Preliminary study for the measurement of the Lense-Thirring effect with the Galileo satellites

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Abstract

The precession of the orbital node of a particle orbiting a rotating mass is known as Lense-Thirring effect (LTE) and is a manifestation of the general relativistic phenomenon of dragging of inertial frames or frame-dragging. The LTE has already been measured by using the node drifts of the LAGEOS satellites and GRACE-based Earth gravity field models with an accuracy of about 10% and will be improved down to a few percent with the recent LARES experiment. The Galileo system will provide 27 new node observables for the LTE estimation and their combination with the LAGEOS and LARES satellites can potentially reduce even more the error due to the mismodelling in Earth’s gravity field. However, the accurate determination of the Galileo orbits requires the estimation of many different parameters, which can absorb the LTE on the orbital nodes. Moreover, the accuracy of the Galileo orbits and hence, of their node drifts, is mainly limited by the mismodeling in the Solar Radiation Pressure (SRP). Using simulated data we analyze the effects of the mismodeling in the SRP on the Galileo nodes and propose optimal orbit parameterizations for the measurement of the LTE from the future Galileo observations.

1 Introduction

In 1918, Lense and Thirring [9] proved that a particle orbiting around a central body endowed with an angular momentum $J$ experiences a nodal precession $\dot{\Omega}$ according to the expression

$$\dot{\Omega} = \frac{2GJ}{\epsilon^2 a^3 (1 - \epsilon^2)^{3/2}}$$

(1)

where $a$ and $\epsilon$ are the orbital semimajor axis...
and eccentricity, \( G \) is the gravitational constant and \( c \) is the speed of light.

One of the main error sources in the estimation of the Lense-Thirring effect (LTE) by using the nodes of an Earth satellite arises from the uncertainties in the Earth’s gravity field model. In particular, the largest errors proceed from uncertainties in the first even zonal harmonics of a spherical expansion of the Earth potential, i.e., \( J_2 \), \( J_4 \), \( J_6 \), ..., and their variations in time.

The combination of two node observables in order to remove the influence of the first even zonal harmonic, \( J_2 \), on the node drift was first proposed in [2]. Then, the two laser-ranged LAGEOS satellites and the high-accurate Earth gravity field models based on GRACE observations (f.i., EIGEN-GRACE02S, EIGEN-GRACE03S, JEM03G), have provided for the measurement of the LTE with an accuracy of about 10% [3]. The combination with the new LARES satellite [12] will allow to eliminate the uncertainties due to both, \( J_2 \) and \( J_4 \), thus being possible to obtain a measurement of the LTE with an accuracy of the order of 1% [3].

The Galileo system will provide a new node observable from a total of 27 satellites, whose combination with the LAGEOS and LARES satellites will potentially reduce the uncertainty due to the mismodeling in the Earth gravity field. However, there are two issues that greatly impact the LTE measurement with the Galileo satellites. The first of those is that the accurate determination of the Galileo orbits and their node drift requires the estimation of many different parameters, such as initial state vectors, empirical accelerations, clock offsets, station coordinates, etc, which can absorb partially or completely the LTE. The second issue is that the final accuracy of the estimated Galileo orbits is mainly limited by the mismodeling in the Solar Radiation Pressure (SRP), which constitutes the primary error source in the determination of the LTE with the Galileo nodes.

In the present work, the effects of both, the mismodeling in the SRP and the orbit parameterization, on the Galileo node drift determination are analyzed by means of simulated Galileo orbits and observations.

2 Simulation of Galileo orbits and observations

A set of Galileo orbits and observations corresponding to days 1-4 of January, 2008 are simulated and used in a series of different numerical tests. In the simulation, the EPOS-OC software (Earth Parameter and Orbit System Orbit Computation [16]) is used.

