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ATTITUDE CONTROL STUDY ON ARTIFICIAL SATELLITES AND SPACE DEBRIS USING LASER DATA

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RESUMEN

Satellite Laser Ranging (SLR) es una técnica que permite medir la distancia a un satélite en órbita con alta precisión y, como aplicación particular, caracterizar la actitud y el espín de éste mediante el análisis de los residuos de distancia obtenidos a partir de la medida de tiempo de vuelo de los pulsos láser. Además, esta disciplina tiene aplicaciones en un amplio rango de campos de investigación, como la geofísica y la geodesia, o en la monitorización de objetos orbitales, entre ellos la basura espacial. Aplicando las técnicas de análisis de residuos de distancia, en primer lugar, sobre satélites pasivos y con fines geodésicos, como el *AJISAI*, y, posteriormente, sobre satélites inactivos (basura espacial), como son el *ENVISAT* o el *TOPEX POSEIDON*, se ha logrado observar con gran precisión los diversos movimientos oscilatorios debidos tanto a la rotación sobre el mismo eje de simetría como a la variación del ángulo de incidencia del haz láser sobre los retrorreflectores del satélite. En el desarrollo de este estudio se han comparado y complementado los resultados obtenidos en análisis anteriores examinando la evolución del periodo de rotación de los objetos estudiados. Esta capacidad de obtener información detallada sobre el comportamiento orbital y rotacional de los satélites inactivos, mediante este tipo de técnicas, permitirá desempeñar un papel notable en el entendimiento y la monitorización de la basura espacial, con el objetivo de anticiparse a posibles accidentes y colisiones previniendo la seguridad de las órbitas y la sostenibilidad del espacio. Además, permitirá comprender la dinámica de estos objetos con el fin de desarrollar modelos precisos de perturbaciones orbitales y facilitará ejecutar estrategias efectivas de retirada de satélites inactivos.

ABSTRACT

Satellite Laser Ranging (SLR) is a technique for measuring the distance to an orbiting satellite with high accuracy and, as a particular application, characterising the attitude and spin of the satellite by analysing the range residuals obtained from the time-of-flight (ToF) measurement of the laser pulses. Furthermore, this discipline has applications in a wide range of research fields, such as geophysics and geodesy, or in the monitoring of orbital objects, including space debris. By applying range residual analysis techniques, firstly on passive satellites for geodetic purposes, such as *AJISAI*, and subsequently on defunct satellites (space debris), such as *ENVISAT* or *TOPEX POSEIDON*, it has been possible to observe with great precision the different oscillatory movements due to the rotation around the same axis of symmetry and to the variation of the angle of incidence of the laser beam on the satellite's retroreflectors. In the development of this study, the results obtained in previous analyses have been compared and complemented by examining the evolution of the rotation period of the objects studied. This ability to obtain detailed information on the orbital and rotational behaviour of inactive satellites, using such techniques, will play a significant role in understanding and monitoring space debris, with the aim of anticipating possible accidents and collisions, preventing the safety of orbits and the sustainability of space. In addition, it will allow understanding the dynamics of these objects to develop accurate orbital perturbation models and will facilitate effective de-orbit strategies for the removal of inactive satellites.

Key Words: Attitude control — Satellite Laser Ranging — Space Debris — Space Surveillance and Tracking — Spin period

1. INTRODUCTION

SLR is a laser telemetry technique that uses short pulses of light, typically with a wavelength of 532 nm, to measure the bidirectional ToF from ground stations to satellite reflectors, thus allowing the dis-

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tance to be determined by applying various corrections.

Corner Cube Reflectors (CCR) are essential elements that are usually installed on the surfaces of satellites in order to implement laser telemetry and to know their orbits with high precision. The particularity of these devices is their ability to reflect light in the same direction in which it strikes them.

