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Envisat Spin and Attitude Determination Using SLR

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Abstract. *Satellite Laser Ranging (SLR) systems successfully measure attitude and spin period of Envisat. During the International Laser Ranging Service (ILRS) campaign the SLR stations observed the satellite and provided measurements that allow determination of the attitude and the spin period of Envisat during year 2013.*

The spin parameters of the spacecraft are stable within a coordinate system fixed with the orbit; the satellite is pointing in the direction opposite to the normal vector of the orbital plane and rotates with a period of 134.74 s (as of September 25, 2013).

Introduction

Satellite Laser Ranging (SLR) measures distances to the satellites with the laser pulses. The laser range measurements are used for precise orbit determination, study of tectonic plate motion, Earth orientation and rotation parameters, as well as determination of the gravity field and the geocenter position (Pavlis, 2002).

The high repetition rate, millimeter accuracy SLR (Kirchner and Koidl, 2004) is the most accurate technology to measure spin of the laser-tracked satellites. During a pass of a satellite over an SLR station, the laser pulses transmitted from the ground station are reflected by CCRs back to the receiver telescope of the SLR system. The spinning array of the CCRs causes a mm-scale modulation of the range measurements what engraves a frequency signal on the SLR data. This frequency can be obtained by spectral analysis of the unequally spaced data (Lomb algorithm; Lomb, 1976) as it was demonstrated in (Otsubo et al., 2000, Bianco et al., 2001, Kirchner et al., 2007, Kucharski et al., 2012). SLR can measure spin parameters of the satellites during day and night, regardless to the sun - satellite - station geometry, and without any additional equipment.

In the case of the active missions designed for the Earth remote sensing (Envisat) or measurement of the Earth's gravity field (GOCE) it is necessary to stabilize the orientation of the spacecraft in such a way that the satellite always points towards the Earth - in the nadir direction. The active missions use SLR as an independent, absolute, and alternative to GPS, technology providing position of the spacecraft. The active, low Earth orbit, laser-tracked satellites are equipped with the small hemispherical panels which consist of 4 to 9 CCRs.

The Environmental Satellite - Envisat (mission of European Space Agency) was launched on March 1, 2002. The satellite was placed in a circular, sun-synchronous, polar orbit at a perigee of 796 km (inclination 98.54°, eccentricity 0.001165).

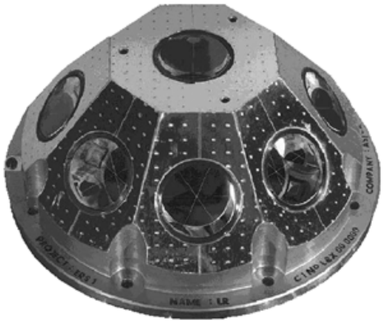

Figure 1. Retroreflector array of Envisat. Courtesy of ESA.

Envisat is equipped with a retroreflector array (RRA) panel for SLR. The panel has a hemispherical shape (20 cm in diameter) and consists of 9 corner cube reflectors (Fig. 1): one nadir looking and 8 symmetrically distributed around a hemispherical housing (oriented 50° off the symmetry axis of the panel). The Envisat mission ended on April 8, 2012, following the unexpected loss of contact with the satellite. After this time the satellite became passive space debris, and lost ability to maintain its attitude in the orbit.

Attitude determination

In order to determine the attitude of Envisat we have analyzed the Full Rate data delivered by SLR stations during the special ILRS campaign (started on May 30, 2013; Pearlman et al., 2002) as well as the data collected by Graz SLR station before the campaign started.

We assume the maximum incident angle between the laser beam and the optical axis of a corner cube reflector at which the reflections are possible to be 40°. Thus the maximum incident angle between the laser beam and the symmetry axis of the retroreflector panel (optical axis of the central CCR) at which the laser echoes can occur is 90°. In order to determine position of the symmetry axis of the retroreflector panel in the Radial Coordinate System we assume that the orientation of the panel is stable in this coordinate system and we fit a reflection cone (aperture radius of 90°) to the observed coordinates of the laser vectors. Assuming that the symmetry axis of the panel is parallel to the satellite's axis of rotation we obtain the spin axis in the Radial Coordinate System at Lon = 269.22°, Lat = -28.14° (Fig. 4 - Right).

During its mission, Envisat was stabilized in such a way that the retroreflector panel was always pointing in the nadir direction (Fig. 4 - Left). After the end of the active phase of the mission, the orientation of the spacecraft started to deviate in the direction opposite to the normal vector of the orbital plane.

Spin period from meter scale range oscillations

The spin axis of Envisat is not convergent with the symmetry axis of the retroreflector panel. The rotation of the retroreflector panel about the spin axis causes oscillations of the range measurement between a ground SLR system and the satellite in the meter scale. This effect is clearly visible in the distribution of the range residuals calculated as observed minus predicted range. The oscillation period of the range residuals can be determined by frequency analysis of the given dataset; the frequency analysis allows the determination of the apparent spin rate of the moving satellite - as seen from the ground site. The apparent spin periods calculated from the analysis of the meter scale range oscillations are presented on Fig. 3.