The Galileo orbits are simulated according to the specifications given by ESA [5], a Walker 27/3/1 configuration with a semi-major axis of 29600 km, an inclination of 56 deg, zero eccentricity, a separation between planes equal to 120 deg and a change of mean anomaly for equivalent satellites in neighbouring planes of 13.3 deg. The main physical background models used in the simulations are presented in Table 1. The corresponding datasets of Galileo code and phase observations for a global network of 80 stations are obtained. In the data simulation and in the subsequent orbit recovery, identical background models are used and hence, the errors due to uncertainties in these models are not addressed in this work.

In EPOS-OC the SRP acceleration \( \ddot{r} \) is computed by means of the expression
\[ \ddot{\mathbf{r}} = \left( \frac{A}{R} \right)^2 \frac{1}{m} F_{\text{rad}} \frac{\mathbf{R}}{R} \]  

(2)

where $A$ represents the Astronomical Unit (AU) in meters, $m$ is the satellite mass, $\mathbf{R}$ is the heliocentric vector pointing out to the satellite with module $R$ and $F_{\text{rad}}$ is the direct pressure force computed by means of a model. For the time being, the SRP models implemented in EPOS-OC are the ROCK4 model \[6\] for GPS-type satellites and the cannon ball or macro models dedicated to specific non-GPS satellites (f. i., \[10\]). In our simulations the Galileo satellites were considered to be GPS-Block-II-like satellites and thus, the ROCK4 model was applied. The ROCK4 model is recommended by the IERS conventions \[11\] for the modeling of the SRP effect. It includes the dimensions and optical properties of the GPS spacecraft surfaces.

Gravity field  | EIGEN-6C 12 x 12 \[7\]  
---|---
Earth tide  | IERS Conv. \[14\]  
Ocean tide  | EOT11a \[15\]  
Atmospheric tide  | Biancale-Bode \[1\]  
Lunisolar and planetary perturbations  | JPL DE421 \[8\]  
Ocean pole tide  | Desai \[4\]  
Earth Orientation Parameters  | EOP08C04  
Nutation and precession  | IERS Conv. \[14\]  
Earth albedo  | Analytic model by Heurtel

Table 1: Physical background models used in the simulation of the Galileo orbits and observations

In order to account for deficiencies in the SRP model, the Eq. (2) is multiplied by a global scaling factor ($F_0$ hereafter) and different parameters can also be added, like global biases in the X, Y and Z directions in a satellite body-fixed reference system. The influence of the Earth’s and Moon’s shadow is also considered.

The creation of a more accurate SRP model for Galileo will require the knowledge of the vehicles characteristics in terms of shape, size, weight and surface optical properties. Then, a macro model could be adopted for the Galileo SRP computation, along with an appropriate attitude model which also accounts for the yaw turns during satellite midnights (shadow turns) and noons. As of today, little information has been published about the characteristics of the Galileo satellites. Some general features taken from \[5\] are compiled in Table 2.

| Bus dimensions | 2.7 x 1.1 x 1.2 m³ |
| Solar array span | 13 m |
| Mass | 700 Kg |

Table 2: Galileo satellite features

3 Optimal parameterizations for the LTE estimation

According to Eq. (1), the nodal precession of the Galileo satellites due to the LTE is $1.7 \cdot 10^{-9}$ deg/d. This node drift holds for all 27 Galileo satellites of the full constellation. Figure 1 shows the comparison of two sets of simulated orbits over a period of 26 h generated with and without modeling of the LTE.

To measure the LTE from Galileo observations the nodal drift due to the LTE must be present in the node positions estimated in a precise orbit determination process where the
LTE is not modeled. This means that the estimated node positions without LTE modeling must differ from the true node positions and this difference must not be absorbed by the estimated parameters. In order to find out under which circumstances this holds, a set of 26 h of Galileo orbits and noise-free code and phase observations are simulated including the modeling of the LTE. Then, the simulated observations are used to recover the Galileo orbits without modeling the LTE, thereby estimating the following parameters:

- Initial orbital elements for each satellite (position and velocity)
- Empirical accelerations in the along-track and normal directions (4 coefficients per arc)
- SRP F0, Y- and Z-bias
- Earth’s albedo scaling factor
- Station coordinates
- Tropospheric delays (10 per satellite-station pair)
- Phase ambiguities
- Clock offsets

The estimated (without LTE) and simulated (with LTE) node positions are compared and the differences analyzed in order to identify the parameters absorbing the LTE. An optimal parameterization for the LTE measurement must allow to observe the node drift when comparing the estimated and simulated orbits.