To develop this discipline, it is also necessary for ground stations to have three optical systems on a single mount. The first of these is a launching telescope capable of projecting laser pulses onto the observed objects. A second telescope acts as a finder, allowing small deviations of the laser beam to be adjusted. Finally, a receiving telescope, usually with an aperture between 600 mm and 1 m, is needed to capture the reflected photons. This last telescope is connected to an optical path that leads the photons to the optical sensors (photodetector), usually C-SPAD (Compensated Single Photon Avalanche Photodiode) type, in which, without going into too much detail, a single photon-generated carrier can trigger an avalanche current. The signal received at this detector allows the ToF of the beam to be stopped in the event timers. With this measurement it is possible to reconstruct the sensor-object distance at each time instant by applying correction models.

There are currently more than 40 stations distributed around the world that form part of ILRS (International Laser Ranging Service), carrying out their own engineering, operations, and data analysis tasks, among others. This technique has various applications in geophysical and geodetic fields, contributing to the definition of the Earth's centre of mass and monitoring its rotation, or helping to analyse the behaviour of the planet's gravity field, tectonic plates or tides. More recently, due to the high accuracy of this discipline, its use as a Space Surveillance and Tracking system for monitoring orbital objects, including space debris, has been proposed (Greene et al. 2002). Due to this feature it is possible, among other applications, to analyse the orbit of these objects and then compare it with their predicted orbits, thus studying their attitude and rotation period.

In this work, data from various satellites have been analysed, initially of the collaborative type, i.e. passive geodesic satellites, such as *AJISAI* (NORAD ID 16908), due to the precision of their orbits and the high availability of observations. As a result, it has been possible to verify the correct functioning of the developed algorithms. Once this milestone was overcome, these algorithms were applied on space debris objects, specifically on defunct satellites such as *ENVISAT* (27386) inactive since 2012, *TOPEX POSEIDON* (22076) inactive since 2006, among others.

2. METHODOLOGY

The files used in SLR to implement this analysis are two: the Consolidated laser Range Data format (CRD) and the Consolidated Prediction Format (CPF). CRDs provide the observations made by a laser station on a particular satellite during a short period of time that can vary from a few seconds to, under normal conditions, several minutes (Ricklefs & Moore 2009). The second type of file, CPFs, contains the ephemerides of the observed satellites, i.e. accurate predictions of the geocentric positions of that satellite over several days (Ricklefs 2006). These data are generated by several institutions with the necessary computational and technical capabilities, usually known as prediction providers. By having these two sets of files available, it is possible to calculate distance residuals, i.e. the difference between observed and calculated distances, which is very important information in laser telemetry data analysis.

Although this study is focused on space debris, the algorithms have been developed with simpler geodetic satellite passes in order to become familiar with the type of data to work with in this field, as well as to be able to clearly observe the residuals and the expected attitude. Still, the procedure is very similar for both types of objects and has been developed in publications such as that of Kucharski et al. (2014).

The first step in this procedure is to extract the observed data and calculate the distance from the station to the observed satellite. To achieve this, the ToF of the laser pulse must be utilized. After being emitted by the station, the laser pulse is reflected on the satellite reflector panel and then detected by the station once again. It is important to note that the timestamp accompanying the ephemerides positioning data provided by the CPF do not correspond to the observed times, so the next step is to interpolate these predictions into the observation times to obtain the position vector in geocentric coordinates. This has been achieved using a Lagrange 9th degree polynomial function, which is the standard according to the ILRS (Ricklefs 2006).

Then, since the laser propagation conditions in the atmosphere are known, it is possible to relate the speed of light, c, to an index of refraction that varies as a function of various parameters, such as wavelength, pressure, temperature, relative humidity, elevation angle, etc. Various models can be used

