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Onboard autonomous conjunction analysis with optical sensor

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Abstract. The increasingly high number of spacecrafts orbiting our planet requires continuous observation to predict hazardous conjunctions. Direct onboard analysis would allow to ease the burden on ground infrastructure and increase the catalogued debris. A spaceborne optical sensor is used to assess the performance in terms of different targets visibility. A fast relative orbit determination algorithm is then proposed to compute the probability of collision for a particular case study and compared to a more accurate ground analysis.

Introduction

The growing number of satellite launches increases the risk of in-orbit collision, with potential cascade effects, further worsening the situation. Given the high number of close encounters every day, estimation processes must be frequently updated to avoid the occurrence of catastrophic collisions such as the Iridium-33/Cosmos-2251 event. The possibility to autonomously analyze any conjunction directly onboard would allow to significantly reduce the burden on ground infrastructure, leading to a faster update rate and lower risk of unexpected collisions. Therefore, in this research, a satellite is equipped with an optical sensor to determine the visibility performance with respect to a catalogue of potentially hazardous objects, with different parameters considered relevant for a significant statistical analysis. The closest encounters are then identified and a novel approach is presented for an accurate and computational efficient onboard orbit determination algorithm, providing results directly at the Time of Closest Approach (TCA), where the conjunctions are analyzed onto the B-plane.

Simulation design

The simulation consists of an asset spacecraft, based on the real satellite COSMO-SkyMed 4, operating in a Sun-Synchronous Low Earth Orbit, and a catalogue of 425 possible threats. The sensitivity analysis is carried out in the first eight days of September 2022. The chosen optical sensor is characterized by a limiting magnitude of 15, 30° field of view and 30° minimum Sun separation, operating in tracking mode; the camera is inertially pointed at the expected target direction, at the beginning of each visibility window, without any attitude information. The chosen sensor allows to see objects as small as 10 cm up to 6000 km [1]. The simulation is carried out though *SOPAC* (Space Object PAss Calculator), a Python library developed by *Politecnico di Milano* to compute all the possible observation opportunities for a given sensor network [2]. First, a sensitivity analysis is carried out, with the sensor performance evaluated both in terms of total visibility and revisit times for all the computed windows and compared to the asset observation uniformity along its orbit. Of the six main keplerian elements, only right ascension of the ascending node (or RAAN) shows a remarkable trend; higher semi-major axis may grant higher visibility, yet the considered catalogue is too limited for a significant inference. The total visibility time is shown on the left of Fig. 1, expressed in hours for three different sensor limits: pure geometry, only illumination and full limitations, as defined before. As expected, the presence of the Earth shadow strongly reduces the total time to values lower than 25 hours, while limiting magnitude and Sun separation have a relevant influence only for particularly small objects. The second relation highlights the total time as function of RAAN and uniformity index, computed dividing the asset orbit in 36 sections covering 10° in true anomaly and counting how many contains at least one potential observation. It is thus an important indication of the quality of measurements taken for the specific target.

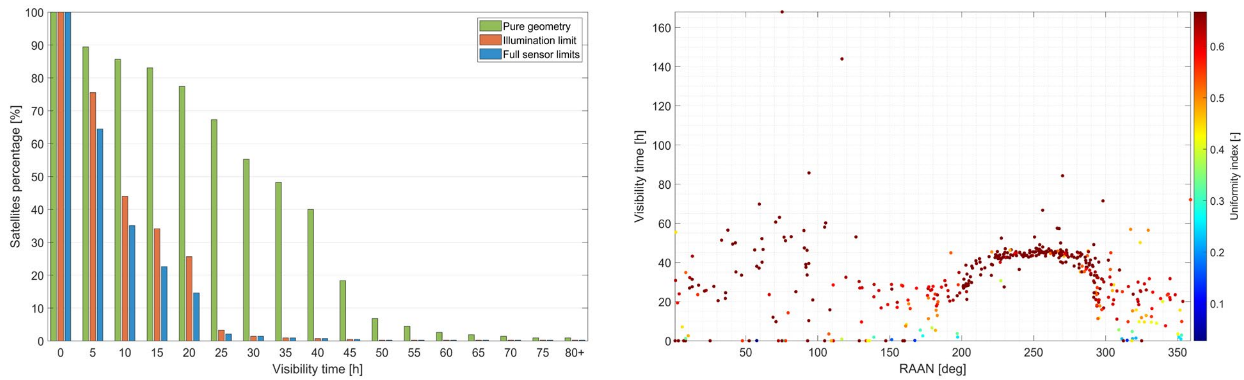

Figure 1 Total visibility time expressed in hours for three different sensor limits (left) and function of RAAN and uniformity index (right).