It was found that the free estimation of the station coordinates introduces large errors in the node positions of the order of $10^{-8}$ deg and, as a consequence, the station coordinates must be either fixed or highly constrained, what can be done by imposing a set of No-Net-Translation-Rotation-Scale (NNTRS) conditions on the whole ground network. In addition, the estimation of empirical accelerations in the normal direction to the orbital plane absorbs part of the LTE and consequently, their estimation must be avoided, with a concurrent loss in orbit recovery accuracy. Provided that these two conditions are fulfilled the LT signal is observed in the differences between the estimated and simulated nodes positions, like in Fig. 2(a). A linear regression of the node position differences provides an estimate of the LTE drift of approximately $1.5 \cdot 10^{-9}$ deg/d, close to the expected value, $1.7 \cdot 10^{-9}$ deg/d, with a standard deviation of $3 \cdot 10^{-12}$ deg/d and a small post-regression RMS of $9 \cdot 10^{-11}$ deg.

In conclusion, this parameterization seems to be optimal for the LTE estimation from 1-day Galileo arcs in the sense that the LTE is not absorbed by the estimated parameters.

An additional test has been performed by estimating another parameter of the SRP model, the X-bias, in addition to F0, Y- and Z-bias. The differences in the node positions are
Figure 2: Orbital node differences (deg) between estimated (without LTE) and simulated (with LTE) Galileo orbits when (a) station coordinates are constrained with NNTRS conditions and the empirical accelerations in the orbit normal direction are fixed (optimal parameterization), (b) the X-bias is additionally estimated and (c) the optimal parameterization is applied to noisy observations.

The results obtained when applying the optimal parameterization to noisy observations are also analyzed. For this purpose, a Gaussian noise has been introduced to the simulated observations with standard deviations of 50 cm for code and 3 mm for phase ranges. The differences between estimated and simulated node positions are shown in Fig. 2(c). In this case, the node drifts due to the LTE is hidden behind the large noise. In fact, the RMS of the node differences is about $2.7 \cdot 10^{-9}$ deg, quite larger than the expected node displacement from the LTE for 1 day, i.e., $1.7 \cdot 10^{-9}$ deg/d. Therefore, in order to obtain a more precise estimation of the LTE, longer arcs shall be used, f. i. with 3-day arcs the LTE amounts to $5.1 \cdot 10^{-9}$ deg/d, which is significantly larger than the noise mentioned before.
Figure 3: Orbital node differences (deg) between estimated (without LTE) and simulated (with LTE) 3-day Galileo orbits when (a) the optimal parameterization for 1-day arcs is applied, (b) the Earth albedo is additionally fixed (optimal parameterization for 3-day arcs) and (c) the optimal parameterization for 3-day arcs is applied to noisy observations.

Thus, for the next tests, 3-day Galileo orbits and noise-free observations are simulated with modeling of the LTE. Then, the Galileo orbits are estimated without modeling the LTE from the observations by applying the optimal parameterization for 1-day arcs. The same number of empirical coefficients are estimated for the 3-day arcs as for the 1-day arcs. The differences between the estimated and simulated node positions are presented in Fig. 3(a), where it can be observed that the LT signal is absorbed for some satellites and hence, the optimal parameterization for 1-day arcs is not suitable for 3-day arcs.

The parameters absorbing the LTE are identified as the SRP Y-bias and the Earth’s albedo scaling factor. Fixing either of them results in a perfect recovery of the LTE, as shown in Fig. 3(b). Nevertheless, fixing the Y-bias to an incorrect value would introduce large errors in the node positions and has to be avoided. On the contrary, the influence of Earth’s albedo on the Galileo orbits is very small and therefore can safely be neglected. Consequently, the optimal parameterization for 3-day arcs coincides with that for 1-day arcs with the ex-
ception of the Earth’s albedo scaling factor, which must be fixed for the 3-day arcs.

