ORBIT DETERMINATION OF SPACE DEBRIS USING RADAR, LASER AND OPTICAL MEASUREMENTS

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ABSTRACT

The combined use of different observation techniques provides certain advantages in the orbit determination process: a) it allows to increase the number of available observations, b) it makes it possible to merge distances and angles, improving the observability of the orbit, and therefore, c) it makes it possible to perform the orbit determination process of more objects, in different orbital configurations, due to the greater density of sensors. All in all, it improves the robustness of the orbit determination process.

In general terms, the precision achieved in orbit determination will depend on several factors, among which the following stand out: the type of observables and the precision of the sensors used, the relative sensor-object geometry, the observed arc length and the distribution and number of observations. In order to evaluate the contribution of each of these factors, a sensitivity analysis has been carried out using a free software orbital dynamics library, Orekit.

The main objective of this study is to analyze the benefits of merging laser distances, radar observations and angular measurements in the same orbit determination process. In order to verify the efficiency of the algorithms used, observation campaigns have been coordinated between the three sensors of the Spanish Ministry of Defence dedicated to Space Surveillance and Tracking (SST) that belong to the national network S3T (Spanish Space Surveillance and Tracking): the S3TSR (S3T Surveillance Radar), the TFRM (Telescope Fabra ROA Montsec) and the San Fernando SLR (Satellite Laser Ranging) station.

1 INTRODUCTION

The proliferation of space debris puts the continuity of space missions at risk and represents a serious challenge to face. The number of objects classified as space debris is increasing rapidly, especially in regions of high interest for their commercial or scientific exploitation [1].

This is the case of LEO (Low Earth Orbit), the region in which the highest concentration of objects is located, but also in others such as the GEO ring (Geosynchronous Equatorial Orbit) and at heights close to the constellations of navigation satellites, that they are in MEO (Medium Earth Orbit). Due to the high added value of these regions, the cataloging, and more specifically, the orbit determination of space debris objects has become a topic of great importance and growing interest [2].

Fig. 1 has been taken from the ESA (European Space Agency) 2022 Annual Space Environment Report [1] and provides an overview of the evolution in the number of objects cataloged, classified by type of orbit, from the beginning of the space race to the present. It can be seen how in the last decade the curve has acquired an exponential growth trend which shows that the problem is far from being under control.

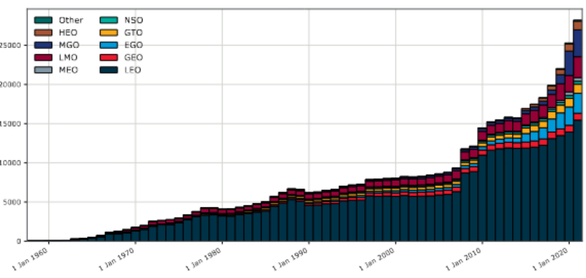

Figure 1. Temporal evolution of the number of objects depending on the type of orbit [1].

Orbit determination (OD) problem have been widely discussed in the literature since the first studies carried out in the s. XIX. Legendre and Gauss formulated the theoretical principles on which the resolution of this problem is based [3].

The basics of estimation begin with the formulation of the method of least squares applied to the fields of astronomy and geodesy. The first problems for calculating orbits use an uncertainty associated with the data obtained during observations. To solve this problem, the dynamical system used, based on Newtonian deterministic mechanics, was considered perfectly known and, therefore, the only assumed uncertainty came from the observations.

The Space Age caused the problem of orbital determination to be redefined based on two main aspects: firstly, the development of computers that

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generalized the calculation and implementation of mathematical algorithms and, secondly, the development of estimation filters formulated by Kalman and the inclusion of uncertainty in the system dynamics.

At present, although the theoretical principles are the same, the technological development linked to the space field has caused significant improvements in the precision of the algorithms used, including in its application to space debris objects over which there is no control of their orbit [4].

This communication presents the Initial Research Plan of the PhD titled "Determination of the orbit of space debris objects from the fusion of the information obtained by different sensors", which is included in the Aerospace Engineering PhD Program of the Carlos III University of Madrid. The main objective of this study is to analyze the benefits of merging laser distances, radar observations and angular measurements in the same OD process.