Objects with RAAN between 200 and 300 degrees are characterized by a higher time and higher uniformity index with no significant influence from initial target conditions. This is an expected result as COSMO-SkyMed 4 has a RAAN of about 70°, approximately 180° apart, resulting in encounters being mostly "head-on". On the contrary, objects with RAAN similar to the asset may reach higher values, though they are strongly dependent on the initial relative position.

An important parameter when scheduling observations is the revisit time, the time between two consecutive passages, reported on the left of Fig. 2. The maximum and minimum revisits are highlighted as function of RAAN, with an upper limit of 3000 seconds. At around 250 degrees, the two values are almost coincident at approximately 2000 seconds.

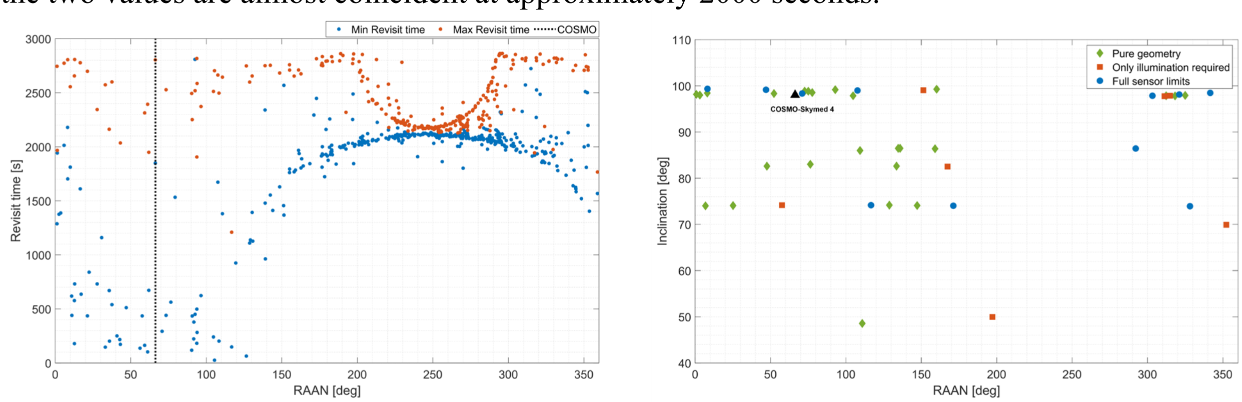

Figure 2 Maximum and minimum revisit (left), non-visible objects as function of inclination and RAAN (right)

Concerning non-visible objects, on the right of Fig. 2, out of the 425 objects, 25 are never visible due to geometric limitations, 7 due to lack of Sun illumination and 11 due to the specific sensor adopted. Once again, satellites with RAAN between 200° and 300° are always visible, regardless of the considered limit.