Finally, the optimal parameterization for 3-day arcs is applied to noisy observations, the differences in the node positions are in Fig. 3 (c). The linear regression provides a trend of $1.7 \cdot 10^{-9}$ deg/d, with an RMS of $1.0 \cdot 10^{-9}$ deg, 5 times smaller than the total displacement of the Galileo nodes due to the LTE after 3 days. In conclusion, the 3-day arcs in combination with the optimal parameterization proposed here seem suitable for the precise measurement of the LTE from noisy Galileo observations in absence of other modeling errors. Then, using real Galileo observations and estimated orbits, the LTE will be measured as the difference between the estimated node positions in the overlap of two consecutive Galileo orbital arcs. Assuming a precision of the estimated node positions at the level of the RMS, this is $1.0 \cdot 10^{-9}$ deg for 3-day arcs, the combination of 27 node observables to compute the difference in the overlap yields a precision of $1.0 \cdot 10^{-9} \cdot \sqrt{2/27} = 0.27 \cdot 10^{-9}$ deg for the LTE estimation. Thus, a precision of about 5% of the LTE would be reached with two 3-day Galileo arcs. Similarly, the average of LTE estimations obtained in a series of $n$ overlaps increases the precision by a factor $1/\sqrt{n}$. Thus, in order to achieve a precision in the LTE estimation of 1%, a minimum of 30 Galileo 3-day arcs need to be processed.

The optimal parameterization has been verified with real GPS data through the estimation of a 3-day GPS orbit in two different cases: with and without modeling of the LTE. The differences in the node positions between the two sets of estimated orbits are in Fig. 4 and show a drift of the GPS nodes of about $2.1 \cdot 10^{-9}$ deg/d, close to the theoretical value of $2.3 \cdot 10^{-9}$ deg/d. This means that this optimal parameterization allows to observe the LTE in the GPS nodes provided that there are no errors in the background models and the nodes are accurately estimated to the few $10^{-9}$ deg level. This however is difficult to achieve mainly due to SRP modeling errors.

4 Effects of the SRP on the Galileo nodes

In this section we analyze the effects of the SRP on the Galileo nodes and the errors in the estimated nodes due to mismodeling of SRP. For that purpose, a set of Galileo orbits is simulated by including various parameters of the SRP model, then they are compared to a set simulated without SRP model. In first place a set of Galileo orbits with F0 equal to 1 and X-, Y- and Z-biases equal to 0 is tested. The effect is shown in Fig. 5 (a). A periodical displacement of the node is observed with an amplitude of up to $3 \cdot 10^{-5}$ deg and a period equal to a complete revolution of the Galileo satel-
lites. Moreover the SRP introduces a drift of\(7 \cdot 10^{-9}\) deg/d, about twice the level of the LTE.

The effects due to the presence of the X-, Y- and Z-bias (all simulated with magnitude \(10^{-10}\) m/s\(^2\)) are shown in Figs. 5(b), (c) and (d) respectively. It can be observed that the X- and Y-bias yield a significant trend of up to \(6 \cdot 10^{-8}\) deg/d and up to \(1 \cdot 10^{-7}\) deg/d respectively, in both cases depending on the orbital planes. Conversely, the Z-bias produces a periodical displacement of the node with an amplitude of \(2.5 \cdot 10^{-8}\) deg and a period of one revolution. The resulting node drift due to the Z-bias is \(5 \cdot 10^{-12}\) deg/d only. In summary, the SRP parameters must be handled carefully, since they can introduce large errors in the node thus easily masking the sought for LTE.

