Available online at www.sciencedirect.com

SCIENCE DIRECT®

New Astronomy 10 (2005) 636–651

New Astronomy

www.elsevier.com/locate/newast

On the measurement of the Lense–Thirring effect using the nodes of the LAGEOS satellites, in reply to "On the reliability of the so-far performed tests for measuring the Lense–Thirring effect with the LAGEOS satellites" by L. Iorio ☆

I. Ciufolini [a,*], E. Pavlis [b]

[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*

Received 23 March 2005; received in revised form 4 April 2005; accepted 11 April 2005
Available online 2 May 2005
Communicated by F. Melchiorri

Abstract

In this paper, we provide a detailed description of our recent analysis and determination of the frame-dragging effect obtained using the nodes of the satellites LAGEOS and LAGEOS 2, in reply to the paper "On the reliability of the so-far performed tests for measuring the Lense–Thirring effect with the LAGEOS satellites" by L. Iorio (doi: 10.1016/j.newast.2005.01.001). First, we discuss the impact of the $\dot{J}_{2n}$ uncertainties on our measurement and we show that the corresponding error is of the order of 1% of frame-dragging only. We report the result of the orbital simulations and analyses obtained with and without $\dot{J}_4$ and with a $\dot{J}_4$ equal to its EIGEN-GRACE02S value plus 12 times its published error, i.e., a $\dot{J}_4$ equal to about 611% of the value adopted in EIGEN-GRACE02S, that is $\dot{J}_4 = 6.11 \times (-1.41 \times 10^{-11}) \simeq -8.61 \times 10^{-11}$. In all these three cases, by also fitting the final combined residuals with a quadratic, we obtain the same value of the measured Lense–Thirring effect. This value differs by only 1% with respect to our recent measurement of the Lense–Thirring effect. Therefore, the error due to the uncertainties in the $\dot{J}_{2n}$ in our measurement of the gravitomagnetic effect can at most reach 1%, in complete agreement with our previously published error budget. Our total error budget in the measurement of frame-dragging is about 5% of the Lense–Thirring effect, alternatively even by simply considering the published errors in the $\dot{J}_{2n}$ and their recent determinations we get a total error budget of the order of 10%, in complete agreement with our previously published error budget. Furthermore, we

☆ doi of the paper by L. Iorio: 10.1016/j.newast.2005.01.001.

* Corresponding author. Tel.: +1 39 380 307 0772.
E-mail addresses: ignazio.ciufolini@unile.it (I. Ciufolini), epavlis@umbc.edu (E. Pavlis).

1384-1076/$ - see front matter
doi:10.1016/j.newast.2005.04.003

explicitly give the results and plot of a simulation clearly showing that the claim of Iorio's paper that the $\dot{J}_{2n}$ uncertainty may contribute to up a 45% error error in our measurement is clearly unsubstantiated. We then present a rigorous proof that any ''imprint'' or ''memory'' effect of the Lense–Thirring effect is completely negligible on the even zonal harmonics produced using the GRACE satellites only and used on the orbits of the LAGEOS satellites to measure the frame-dragging effect. In this paper we do not discuss the problem of the correlation of the Earth's even zonal harmonics since it only refers to our previous, 1998, analysis with EGM96 and it will be the subject of a different paper; nevertheless, we stress that in the present analysis with EIGENGRACE02S the total error due to the static Earth gravity field has been calculated by pessimistically summing up the absolute values of the errors due to each Earth's even zonal harmonic uncertainty, i.e., we have not used any covariance matrix to calculate the total error but we have just considered the worst possible contribution of each even zonal harmonic uncertainty to the total error budget. We also present and explain our past work on the technique of measuring the Lense–Thirring effect using the LAGEOS nodes and give its main references. Finally we discuss some other minor points and misunderstandings of the paper by Iorio, including some obvious mistakes contained both in this paper and in some other previous papers of Iorio. In conclusion, the criticisms in Iorio's paper are completely unfounded and misdirected: the uncertainties arising from the possible variations of the $\dot{J}_{2n}$ are fully accounted for in the error budget that we have published.

PACS: 04.80; 04.80.Cc

Keywords: Gravitation; Relativity; Lense–Thirring; Gravitomagnetism; Laser ranging

1. Error due to the $\dot{J}_{2n}$ in the 2004 measurement of the Lense–Thirring effect

In order to discuss the error analysis and the total error budget of our measurement of the Lense–Thirring effect (Ciufolini and Pavlis, 2004a), we first stress that in the data reduction of our recent measurement of the Lense–Thirring effect we have used the value of $\dot{J}_4 = -1.41 \times 10^{-11}$, adopted by GFZ in the EIGEN-GRACE02S Earth gravity model (Reigber et al., 2005), and we have fitted our combined residuals with a secular trend only plus a number of periodical terms. We can of course introduce $\dot{J}_4$ as a free parameter in our fit (see below). In this case, together with the measurement of the Lense–Thirring effect, we also measure the effect of the secular variations of J_2, J_4 and J_6 on the combination of the nodal longitudes of the LAGEOS satellites; this is described by a $\dot{J}_4^{\text{Effective}}$ (Eanes, 1995) in our combination, which includes the effect of the secular variation of the higher even zonal harmonics. In Ciufolini et al. (2005) it is indeed reported an effective value of $\dot{J}_4^{\text{Effective}} \cong -1.5 \times 10^{-11}$ for the combination of the LAGEOS satellites nodes, which is consistent with the EIGEN-GRACE02S model since, on our combination of the nodal longitudes of the LAGEOS satellites, it just represents a 6% variation of the value given with EIGEN-GRACE02S and, however, it includes the effect of any higher $\dot{J}_{2n}$, with $2n \geqslant 4$; *this value is also fully consistent with our published result of a Lense–Thirring drag equal to 99% of the general relativity prediction with an uncertainty of 5–10%.* It is easily seen, even by visual inspection, that our combined residuals would clearly display any large value of such quadratic term. Indeed, in Fig. 1 we show the residuals obtained using the $\dot{J}_4$ value given with EIGEN-GRACE02S that should be compared with a simulation of the orbital residuals, shown in Fig. 5, obtained using in the data reduction a strongly unrealistic value of $\dot{J}_4$ corresponding to the value adopted in EIGEN-GRACE02S *plus* 12 times its published error and which produces a ~45% variation of the secular trend as a possible error claimed by Iorio (2005)! It is clear that only the first figure can be simply described by a linear dependence.

In the EIGEN-GRACE02S model (Reigber et al., 2005), obtained by the GRACE mission only, the Earth gravity field was measured during the period 2002–2003. Corrections due to $\dot{J}_2$ and $\dot{J}_4$ were then applied to this 2002–2003 measurement in order to obtain a gravity field