The theoretical fundamentals of the elements that have to be considered in the development of the thesis are included in sections 2 and 3, and then the methodology that will be followed during the thesis is detailed. Below are collected the preliminary results obtained for the validation of the tools used in determining the orbit and some conclusions reached with this analysis.

2 THE ORBIT DETERMINATION PROCESS

In general terms, orbital determination can be described as the process that makes it possible to define, at different instants of time, the state vector of an object in orbit. It is therefore possible by solving this problem to calculate the trajectory of an orbiting object in a given reference system as in Fig. 2.

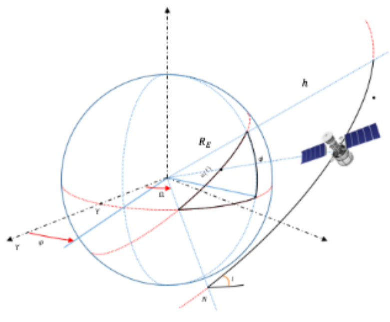

Figure 2. Satellite trajectory in an ECI system

The motion of the object is modelled by means of a set of ordinary differential equations, from which the state is updated using a set of discrete observations that are subject to random and systematic errors. It is assumed that the orbiting object is subject to the influence of various external forces [3], which include Earth's gravity field, atmospheric drag, solar radiation pressure, disturbances generated by third bodies and the effects of terrestrial and ocean tides.

2.1 Types of estimators

Currently, there are three groups of algorithms that are used to solve the OD problem [5]: batch estimators, based on least squares methods and its variants [6], recursive or sequential estimators [7], fundamentally characterized by Kalman filters and, finally, mixed methods called sequential-batch, using Bayesian filters that combine the advantages of the two previous ones [8].

The three groups of estimators allow, through the observations made by sensors, to recalculate the state vector and, therefore, the orbit of the object in question. The fundamental difference between the three procedures resides in how the observations are treated during their processing, either in the form of data groups, or sequentially each time a new measurement is obtained.

2.1.1 Batch estimators

The basic problem is solved by means of the linear method of least squares, which also serves to establish the fundamental principles of its formulation. This procedure is improved with the method of weighted least squares in which weights are introduced to allow taking into account the differences in the precision of the measurements obtained by different sensors.

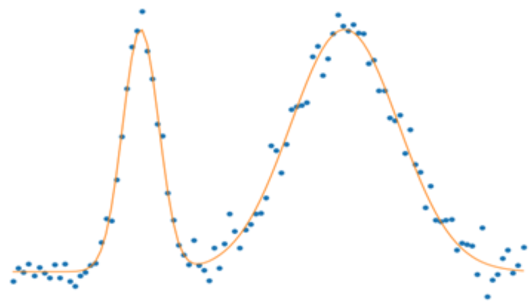

Figure 3. Estimation of a trajectory applying the nonlinear method of least squares.

Fig. 3 represents the estimate of the trajectory of an object calculated by the non-linear method of least squares using different observations at different moments in time.

The most general situation in the OD process is solved by the non-linear method of least squares using the differential correction technique.

$$\boldsymbol{\delta x} = \boldsymbol{P A^T W b} \qquad (1)$$

Using Eq. (1), it is possible to calculate the corrections to the state vector, $\boldsymbol{\delta x}$, from the covariance matrix, $\boldsymbol{P} =$

$(\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}$, the Jacobian or matrix of partial derivatives, $\boldsymbol{A}$, the matrix of weight, $\boldsymbol{W}$ and the residual matrix, $\boldsymbol{b}$.

The covariance matrix is a useful tool to assess how the type, number, distribution, and precision of observations affect the estimation process. This matrix provides the uncertainties of the estimated parameters.

