THE
ITALIAN SPACE AGENCY


LARES DM before mounting the CCR



THE LARES SATELLITE AT THE OFFICINE OMPM IN SALERNO



Conclusions

* Frame-dragging (Lense-Thirring effect) has been measured with accuracy of approximately 10 % using LAGEOS, LAGEOS II and the GRACE Earth's gravity models.

* After a few years of the LARES satellite (to be launched at the end of 2011) laser-ranging data will be available, together with future improved Earth's gravity models, the accuracy of the frame-dragging measurement should approach 1 %.

THE END