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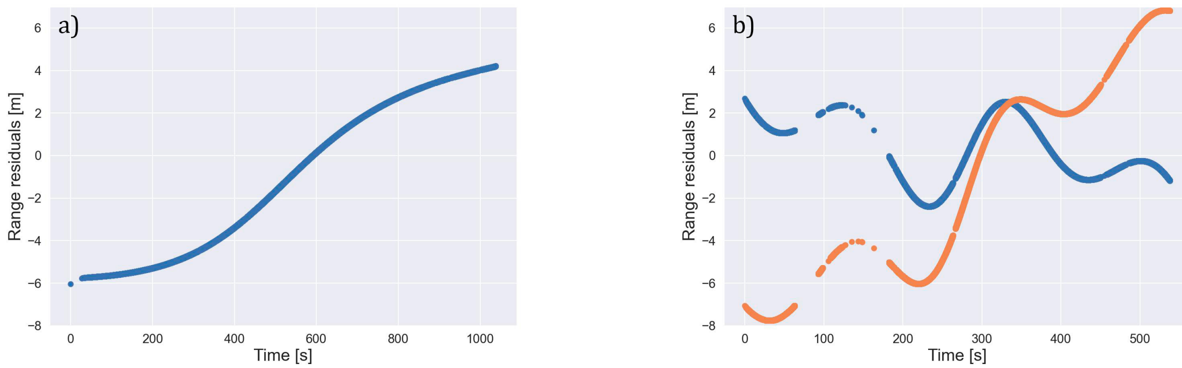

Fig. 1. (*a*) Range residuals calculated for an *AJISAI* tracking measured by Graz SLR station on December 8, 2023. (*b*) Range residuals calculated for an *ENVISAT* pass measured by Graz SLR station on January 31, 2018.

to apply this tropospheric correction, such as that of Mendes & Pavlis (2004) or that of Marini & Murray (1973). For this project, the latter model was used; however, it should be noted that below an elevation of 10, its equations become unreliable due to the increased atmospheric errors as light travels further. Because of the dependence on the elevation angle, it is essential to make use of the topocentric coordinates of the satellite, which are extracted from its geocentric coordinates, to solve for the elevation required in the model. Other corrections can be considered in relation to the eccentricity on the ground or on the satellite, or to the delay of the signal at the station, although depending on the case, the error of the measurement may exceed the correction itself due to the characteristics of the laser equipment.

After correcting the data, it is possible to determine the range residuals by the difference between the predicted and observed distance.

In figures 1 (*a*) (collaborative satellites) and (*b*) (inactive satellites) there is a clear trend in the data that can be either increasing or decreasing. This variation with time is due to a time bias that may have been caused by both a time lag in the ephemerides and an incorrect time correction in the measurements taken by the station, thus causing a time lag in the observed measurements.

Unlike the case of collaborative satellites, inactive ones show oscillations in the residuals, generally of several metres in amplitude (depending on the size of the satellite) due to their abandonment and the consequent absence of their attitude control. Specifically, the oscillation is due to the displacement, H, between the rotation axis of the retroreflector panel and its symmetry axis, which causes the distance between the CCR panel and the station to vary along the trajectory. This effect is absent in active satellites due to its repositioning systems and in geodetic collaborative satellites, exemplified by *AJISAI*, thanks to its spherical shape. So, as it was being said, in order to be able to work with the range residuals in defunct satellites, it is necessary to eliminate the trend to continue working correctly. Figure 1 (*b*) shows the range residuals before (orange curve) and after (blue curve) eliminating the trend.

With these oscillations, the period of rotation of the CCRs is determined by applying the Lomb algorithm (or Lomb-Scargle method), which makes it possible to detect the periodicity, as well as to obtain the angular frequency, of irregularly spaced data by means of a spectral analysis. In figure 3 the algorithm is applied to an *ENVISAT* tracking as an example, where a dominant frequency can be seen. There is usually another oscillation in the residuals of several millimetres mainly due to the variation of the distance measured by the laser, as it passes through the individual CCRs as a function of the spin of the satellite and the variation of the angle of incidence (Fig. 2). However, these millimetre-scale distance variations can only be observed with high-precision data, in this case provided by the Graz station, thanks to both its 10 kHz laser and the C-SPAD detector.