2.1.2 Sequential-batch estimators

The hybrid estimation technique, also called sequential least squares, processes the data separately and then combines them using the conditional probability of Bayes' Theorem to obtain the covariance matrix. In Eq. (2) Bayes' rule defines the conditional probability of any event A_i in the presence of another event, B.

$$P(A_i|B) = \frac{P(B|A_i)P(A_i)}{P(B)} \qquad (2)$$

2.1.3 Sequential estimators

Finally, in this category are the different types of Kalman filters. These algorithms use a predictor-corrector method to calculate the best estimate taking into account the noise present in the observations. That is, the system is made up of two sets of equations: prediction and correction. The prediction equations allow obtaining the predictions of the state variables taking into account the dynamics of the system. On the other hand, the correction ones improve the predicted data using the information of the observable variables for a known later instant of time. In each of the iterations, both the gain matrix and the covariance matrix are recalculated. By means of the values of the gain matrix, a greater or lesser importance is given to the measured value or the estimated value in the estimation process.

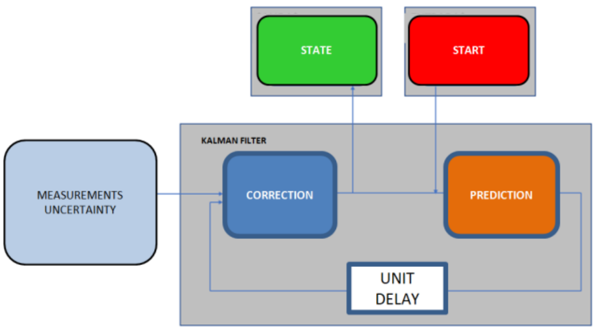

Figure 4. Block diagram of the structure of the Kalman filter.

In the case of nonlinear dynamical systems, it is possible to use a modification of the algorithm called Extended Kalman Filter. This process linearizes the system, using a Taylor approximation, with respect to the current estimate in order to calculate the appropriate gain and correction.

Sequential algorithms are useful for problems in which a continuous stream of observations takes place, for example, tracking a space debris object in the early stages of reentry into the atmosphere. In addition, a particularity of this type of estimators is that they allow considering variations in the models used, for example, in terms of variations in atmospheric friction due to changes in the solar flux or due to magnetic activity.

2.2 Perturbations

Estimation is a two-step process: propagation of the current estimate and its update. The propagation step is critical when the time between measurements is large. In these cases, the dynamical model should provide an accurate propagation of the previous estimate.

2.2.1 Earth's anomalous gravity field

The dominant perturbing force on orbits of near-Earth artificial satellites is due to Earth's oblateness. This is due to the fact that the Earth, like all planets with rotational movement, widens in the zone of the equator due to the centrifugal force caused by its rotational movement.

Because the Earth is a sphere flattened at the poles, its symmetry is not perfectly spherical. This truncation of spherical symmetry shows that the gravitational force of a satellite orbiting the Earth is not always pointed towards the center of the Earth. Despite the fact that the gravitational potential of a perfectly spherical body depends only on the distance from its center, the flattening produces a variation in the potential that will make it depend not only on the radius but also on the latitude of the point where the satellite is projected on the earth's surface.

This particularity causes that the angular distance from the equator will be different than the angular distance from the poles, thus causing a disturbance in the satellite's orbit. In terms of orbital elements, this effect causes a quite remarkable variation of the right ascension Ω, as well as the perigee argument ω, as a function of the inclination i of the satellite orbit.

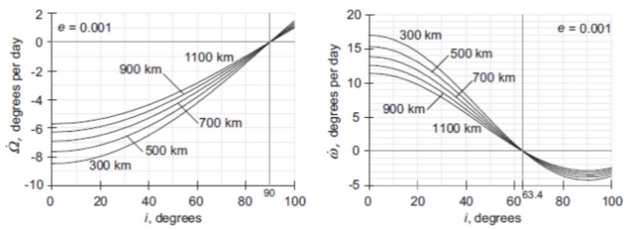

Figure 5. Variation, of the right ascension Ω and of the argument of the perigee ω, over time, as a function of the inclination i [9].

