LAGEOS SPIN AXIS AND NON–GRAVITATIONAL EXCITATIONS OF ITS ORBIT

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ABSTRACT

The analysis of the orbit residuals of LAGEOS–type satellites provides an opportunity to measure tiny perturbing forces of non–gravitational origin. Some of these effects require a knowledge of the satellite spin axis orientation. Until 1996, a standard dynamical model of the LAGEOS spin axis evolution was able to explain most of the residual excitations. This is no longer the case after 1996. However, the orbit residuals can still be successfully explained if the axis dynamical model is supplemented by empirical corrections. A good agreement with direct observations of the LAGEOS axis orientation in 1995 and 1996 enhances credibility of these empirical modifications. Their theoretical understanding remains an interesting challenge for the future.

INTRODUCTION

There has been a long–standing investigation of the non–gravitational perturbations of the LAGEOS semimajor axis since the announcement of its secular decrease by Smith and Dunn (1980). Later, Ries *et al.* (1993) reported that LAGEOS eccentricity and longitude of perigee undergo significant variations that are also likely to be of non–gravitational origin. These variations represent an obstacle for improvements of the geopotential model and its long–term temporal variations (notably of the odd zonal harmonics; Tapley *et al.*, 1993; Eanes, 1995). It is thus important to understand which part of the eccentricity and perigee variations are due to the non–gravitational effects.

An "Ockham razor" approach has been proposed by Métris *et al.* (1997), who applied the same non–gravitational effects as have been previously used in the case of the semimajor axis, to model the eccentricity variations. It concerns namely (i) the Yarkovsky–Schach effect (Afonso *et al.*, 1989), (ii) the optical asymmetry of the LAGEOS surface (Scharroo *et al.*, 1991), and (iii) a small redefinition of the total reflectivity coefficient. Métris *et al.* (1997) observed that most of the eccentricity and perigee residual perturbations may be indeed explained by this model if two hypotheses are accepted: (i) the two parameters of the Yarkovsky–Schach model are properly adjusted, and (ii) the satellite spin axis begins to experience rapid variations in the late 80s. The first item seemed to be acceptable since the model of the semimajor axis variations left the two parameters correlated, though this issue remains an important unsolved problem of the LAGEOS dynamics because the adjusted values are in contradiction with the best available thermal model of this satellite (Slabinski, 1997). As for the second item – LAGEOS spin axis evolution – we mention that the work of Farinella *et al.* (1996), followed by Métris *et al.* (1997), seemed to reconcile the dynamical model of Bertotti and Iess (1991) with the LAGEOS orbit residual model. Indeed, Farinella's *et al.* (1996) numerical integration of the LAGEOS spin axis naturally explained the onset of its rapid motion around the south pole as a forced precession due to the Earth geopotential torque acting on the satellite.

This paper reviews the progress in understanding the non-gravitational effects on the Lageos orbit as well as the challenge that still confronts us. The main purpose of the paper is to show that – once again in science – new observational data forces the re-examination of the old theories and models. The orbit residuals of LAGEOS recorded during 1997 can no longer be represented by the spin axis dynamical model of Farinella