3. RESULTS

3.1. *Geodetic Satellites. AJISAI*

For *AJISAI*, a pass on December 8, 2023, measured by Graz laser telemetry station has been studied (Fig. 1 (*a*)). Figure 2 (*a*) and (*b*) show the distance residuals for a section of only 2 seconds duration and, as mentioned above, oscillations of only several millimetres amplitude are shown. On figure

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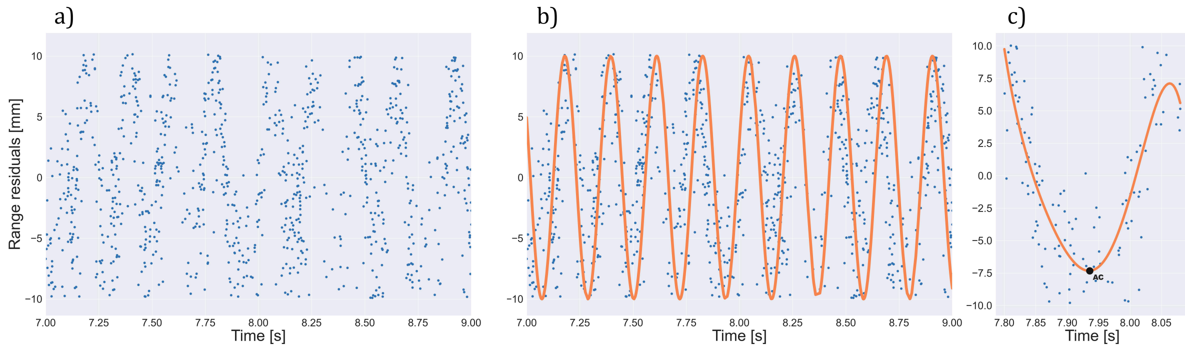

Fig. 2. (a) 2 second section of the *AJISAI* pass shown in figure 1 (a). (b) The same residuals section with a sinusoidal function fitted to the data, to better appreciate the oscillations. (c) Zoom of a peak, given by a single CCR. The curve-fitted polynomial and the CA point marked at the minimum are shown.

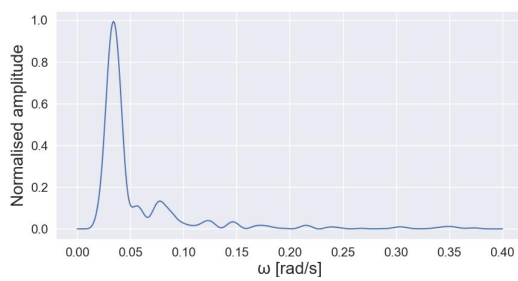

Fig. 3. Dominant frequencies calculated using the Lomb-Scargle method. For an ENVISAT pass measured by Graz SLR station on January 29, 2018, the dominant frequency is 0.0340 rad/s.

2 (c) is shown a zoomed region of one of the minimum residual values that corresponds to a Closest Approach (CA) position of a given CCR. To calculate this point, one can simply fit the curve with a 6th degree polynomial function and determine the minimum. By further study of these residuals it would be possible, knowing the distribution of the CCRs, to identify which ring each minimum corresponds to. In addition, it is known that the *AJISAI* spin axis is nearly parallel to the Earth's spin axis and is stabilised by a passive nutation damper, so it is possible to develop a simulation model capable of predicting the latitude of the satellite at which the laser is always pointing (Kucharski et al. 2010).

3.2. *Space debris. Defunct satellites*

In the case of defunct satellites, we have worked with *ENVISAT* and *TOPEX POSEIDON*, as shown in figures 1 (b) and 5, which show data from a track on 31 January 2018 measured by the Graz station and one on 3 January 2019 observed by the Borowiec station, respectively. From these values we therefore determine the frequency and the apparent spin period of the satellite during both passes, which for *ENVISAT* are 0.026 rad/s and 241.329 seconds respectively, and for *TOPEX POSEIDON* 0.621 rad/s and 10.124 seconds.