Spin period from millimeter scale range oscillations

Among the analyzed Envisat passes only the highly accurate data delivered by Graz SLR station allows to distinguish between the range measurements given by the single CCRs. The Graz SLR system measures distances to the satellites with a 2 kHz repetition rate laser (10 ps pulse width) since October 9, 2003 (Kirchner and Koidl, 2004). The system uses a “Compensated Single Photoelectron Avalanche Detector” (C-SPAD) which detects the arrival time of the first photons reflected by the satellite, thus measures the distance to the nearest CCR of the panel observed during a pass.

Fig. 2-A shows the range residuals after the polynomial fitting of a 130 s part of an Envisat pass measured by Graz on July 14, 2013. The range residuals oscillate with an amplitude of about 6 mm which is caused by the rotation of the retroreflector panel. The single down-peak (Fig. 2-B) represents change of the incident angle between the optical axis of the given CCR and the laser beam of the SLR system. The minimum incident angle occurs when the CCR points towards the ground SLR station and indicates the closest approach (CA) between the CCR and the SLR system.

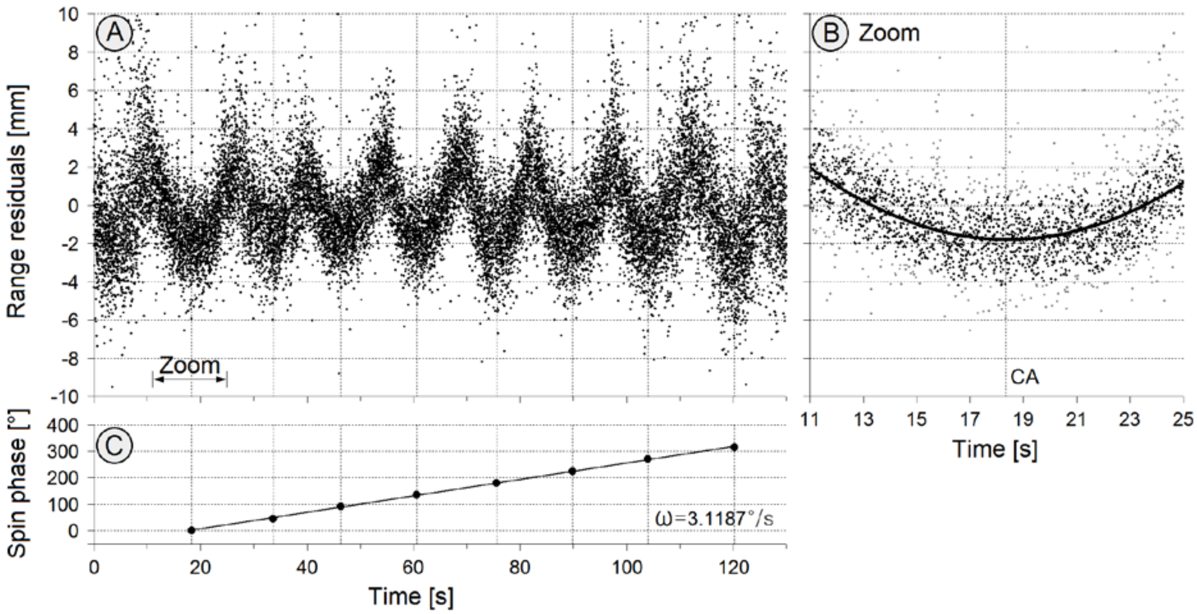

Figure 2. SLR data of Envisat measured by Graz on July 14, 2013. A: range residuals, zero is the mean level. B: zoom of a peak given by a single CCR and a polynomial function, the closest approach (CA) is marked. C: Spin phase of the satellite is changing over time - the linear trend represents the spin rate of the body ω=3.1187 °/s. The time scale is in seconds from the second of day = 76180. The vertical lines indicate epochs of the closest approach of the CCRs.

The retroreflector array of Envisat consists of the central CCR mounted on the top of the panel and 8 CCRs distributed symmetrically around the ring with an azimuthal separation angle of 45°. Supposing that the spin parameters of the satellite are stable during a single pass it is possible to calculate the spin rate of Envisat by analyzing time between the closest approach epochs of the consecutive peaks - it takes peak-to-peak time for the satellite to rotate by an angle of 45° about its spin axis. The observed change of the spin phase of the satellite (Fig. 2-C) can be approximated by a linear trend function which indicates an inertial spin rate of the body. Fig. 3 presents results of the spin period determination: the apparent and the inertial values.