2.2.2 Third bodies

The third body problem has a greater impact on satellites with high orbit heights. The cause of the disturbance in the trajectory is the gravitational attraction of a third body, usually the Sun and the Moon.

$$\ddot{r} = -\frac{GM}{r^3}r + G\left[m_S\left(\frac{r_S - r}{(r_S - r)^3} - \frac{r_S}{r_S{}^3}\right) + m_M\left(\frac{r_M - r}{(r_M - r)^3} - \frac{r_M}{r_M{}^3}\right)\right] \quad (3)$$

In Eq. (3), the first term is due to the central acceleration caused by the Earth, while the second term is due to the perturbing acceleration, caused by the gravitational attraction of the Moon and the Sun respectively acting on the satellite.

This type of equations does not have an analytical solution, that is, it is not possible to obtain a function of time that expresses at each moment where each of the three bodies is located.

The secular effect of these perturbations on the orbital elements, Ω and ω, can be evaluated thanks to the Kozai equations [10].

2.2.3 Atmospheric drag

On our planet, it is accepted that space begins above 100 km above sea level. This boundary between the atmosphere and outer space is known as the Karman line and is obtained by calculating the height at which the density of the atmosphere is so low that the speed of an aircraft to achieve lift should be comparable to the orbital speed for that same height.

Although there is an extremely attenuated atmosphere above 100 km, the density of atmospheric air above this altitude is not enough to slow down the bodies by atmospheric friction. The relative speed of the satellite with respect to the Earth is given as the difference between the speed of the satellite with respect to the non-inertial reference system and the speed of the atmosphere with respect to the same non-inertial frame. As the atmosphere spins around the Earth dragged by its rotation movement, its angular speed will be the speed angle of the Earth.

Atmospheric friction is interpreted as a force acting in the opposite direction to velocity vector, in this case, the relative velocity vector of the satellite with respect to the Earth.

2.2.4 Solid Earth tides and Ocean tides

The terrestrial and oceanic tides cause variations in the gravitational potential of the Earth and therefore cause additional accelerations acting on the satellite.

2.2.5 Solar radiation pressure

This type of disturbance is produced by the electromagnetic pressure exerted by photons from the Sun on the surface of the satellite. Solar radiation is made up of photons, that is, electromagnetic waves that propagate at the speed of light. Because each wave has energy and momentum even though it has no mass, there is a transfer of momentum with the satellite at the moment of impact. This moment is understood as a pressure exerted by solar radiation on the surface of the satellite.

2.3 Other factors to consider

Once the different types of estimators are known, it is important to take into account that the precision achieved in the OD process depends on several factors among which stand out [11]: the type of observables used, the precision of the sensors that have been used, the relative geometry between the sensors and the observed object [12], the observed arc length [13, 14] and the number and distribution of observations have been used.

3 THE USE OF LASER RANGING AND ITS APPLICATIONS

Despite the limited dissemination of laser sensors, this study aims to demonstrate the advantages of their use by showing the considerable improvement that the use of their observations supposes in the orbit determination results.

The evolution of laser telemetry, in its little more than 50 years of history, has been evident in the improvement in the precision of its measurements. This parameter is closely linked to the size of the laser pulses. The first generation of lasers achieved results with precisions of the order of meters. Currently, the accuracy is within a few millimetres for the best performing stations [15].

Laser ranging is not only used to determine the orbit of satellites but also contributes, together with other geodetic techniques, to the study of plate tectonic movement, the deformation of the earth's crust, the determination of the Earth's orientation parameters and of the gravitational field. In addition, at present, it is used in the determination of the Terrestrial Reference Frame (ITRF) and as support, through the determination and validation of precise orbits, to Earth observation satellites [16]. Additionally, laser ranging provides high accuracy for distance measurements [17] and attitude control [18] of space debris objects, in both day and night periods [19].

4 DESCRIPTION OF THE METHODOLOGY TO BE USED

This research will be structured in three blocks: theoretical, practical application and experimental development.