In addition to the determination of the period, one could try to estimate the displacement H between the spin axis of the satellite and the symmetry axis of the CCR panel, which is the cause of the oscillations shown. This would require a much more in-depth analysis in which, working in the Body-Centered Satellite, BCS, coordinate system, the incident angles of the laser vector on the CCR panel symmetry axis would have to be calculated to estimate the H-offset from a sinusoidal fit (Kucharski et al. 2014).

By examining several tens of different passes over a given period, it is possible to estimate the apparent rotation rate. In this case, the spin evolution of *ENVISAT* during 2017 and 2018 (Fig. 4 (a)) and of *TOPEX POSEIDON* during 2019 (Fig. 4 (b)) has been studied. The adjustment slope of the *ENVISAT* passes seems to indicate that the apparent spin trend remains approximately constant, with a decreasing trend of approximately 40 ± 30 ms/day, and with an average period of 190 ± 30 seconds. For *TOPEX POSEIDON*, the evolution of the period also seems to remain almost constant throughout the year, with a decrease of 1.1 ± 0.2 ms/day, practically imperceptible, and an average of 10.00 ± 0.15 seconds.

As for *AJISAI*, other oscillations can be found in the *ENVISAT* tracks because of their high accuracy as they are taken by a kHz laser from the Graz station. In this case they have an amplitude of between 6 and 8 mm and as mentioned, each of the peaks represents the change in the angle of incidence between

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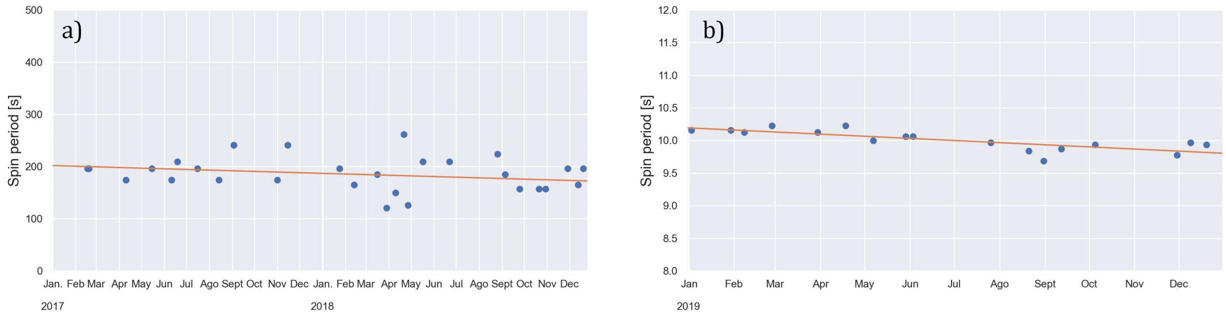

Fig. 4. (a) Evolution of the apparent spin period of *ENVISAT* during years 2017 and 2018. (b) Evolution of the apparent spin period of *TOPEX POSEIDON* during year 2019. The linear function indicates the decreasing trends during time.

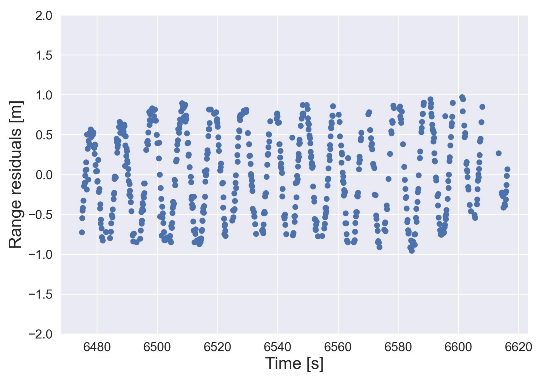

Fig. 5. Range residuals calculated for a *TOPEX POSEIDON* pass measured by Borowiec SLR station on December 8, 2023.