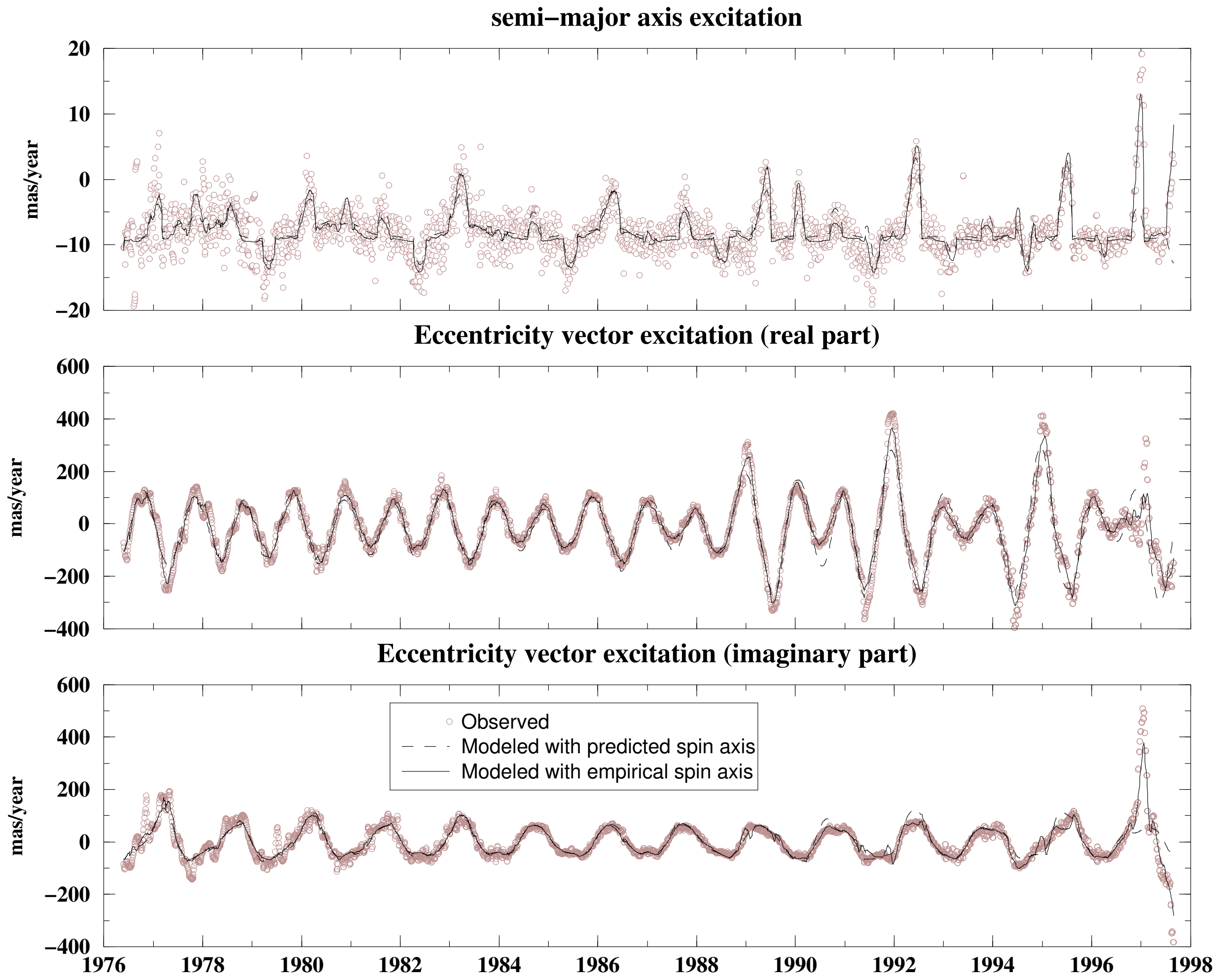

Fig. 1: *The observed orbit excitations of LAGEOS compared with two models. Both of them contain the same non–gravitational forces as used by Métris et al. (1997). Their difference is due to the spin axis evolution: (i) dynamical model of Farinella et al. (1996) – dashed curve, and (ii) empirical spin axis derived in this paper – solid curve.*

et al. (1996). This opens a new challenge, a first step of which will be discussed below.

LAGEOS SPIN AXIS EVOLUTION

The history of the LAGEOS spin axis evolution shows an interesting interplay between the observations and the theory. At the "prehistory" phase of this issue, a constant orientation of the spin axis suited well to explain the semimajor axis variations (Rubincam, 1990; though Rubincam was already aware of the rotation despin and a possible spin axis evolution). At the same time, Bertotti and Iess (1991), attempting to explain a directly observed despin of LAGEOS, developed a dynamical model of its rotation. It basically consists of two physical phenomena: (i) a magnetic torque due to the induced eddy currents in the mantle of the satellite, and (ii) a gravitational torque due to the dynamical flattening of LAGEOS. They also predicted a rapid evolution of the spin axis orientation in the late 80s due to the influence of the gravitational torque. This latter phase of the axis evolution is preceded by only a very slow drift toward the south pole due to the influence of the magnetic torque. Bertotti and Iess (1991), however, did not attempt to make use of their predictions for modeling the long–term semimajor axis variations of LAGEOS.

The need of the axis mobility for the orbit excitation has been noticed by Scharroo *et al.* (1991), who implemented the slow drift phase in their analysis. Later on, when the LAGEOS orbit data of the 80s became available, it became clear that a much more complex motion of its spin axis was required (Ries