In the study of the theoretical part, a detailed analysis of the orbit determination process will be carried out, with special emphasis on the particularities involved in carrying out the observation with each type of sensor. Observations, typically azimuth and elevation angles and distance measurements, are the raw data set that, once fed into algorithms, allow orbit determination to be implemented. The combined use of different observation techniques provides certain advantages in the orbit determination process: a) it allows to increase the number of available observations, b) it makes it possible to merge observed distances and angles, improving the observability of the orbit and, therefore, c) makes it possible to determine the orbit of more objects in different orbital regimes due to the higher density of sensors. Once the orbit of an object has been defined, it is possible to predict future positions by means of different propagation techniques. As time progresses, the actual trajectory and orbit predictions tend to diverge due to disturbances such as atmospheric drag.

The practical block of this study will be based on the analysis of data, both synthetic and real, in order to corroborate the premises raised in the theoretical block. With the aim of obtaining real data, verifying the efficiency of the developed algorithms, improving them and solving possible errors, observation campaigns have been and will be coordinated in which the three types of available sensors belonging to the Ministry of Defence participate: passive optical (TFRM telescope), laser (SFEL) and radar (S3TSR).

Figure 6. S3T sensors belonging to the Ministry of Defence and their location.

Fig. 6 shows the three S3T sensors belonging to the Ministry of Defence and their geographical location. The use of observations in a combined way during the campaigns has as a general purpose the generation, autonomously, of improved orbits of the observed objects. The configuration of proposed sensors, radar, telescope and laser, along with observations from other ILRS (International Laser Ranging Service) laser sensors, will allow the factors influencing orbit determination to be dealt with in detail.

It is interesting to note that the use of various types of sensors provides the additional possibility of making quasi-real-time corrections to the orbit, which allows optimizing the precision of the ephemeris used to initiate tracking by subsequent sensors. This idea will be analyzed in the last block, experimental development, with the aim of exploring contributing techniques between the different sensors that optimize the results achieved during the observations.

5 PRELIMINARY RESULTS

Orekit, an open orbital dynamics library, has been used to carry out the OD process. This library provides the framework with higher-level interfaces and classic implementations, such as the use of angular measurements and distances. The design features of this library provide enough tools for classical OD and can be extended to address more operational needs.

As a validation task of the tools to be used during the analysis, the preliminary results of the OD process have been calculated using laser data for different satellites. To verify the correct functioning of the algorithms used, two comparisons have been made. The first one has consisted of using a reference tracking obtained by a laser station and checking how the residuals are reduced after carrying out the OD.

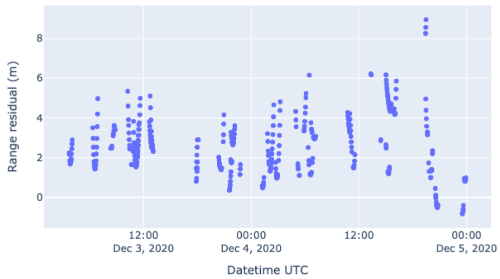

Figure 7. Range residuals from Lageos 2 observations used in the OD process.

Fig. 7 shows the distance residuals of the observations made on the Lageos 2 satellite during the period between December 3rd and 5th, 2020. This set of observations has been used to carry out the OD process.

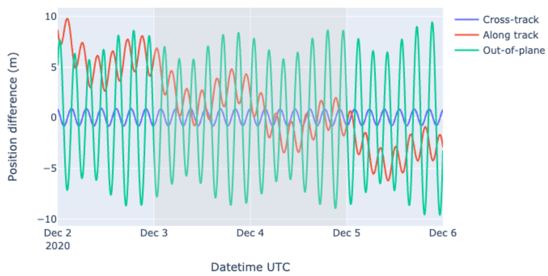

Figure 8. Delta position between CPF and estimation in LVLH frame. Three traces show the cross-track (blue), along-track (red) and out of plane (green) components.

Fig. 8 shows the delta position between Consolidated Prediction Format (CPF) and estimation in Local Vertical Local Horizontal (LVLH) frame. This graph breaks down the values in the three components cross-track (blue), along-track (red) and out of plane (green) with precisions of the order of meters.