As a next step, the error in the estimated nodes due to the mismodeling in the SRP is analyzed in two different cases. In the first case 1 day of Galileo orbits and observations are simulated with \(F_0 = 1\) and the orbits are recovered from the observations by fixing \(F_0 = 1.2\). This represents a deliberate error of 20% of the full SRP model coming from a mismodeling in the satellite area, mass, surface properties, etc. In GPS orbit determination \(F_0\) varies periodically ranging from 0.5 to 1.5 or even more and hence, an error of 20% seems realistic. No X-, Y- and Z-bias are considered in this first case and the optimal parameterization for 1-day arcs is used in the recovery. Like in the previous tests the LTE is introduced in the data simulation but it is not modelled in the recovery of the orbits. The differences in the node between estimated and simulated orbits are presented in Fig. 6(a). A periodical error with a magnitude of up to \(1 \cdot 10^{-7}\) deg is clearly observed, the node drift due to the LTE is not visible. As a consequence, the global scaling factor of the SRP model shall not be fixed or highly constrained, but rather estimated. The estimation of \(F_0\) absorbs the deficiencies in the SRP model and does not affect the measurement of the LTE, as shown in Section 3.

In a second case, the Galileo orbits and observations are simulated by including Y- and Z-biases in the SRP model and an increasing \(F_0\) from the beginning to the end of the arc, according to the values given in Table 3. These values are realistic since they are obtained from the determination of GPS orbits. In the subsequent estimation of the Galileo orbits, \(F_0\) is fixed to 1 and the Y- and Z-biases are fixed to 0. The differences between estimated and simulated nodes are shown in Fig. 6(b). This time, the errors observed in the estimated nodes reach more than \(1 \cdot 10^{-7}\) deg mainly due to the mismodeling of the Y- and Z-bias, the LT node drift is not visible. Thus, the Y- and Z-bias of the SRP shall not be fixed but rather estimated since fixing them to incorrect values introduces errors in the node position two orders of magnitude larger than the LTE.

| parameter | value |
|-----------|-------|
| \(F_0\)   | 0.999 - 1.001 |
|           | (total variation = 0.002) |
| Y-bias    | -0.59600E-10 |
| Z-bias    | -0.13400E-07 |

Table 3: SRP parameters as obtained from GPS orbit determination and used in the simulations

Finally, to analyze the effects of the SRP depending on the satellite surface properties, a test is performed by using a macro model for the Galileo satellites. A macro model (sometimes also called box-wing model in the literature) takes into account the size and reflection properties of each surface of the satel-
Figure 5: Effect of the SRP on the Galileo nodes of simulated orbits (deg) when the following parameters are considered: (a) F0 only, (b) X-bias only, (c) Y-bias only and (d) Z-bias only.

lite. The Galileo attitude model is neglected here. It must be stressed however, that the attitude model is critical for the computation of the SRP effects on the Galileo orbits, since their panels are continuously reoriented to face the Sun. Thus, the results obtained here are a simplification of the real behaviour of the Galileo nodes.

According to different illustrations of the Galileo satellites (e.g. [5] or [13]), two different sets of parameters are set up, corresponding to two different satellite coatings, a gold coating and a silver (similar to aluminium) coating. The parameters of the macro models used are summarized in Table 4. It can be noted that the differences of the coefficients due to the choice of the coating amounts to 25% already. This will directly transfer into the SRP modeling and corresponds roughly with the uncertainties of the SRP model used in the above. The effect on the nodes due to the choice between the two different coatings can be observed in Fig. 7. The node differences are tremendous reaching $2.8 \cdot 10^{-7}$ deg peak to peak. In the end however, in Galileo orbits estimation the error due to a wrong choice of the surface coating will be reduced by the estimation of certain SRP parameters.

In conclusion, the measurement of the LTE with the Galileo nodes requires an accurate
SRP model for what it is essential to know the Galileo vehicles shape and surface properties. Also some model parameters such as F0, the Y- and Z-biases need to be estimated. The uncertainty arising from the SRP model is unavoidable, however a significant reduction could be achieved only if the Galileo satellites would be equipped with accelerometers, which measure all non-conservative forces acting on the satellites.