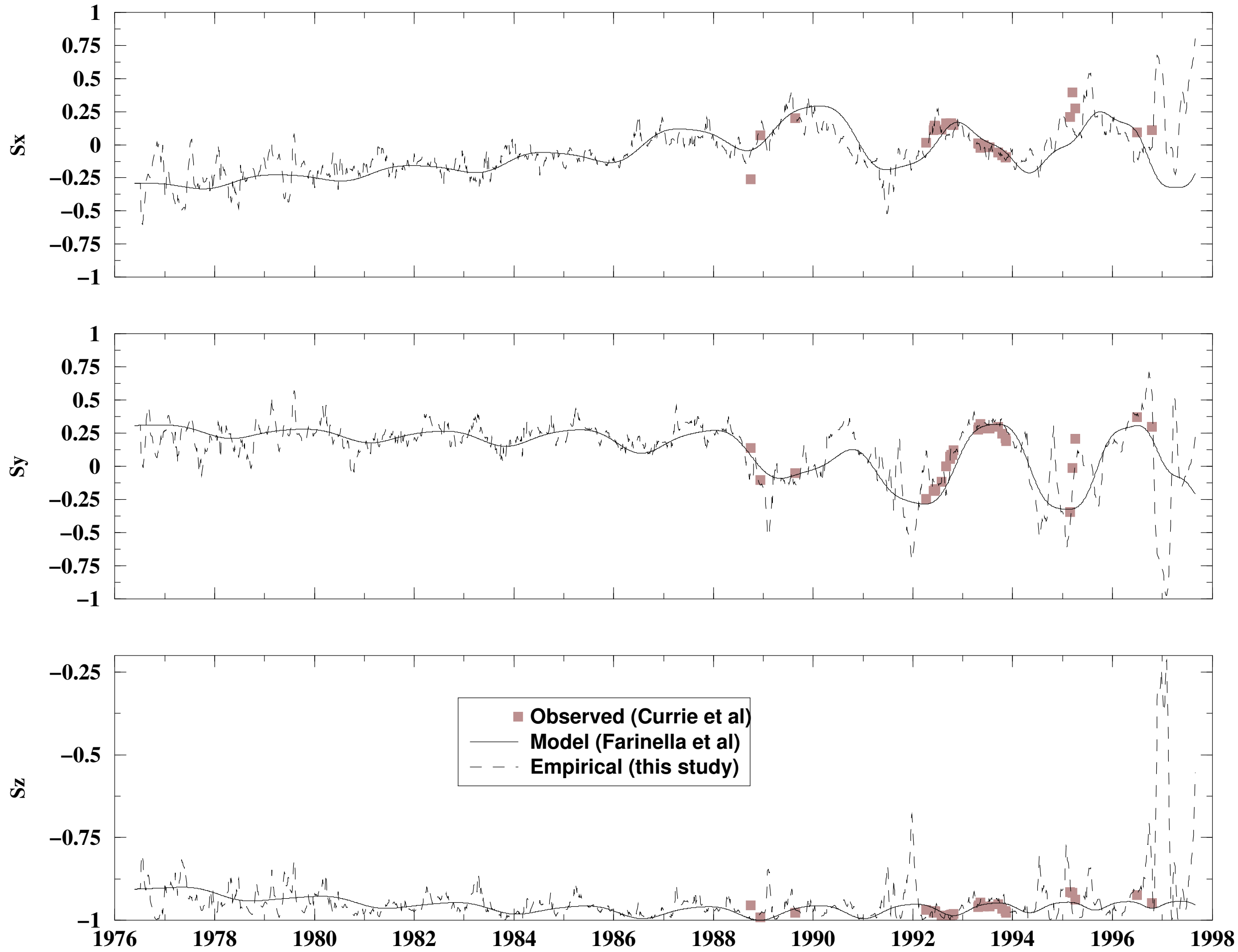

Fig. 2: *Cartesian coordinates of the LAGEOS spin axis unit vector: (i) dynamical model of Farinella et al. (1996) – solid lines, (ii) empirical model resulting from the orbit excitation adjustment – dashed lines. Direct observation by Currie et al. (1997) in squares.*

et al. 1993; Kolenkiewicz *et al.* 1995), but interestingly it remained to Farinella *et al.* (1996) to understand that the Bertotti and Iess (1991) theory yields essentially the right predictions. The satisfaction with the dynamical model of the LAGEOS rotation has been strengthened by the simultaneous analysis of the LAGEOS semimajor axis, eccentricity and perigee excitations by Métris *et al.* (1997). They have shown that all the mentioned excitations may be fairly well explained by the "standard" model of the non–gravitational forces affecting the LAGEOS orbit and still using the Bertotti and Iess (1991) predictions of the spin axis variation. In fact, it was the high credibility of the spin axis dynamical model that was the major argument of Métris *et al.* (1997) theory, since the alternative was to accept unexpectedly large values of the LAGEOS thermal model parameters [that are in conflict with the Slabinski (1997) theoretical estimation].

The purpose of this paper is to show that there are observations (once again) that prompt us to reconsider the theoretical models. Figure 1 shows the LAGEOS orbit excitations accumulated up to September 1997. We observe excitations of an unexpected amplitude in the imaginary part of the eccentricity vector ($-e\sin\omega$) and in the semimajor axis. These can be no longer explained by the force model of Métris *et al.* (1997) if the dynamical spin axis model of Bertotti and Iess (1991) is assumed.

In this situation, we decided to follow again the minimum modification approach of Ockham, trying first to empirically modify the spin axis evolution model prior to supplementing the force model by new phenomena. Notice that this is by no means a trivial exercise. By modifying two orientation parameters of the spin axis and keeping the force model unchanged, we attempt to explain three excitation components (in fact, the solution is not trivial even if we consider the semimajor axis only; for preliminary results see Ries *et al.*, 1997). In practice, we adopted a running window method, adjusting the axis position once per 60 days to minimize the O–C difference of the orbit excitations (the semimajor axis excitation contributes with a weighting–factor of 3 to the fitting procedure; a similar method has been previously used by Ries *et al.*, 1993).