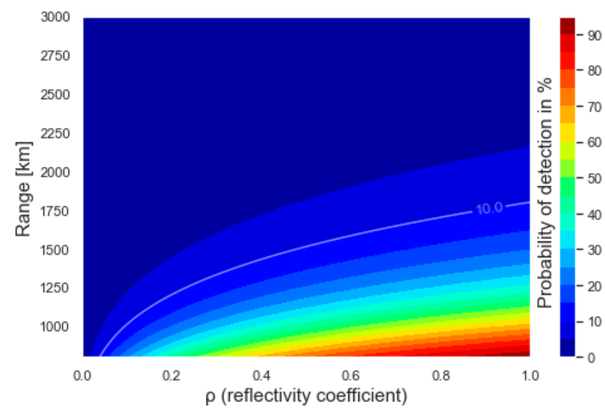

Fig. 6. Probability of detection as a function of the range to the satellite and the reflectivity of its surface (ρ).

the station's laser and the optical axis of the CCR on which the laser is currently incident. As with *AJISAI*, the minimum angle of incidence occurs when the CCRs axis is pointed towards the SLR ground station, this situation indicates the minimum angle of incidence CA between the optical axis of the reflector and the system laser.

Apart from the previous analysis of the residuals, it is interesting to briefly introduce the Laser-Radar transmission equation (Degnan 1993), although in this work the modified equation for space debris (Zhang 2012) has been used. This is very relevant when working with SLR techniques on space debris, as it measures the probability of obtaining laser echoes in tracking various orbital objects, such as satellites or space debris. It takes into account the structural characteristics of the object, such as its radar cross section (RCS); the reflectivity of its surface (ρ), which depends in part on whether it has mirrors and retroreflectors; various atmospheric effects; characteristics of the optical devices involved (transmission and reception efficiency); and the satellite's own position with respect to the station.

Using the Laser-Radar equation, it is then possible to test the probability of detecting laser echoes as a function of various parameters. In this case it is of interest to see the differences between satellites with different reflectivity coefficients ρ. For geodesic satellites it has the highest reflectivity on its surface, $\rho \approx 1$, but for other satellites or space debris in general the reflectivity tends to be lower and very variable from one object to another, $\rho < 1$. This is due, not surprisingly, to the presence of retroreflectors or mirrors or the reflectivity of the surface material. Figure 6 shows the dependence of the probability on the distance to the satellite and on the reflectivity.

4. DISCUSSION

From the various *ENVISAT* data analysed over the years 2017 and 2018, it has been determined that there appears to be an increase in the apparent spin period of 132 ms/day. This result at first seems to contradict the results shown in the reference article (Kucharski et al. 2014), where it is indicated that in 2013 there seemed to be a clear increase in the period of 36.7 ms/day; however, if this growth rate in 2013 is taken into account and extrapolated to 2017/2018 it seems to be close to the average period of 190 ± 30 seconds corresponding to the evolution during these last years. Perhaps the discrepancy is simply due to the accuracy of the results. As for *TOPEX POSEIDON*, it is estimated that, during 2019, its period has remained approximately constant with a growth of 0.4 ms/day on average and an average period of 10.00 ± 0.15 seconds.

Apart from the actual rotation of the satellites about their centre of mass, another type of movement related to the variation in the angle of incidence between the laser and the optical axis of the CCRs has been observed. This motion is reflected in a series of millimetre-scale oscillations in the debris, only observable with high-precision SLR systems. This is why they have only been observed in *AJISAI* and *ENVISAT*, whose measurements are taken from the Graz laser station, and not in the *TOPEX POSEIDON* tracks.

5. CONCLUSIONS

Ultimately, accurate observation of the orbits of any uncontrolled object, whether by laser telemetry or any other technique, is crucial to gain a better understanding of the space environment. Being able to anticipate possible accidents and collisions between objects allows mitigating the effects and even avoiding such accidents and protecting orbital integrity. Furthermore, understanding rotational dynamics and their evolution not only allows the development of accurate models of orbital perturbations, but also provides the basis for effective automated decommissioning strategies for inactive satellites. This will ensure sustainable orbital space management and the viability of future clean and safe space missions.

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