Table 4: Macro model parameters for the Galileo satellites based on gold and silver coatings.

| Surface  | Area (m²) | Refl. coeff. visible | gold | silver |
|----------|-----------|----------------------|------|--------|
|          | geom      | diff | geom | diff |
| bus top  | 1.32      | 0.14 | 0.56 | 0.18 | 0.72 |
| bus bottom | 1.32     | 0.14 | 0.56 | 0.18 | 0.72 |
| bus left | 2.75      | 0.14 | 0.56 | 0.18 | 0.72 |
| bus right | 2.75    | 0.14 | 0.56 | 0.18 | 0.72 |
| bus front | 3.00     | 0.14 | 0.56 | 0.18 | 0.72 |
| bus back | 3.00      | 0.14 | 0.56 | 0.18 | 0.72 |
| panel left | 11.70 | 0.04 | 0.16 | 0.04 | 0.16 |
| panel right | 11.70 | 0.04 | 0.16 | 0.04 | 0.16 |

Figure 6: Orbital node differences (deg) between estimated (without LTE) and simulated (with LTE) Galileo orbits (a) with an error in F0 of 20% and (b) with an error in F0, Y- and Z-bias.

Figure 7: Orbital node differences (deg) between simulated orbits considering gold or silver/aluminium coatings.

5 Discussion and Conclusions

Using simulated Galileo orbits and observations, the effect of the orbit parameterization on the detection of the LTE and the effects of SRP on the Galileo nodes are analyzed. The best parameterizations for the LTE estimation with 1-day and 3-day Galileo orbits are proposed. It is shown that the best parameterization depends on the arc length. In general,
the station coordinates cannot be freely estimated but they must be fixed or highly constrained, f. i. by imposing a set of NNTRS conditions. In addition, the empirical accelerations in the normal direction to the orbital plane and the X-bias of the SRP model must not be estimated, since they absorb the LT signal in the orbital nodes. When processing 1-day arcs, the SRP parameters (F0, Y- and Z-bias) and the Earth’s albedo scaling factor can simultaneously be estimated, however with 3-day arcs the Earth albedo must be fixed. These optimal parameterizations allow to estimate the LTE from noise-free observations provided that there are no errors in the background models. The possible errors due to the mismodeling of the background models shall be analyzed in future tests.

The 3-day arcs in combination with the optimal parameterization seem suitable for a precise estimation of the LTE from noisy Galileo observations, since the noise in the estimated nodes is 5 times smaller than the total displacement of the node due to the LTE after 3 days. In the future this must be confirmed with real Galileo observations. Then, assuming no errors in the background and SRP models, the LTE seems to be estimable from real Galileo data with a precision of 1% by using the nodes of 27 satellites and a minimum of 30 3-day arcs, again assuming no errors in the background models.

The SRP introduces large periodical displacements on the Galileo nodes, four orders of magnitude larger than the LTE. The deviations mainly cancel out after each complete revolution. The resulting node drift is twice the value of the LTE. In addition, the presence of X- and Y-biases produces significant nodal drifts, two orders of magnitude larger than the LTE depending on the orbital plane. The Z-bias introduces small periodical effects and an insignificant node drift. Fixing the SRP parameters (F0, Y- and Z-bias) to incorrect values yields large errors in the estimated nodes. Hence, these parameters shall not be fixed or highly constrained in the estimations, allowing them to absorb the deficiencies in the SRP model. The choice of wrong reflectivity coefficients of the surface of the satellites can give place to deviations of the nodes of up to two orders of magnitude larger than the LTE, which in the end can be reduced by the estimation of certain SRP parameters.

As a consequence, the measurement of the LTE by using the Galileo nodes requires an accurate SRP model, like f. i. a macro model fitted to the shape, size, weight and surface properties of the Galileo satellites. The macro model needs to be accompanied by an appropriate attitude model. The SRP parameters shall be estimated (F0, Y- and Z-bias), allowing them to absorb the deficiencies of the SRP model.

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