The spin–axis fitting procedure is basically a two–stage least square method which can be outlined as follows. In the first step, we use a reference model both for the non–gravitational excitations and for the spin axis evolution, and compare the results with the observed residual excitations determined by UT/CSR. The reference orbital model is taken from Métris *et al.* (1997) and the initial spin axis orientation is taken from Farinella *et al.* (1996). As mentioned above, the model is able to explain the observed orbit excitations fairly well till 1996 but fails for later epochs. Since we assume that the unexplained part of the observed excitations is due to the spin axis corrections, we compute partial derivatives of the non–gravitational excitations with respect to the cartesian coordinates of the spin axis unit vector. At the second stage of our procedure, we use the pre–computed partials to obtain corrections of the spin axis orientation using the standard (linear) least square method. Ideally, the correction should be a smooth enough function of time, but in practice we must use some kind of numerical technique to filter the rapid variations: similarly to Ries *et al.* (1993), we have computed a fixed correction per temporal window of 60 days and assigned this correction to the axis position at the central epoch of the window. The window is shifted by steps of 3 days (which corresponds to the data density). The procedure is then iterated until convergence.

A few words about the variables describing the spin axis position are in order. We first tried to ajust two angular parameters (right ascension and declination) characterizing the unit vector of the spin axis. However, our experience shows that this highly non–linear procedure typically fails to give a reasonable results. We then decided to use the three cartesian coordinates (s_X, s_Y, s_Z) of the spin axis with an obvious constraint $s_X^2 + s_Y^2 + s_Z^2 = 1$. Through not completely linear, the problem yields much more satisfactory results. We needed two iterations of the above procedure to converge to the solution given in this paper.

The resulting excitations computed with the model by Métris *et al.* (1997) but with our empirical spin axis are given in Figure 1. For sake of comparison we also show the observed exitations that serve as data in our least square procedure, and the theoretically predicted orbit excitations using the spin axis evolution model by Farinella *et al.* (1996). Results in Figure 1 indicate that the model with empirically adjusted spin axis is significantly better (especially in the semimajor axis and imaginary part of the eccentricity excitations). The solution may be even improved if we allow aditional modifications of the non–gravitational model parameters. It would be reasonable to suppose that the model parameters currently used are not completely valid if the spin axis position is now dramatically different from the position it occupied for the first two decades.

An important hint favoring validity of our procedure comes from the comparison of the spin axis models – the dynamical model of Farinella *et al.* (1996) and the empirical model derived above – with the direct axis observations shown in Figure 2 (for the observations see Currie *et al.*, 1997; Avizonis, 1997). Till 1995, the two models are able to explain the observations with a comparable precision. Although during 1995 and 1996 the dynamical spin axis model yields still a reasonably good prediction, we observe that the empirical spin axis model appears to be of better quality (notice especially the y–projection of the three observations in 1995). It should be noted that the empirical axis model has not been constrained by these observations at all, making this better correspondence very significant. It is in 1997 when the two spin axis models diverge the most. Notice especially the huge excursion of the axis towards the equator in mid 1997, which is in fact responsible for the extrema observed in the imaginary part of the eccentricity excitation and the semimajor axis excitation. Unfortunately, we do not have available any direct observations of the axis orientation during this period.

CONCLUSIONS AND OUTLOOK

Unexpected features in the 1997 excitations of the LAGEOS orbit cannot be explained by the model of Métris *et al.* (1997). There are two options how to handle this situation: (i) to modify the force model affecting the LAGEOS orbit, and/or (ii) to modify the spin axis evolution model, since a large sensitivity to this parameter has been realized previously. None of these two possibilities represents a simple extension of the model. In this paper, we chose the second and derived an empirical model of the spin axis evolution that best suits the orbit observations. The existence of such a solution is not trivial, but additional credibility is gained by the fact that this empirical solution fits well the 1995 and 1996 direct observations of the LAGEOS spin axis. This suggests that the dynamical model of the LAGEOS spin axis indeed ceases to predict its evolution in 1997.

Though highly plausible, these hints may be turned to certainty by (i) a theoretical understanding of the LAGEOS spin axis evolution during 1997, and/or (ii) direct observations of the LAGEOS spin axis at the post–1997 period. Both warrant further attention in the future. Finally, we should not exclude the possibility that only an entire revisit of the LAGEOS orbit excitations *and* its spin axis evolution would solve the problems. We note that the empirical solution of this paper (Figure 1) still uses an anomalously high amplitude of the Yarkovsky–Schach effect (see Métris *et al.*, 1997).

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