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An estimation of Envisat's rotational state accounting for the precession of its rotational axis caused by gravity-gradient torque ☆

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Abstract

The rotational state of Envisat is re-estimated using the specular glint times in optical observation data obtained from 2013 to 2015. The model is simplified to a uniaxial symmetric model with the first order variation of its angular momentum subject to a gravity-gradient torque causing precession around the normal of the orbital plane. The sense of Envisat's rotation can be derived from observational data, and is found to be opposite to the sense of its orbital motion. The rotational period is estimated to be $(120.674 \pm 0.068) \cdot \exp\left((4.5095 \pm 0.0096) \times 10^{-4} \cdot t\right)$ s, where t is measured in days from the beginning of 2013. The standard deviation is 0.760 s, making this the best fit obtained for Envisat in the literature to date. The results demonstrate that the angle between the angular momentum vector and the negative normal of the orbital plane librates around a mean value of $8.53^\circ \pm 0.42^\circ$ with an amplitude from about 0.7° (in 2013) to 0.5° (in 2015), with the libration period equal to the precession period of the angular momentum, from about 4.8 days (in 2013) to 3.4 days (in 2015). The ratio of the minimum to maximum principal moments of inertia is estimated to be 0.0818 ± 0.0011, and the initial longitude of the angular momentum in the orbital coordinate system is $40.5^\circ \pm 9.3^\circ$. The direction of the rotation axis derived from our results at September 23, 2013, UTC 20:57 is similar to the results obtained from satellite laser ranging data but about 20° closer to the negative normal of the orbital plane.

Keywords: Envisat; Gravity-gradient torque; Rotational state estimation; Space debris

1. Introduction

The ESA Environmental Satellite (Envisat) was launched in 2002 (Louet and Bruzzi, 1999) and became massive space debris in April 2012. As its 800-km-height sun-synchronous orbit is one of the most concentrated regions of space debris, Envisat has been identified as a candidate target for active debris removal (Bonnal et al., 2013; Shan et al., 2016). Envisat's rotational states have been studied recently (Ortiz Gómez and Walker, 2015) as part of the development of an active removal strategy (Liou, 2011).

To measure Envisat's rotational states from the ground, Kucharski et al. (2014) carried out an estimation using satellite laser ranging (SLR) data. Assumed to be parallel to the symmetry axis of the retroreflector, the direction of Envisat's spin axis was determined, based on the construction of the corner cube reflector, to be Lon = 269.22°, Lat = -28.14° in the radial coordinate system at September 23, 2013, UTC 20:57. This would mean the spin axis is nearly perpendicular to the velocity vector and makes about a 28° angle with the negative

☆ This template can be used for all publications in Advances in Space Research.

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normal of the orbital plane to the nadir direction. Following this estimation, the SLR data obtained from April to September 2013 were used to fit the variation of the rotational period, which was found to be $0.0367320 \cdot D + 124.883$ s, RMS = 0.91 s, where D represents the days of the year in 2013.

Optical observation is another important method that can be used to measure the rotational states of space debris (Ping and Zhang, 2017). Using Envisat's optical observation data from 2013 to 2015, Koshkin et al. (2016) extracted specular glint times to derive the satellite's synodic periods. When the standard deviation of the quadratic polynomial fit of the rotational period variations with time is at a minimum, a rotational axis that cannot be determined from one arc, as in the case of the SLR data, is estimated to coincide with the negative normal of the orbital plane. The rotational period was fit as $0.000021534 \cdot T^2 + 0.04936003 \cdot T + 121.18195$ s, RMS = 1.029 s, where T is measured in days from the beginning of 2013. However, the authors still speculated that the spin axis suffers some oscillations in the vicinity of the normal to the orbit.

The cause of the oscillations probably comes from the external torques in space. The influence of external torques could be left out in the estimate of the satellite's rotational state over just a short time, and then the rotational axis can be assumed to remain unchanged relative to the inertial system. However, the external torques cannot be neglected over time spans of months or years. Especially for Envisat, which has large gaps among its principal moments of inertia (Virgili et al., 2014), the effect of the precession of its rotational axis caused by gravity-gradient torque is more significant (Lin et al., 2016). Therefore, in this paper, we improve the rotational motion model by including the precession effect caused by the gravity-gradient torque, basing our model on the specular glint time data presented by Koshkin et al. (2016) and re-estimating the rotational state of Envisat using multi-parameter fitting.