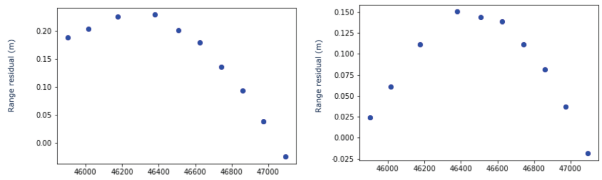

Figure 9. Range residuals by Mt Stromlo station on the Lageos 2 satellite before (left) and after carrying out the OD (right).

Fig. 9 shows the range residuals from a reference tracking carried out by Mt Stromlo station on the Lageos 2 satellite in two cases: before (left) and after carrying out the OD (right). The process verifies an improvement in precision of the order of centimetres.

The second verification method was to use the precise SP3 (Extended Standard Product-3) orbits of different satellites (Lageos 1-2, Ajisai, etc.) in order to compare the position accuracy with the results of the OD process.

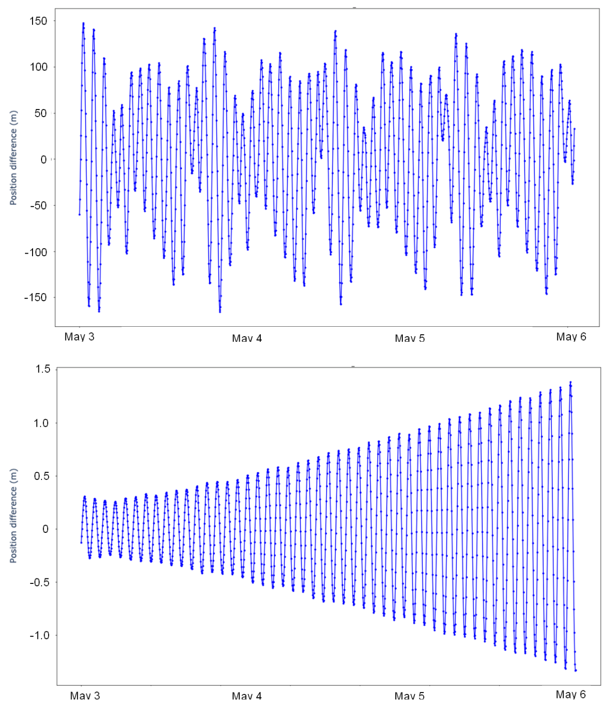

Figure 10. Analysis of the differences between the initial orbit (TLE) and SP3 (above) and the improved orbit generated after OD (below).

Fig. 10 shows the differences between the initial orbit (TLE) with respect to SP3 and the improved orbit generated after the OD for the Ajisai satellite during a period of 3 days. The comparison shows the considerable improvement after the OD that goes from the order of hundreds of meters to be below one meter.

6 CONCLUSIONS

The main contribution of this thesis will be to show the fusion of different types of observables as a technique to improve the results of OD in the same calculation process. This objective will be materialized by demonstrating the benefits of fusing laser distances with radar observations and angular measurements in the same OD process. A novel aspect is to make a comparison between the available systems, analyzing what the gain would be using each type of sensor. This process could be developed in a geometric context by observation technique, statistical by the quality of the observations and at a system level taking into account the technical characteristics of each sensor.

According to these premises, the following general objectives are proposed for the development of the thesis:

- Deepen the OD problem in order to optimize the results by fusing various sensors: optical and others whose observable are distances.

- Investigate the different algorithms and mathematical methods that lead to the orbital determination, evaluating advantages and disadvantages at each step, mainly in terms of precision in the results versus execution time, a crucial aspect to generate corrections to the orbit in quasi-real time.

- Analyze, through an error study, how the observed sensor-object geometry affects the results, the precision of the sensors used, the number of observations used and the observed arc length, among other factors.

- Explore techniques that allow applying corrections in quasi-real time on the analyzed orbits. These observation methods will enable the collaborative use of different types of sensors in a coordinated manner, which would significantly increase their observational capabilities.

As an added contribution of this study, it is expected that the use of different types of sensors will allow the exploration of new techniques that apply corrections in quasi-real time [20] that is improving the observations of sensors during the same arc of orbit. It is foreseeable that the observational performance will increase significantly through the coordinated use of surveillance-type sensors with those of monitoring.

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