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Methodology

The conjunction events are searched in the 8 days after the statistical analysis. The optical sensor accuracy is set at 0.01° for both right ascension and declination, to account for lower performance of an onboard system, as well as possible mounting errors. Since the proposed filtering method is based on the linear, minimum variance Least Squares, the propagation should be close to the real motion to ensure accurate results even with a single iteration. The best compromise is found by propagating directly from the TLEs using SGP4, allowing to keep a low computational time and high accuracy. On the contrary, the contribution of the State Transition Matrix (STM) is much less sensitive to inaccurate orbit modeling and a simple J2 effect can be implemented without excessively diminishing the estimation accuracy. The proposed method is based on the property of the STM to map each observation to the relative state directly at the TCA, without the need to further propagate the solution, which would result in a higher computational time and lower accuracy. If the primary spacecraft motion is assumed to be perfectly known, then the relative state deviation is equal to the target one, allowing to work in terms of absolute quantities, as reported in Algorithm 1. Although the asset spacecraft is tracked by ground stations providing accurate orbit determination, its trajectory is still affected by uncertainties, included in the filter post-processing through the Consider Covariance Analysis (CCA) [3]. Given the solution of the filtering process, relative position and covariance at the TCA are projected onto the B-plane, reducing the state dimension from six to only two positional coordinates, greatly simplifying the conjunction analysis and a potential CAM design [4]. The probability of collision is thus computed according to the Chan formulation, truncated to the third order [5]. The results provided by the onboard algorithm are compared to the ones obtained with a classic Unscented Kalman Filter (UKF), with observations coming from a set of three stations part of the EU SST sensor network (EU Space Surveillance and Tracking): S3TSR, MFDR and Cassini.

Algorithm 1: *OnBoard conjunction analysis*

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Identify conjunction events and visibility windows
Simulate real measurements, according to the defined camera frame
Propagate reference trajectory from TLEs
For each measurement
    | Compute reference observations
    | Compute measurements deviation
    | Integrate STM to linearly map each observation to TCA
end
Compute target state and covariance at TCA
Project onto the b-plane and compute probability of collision
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Conjunction result

The results of the onboard relative orbit determination and conjunction analysis are here presented for the closest event, involving Falcon 1 rocket body, orbiting in a quasi-equatorial orbit of 9° inclination at approximately 650 km of altitude. Despite the low visibility time of only 16 hours, 284 measurements are processed. As highlighted in Fig. 3, the estimated error is 23 m, with a covariance of 76 m computed from the Least Squares, and 120 m added from the CCA. Considering the miss distance of 871 meters, the probability of collision is effectively equal to zero. The ground-based analysis is performed for all the involved objects, computing error and covariance of the orbit determination process alone, in order to directly compare the two methodologies. The square root of the covariance trace and the positional error highlight similar trends for both the asset and the target spacecrafts. The final values are 33 and 23 meters respectively for COSMO, 110 m and 120 m for Falcon 1. The latter lies in correspondence of a spike, though the steady-state values are comparable to the asset. In general, the UKF results are slightly better, especially in terms of covariance, with the advantage of a real-time estimation process; however, the difference in computational time is considerable, with the Least Squares providing results in few seconds. Furthermore, the space-based platform is capable of seeing objects with very different orbits, still with a sufficiently high number of measurements, thus showing greater flexibility especially for low-inclination targets.

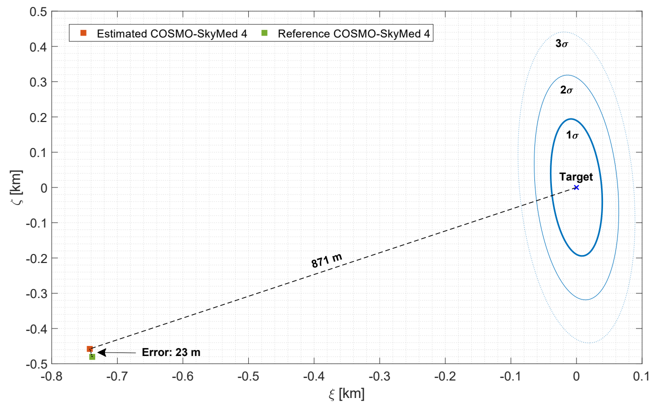

Figure 3 COSMO-SkyMed 4 and Falcon 1 projected onto the B-plane at the conjunction epoch. The combined covariance is centered at the target.

Conclusions
The proposed filtering method allows to estimate target position and covariance directly at the conjunction epoch in a fraction of the time required by typical ground-based algorithms. The sensitivity analysis performed for the onboard camera showed good performance in terms of target visibility for all the objects characterized by RAAN between 200 and 300 degrees. In future, the method could be expanded to include fully autonomous initial orbit determination and threat detection, allowing to reduce the burden on ground infrastructure and improve the sustainability of human activities in space.

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