2. Rotational motion model

2.1. Dynamic model for angular momentum change

As shown in Fig. 1, three rectangular coordinate systems (Crenshaw and Fitzpatrick, 1968) are built with their common origin O fixed at the centre of mass of Envisat. The orientation of the $OX^*Y^*Z^*$ system is fixed in the space for which the fundamental plane is the equatorial plane of the Earth, and the OX^* axis points to the vernal equinox. The $OX^OY^OZ^O$ system is the orbital coordinate system of Envisat, and the OX^O axis is in the direction of its ascending node. The $OXYZ$ system is a system associated with the angular momentum vector $\mathbf{h} = h\hat{\mathbf{h}}$ of the self rotation of Envisat, along which the OZ axis is directed, and the OX axis is an optional direction. $OXYZ$ can be obtained from

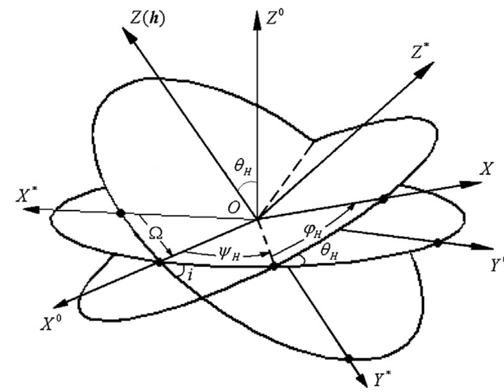

Fig. 1. Coordinate systems.

$OX^OY^OZ^O$ by three successive rotations around the OZ^O, OX^O and OZ^O axes through the angles ψ_H, θ_H and φ_H. Thus, the variation of the orientation of the angular momentum $\mathbf{h}$ with respect to the orbital coordinate system $OX^OY^OZ^O$ can be expressed through ψ_H and θ_H.

Because of the slender main body of Envisat with a launch configuration of 10.5-m length and 4.57-m envelope diameter (Louet and Bruzzi, 1999), the two principal moments of inertia, A and B, along the two shorter axes, are much larger than C along the major axis, as derived from Virgili et al. (2014) that $A = 129182.7\ \mathrm{kg\,m^2}$, $B = 124798.7\ \mathrm{kg\,m^2}$, and $C = 16979.8\ \mathrm{kg\,m^2}$. Hence, Envisat can be simplified as a uniaxial symmetric model, i.e., $A = B$. Then the variation of ψ_H and θ_H under the effect of a gravity-gradient torque can be expressed with a first-order approximation as (Lin et al., 2016)

$$\begin{aligned} \psi_H &= \bar{\psi}_H + \frac{\omega^*_{\psi_H}}{\omega_{\psi_H}} \sin \bar{\psi}_H, \\ \theta_H &= \bar{\theta}_H + \frac{\omega_{\theta_H}}{\omega_{\psi_H}} \cos \bar{\psi}_H, \end{aligned} \tag{1}$$

where $\bar{\psi}_H$ is the long-term change of ψ_H, and $\bar{\theta}_H$ is the mean value of θ_H.

As inferred from the results of the SLR data study (Kucharski et al., 2014), there is only one single period in Envisat's rotational motion. Therefore, the rotation should be around its axis of maximum inertia, with the angular momentum then coinciding with the angular velocity (both along the OZ axis), i.e., $\mathbf{h} = A\boldsymbol{\omega}$. According to the research on eddy current torque (Lin and Zhao, 2015), an exponential function is more in line with the decay rule of the angular velocity than the polynomial one used in previous work (Kucharski et al., 2014; Koshkin et al., 2016). The value of the angular velocity can be defined as (Smith, 1965)

$$|\boldsymbol{\omega}| = \frac{2\pi}{\alpha} e^{-\beta t}, \tag{2}$$

where α and β are both constant parameters to be estimated. The change of the rotational period with time t is