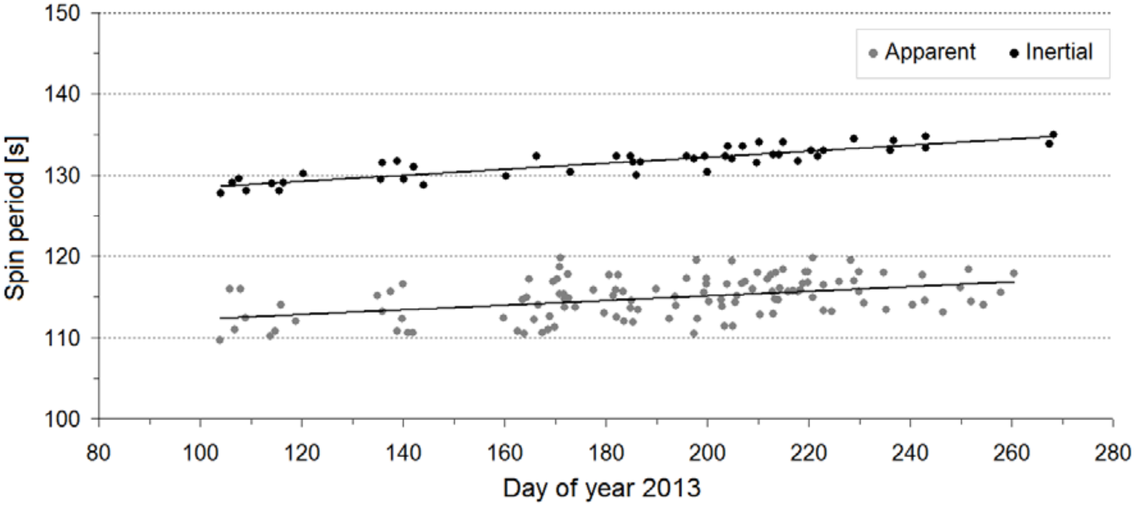

Figure 3. Spin period of Envisat during year 2013. Inertial spin period (black points) and apparent spin period (gray points) are approximated by linear trend functions.

The apparent and the inertial spin periods can be approximated by the linear trend functions:
$T_{\mathrm{apparent}} = 0.0290416 \cdot D + 109.352$ [s], RMS = 2.23 s,
$T_{\mathrm{inertial}} = 0.0367320 \cdot D + 124.883$ [s], RMS = 0.91 s,
where D is in days of year 2013.
Due to the long spin period in relation to the pass duration (about 3 rotations per pass) the apparent effect has a significant impact on the spin determination (about 15%), thus the method based on the analysis of the rotational phase (Fig. 2) should be used.

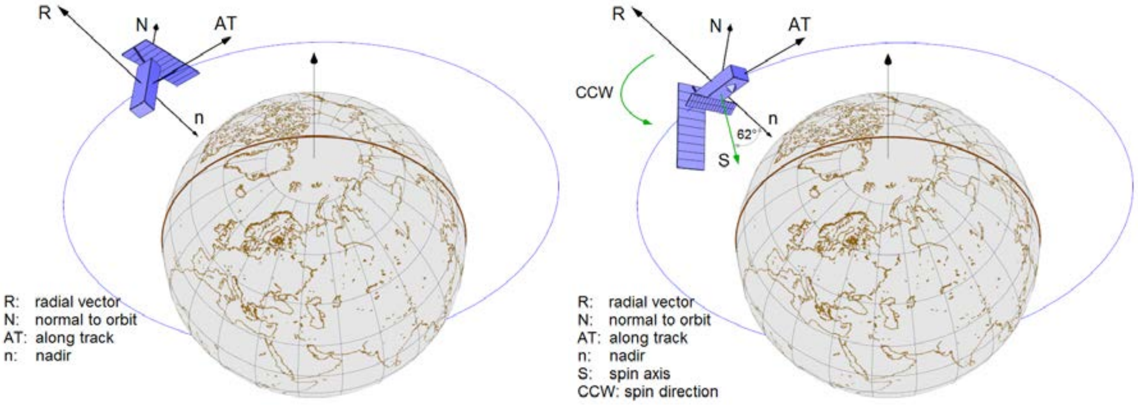

Figure 4. Orientation of Envisat during the mission - nadir stabilized (Left), and after May, 2013 (Right): the satellite spins in the counter clockwise direction about the spin axis S. Vectors: radial (R), normal to the orbital plane (N), along track (AT), nadir (n); a ground track of the polar orbit is marked.

Conclusions and potential application

Envisat has been operated for 10 years - doubling its planned five-year lifetime. The unexpected loss of the contact with the satellite on April 8, 2012 led to an end of the mission leaving the satellite in an unknown condition.

During the ILRS campaign the SLR stations successfully tracked Envisat and delivered the range measurements that allowed to determine the attitude and the spin period of the satellite. The recent SLR measurements indicate stable orientation of the spacecraft within the Radial Coordinate System - the retroreflector panel points in the direction opposite to the normal vector of the orbital plane. The satellite rotates with a period of 134.74 s (September 25, 2013) and slowly loses its rotational energy - the spin period increases by ~ 37 ms per day.

The passive Envisat is a massive space debris on the crowded Low Earth Orbit. Its orbital motion should be carefully analyzed and the possibility of the conjunctions with another objects should be monitored.

The SLR data remain the most efficient source of information about the spin dynamics of the passive Envisat, thus we recommend the ILRS community to continue tracking this satellite.

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