POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

Executive Summary of the Thesis

Onboard autonomous conjunction analysis with optical sensor

Laurea Magistrale in Space Engineering - Ingegneria Spaziale

Author: Luca Capocchiano

Advisor: Prof. Pierluigi Di Lizia

Co-advisors: Prof. Mauro Massari, Michele Maestrini

Academic year: 2021-2022

---

1. Introduction

Since the beginning of human activities in space, objects as decommissioned satellites, spent upper stages or generic fragments have accumulated in Earth orbit. The growing number of satellite launches increases the risk of in-orbit collision, with potential cascade effects, further worsening the situation [3]. Collision Avoidance Manoeuvre (CAM) is one the most important mitigation approaches along with post-mission disposal; a CAM is designed if the conjunction probability of collision is greater than a certain threshold. 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, producing thousands of catalogued fragments, where no action was deemed necessary due to a predicted minimum distance of approximately 500 meters. 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 thesis, 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 relative orbit determination algorithm. The method allows to provide results directly at the nominal Time of Closest Approach (TCA), where the conjunctions are analyzed onto the B-plane and the probability of collision computed. Eventually, a ground-based sensor network is implemented to validate the onboard filter results, comparing both accuracy and computational time.

2. 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. A catalogue of possible threats is generated using the *Advanced CAT Tool* of AGI's STK, setting a default ellipsoid threshold of 20 km and an apogee-perigee filter of 30 km; the output is a list of 425 different objects, ranging from active and decommissioned satellites, to debris and rocket bodies. The sensitivity analysis is carried out between the midnight 1st to midnight 8th September 2022, with the Two-Line Element sets (TLEs) retrieved using the *ELSET Search* from Space Track. The chosen optical sensor is characterized by a limiting magnitude of 15, 30° Field of View (FoV) 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, with the apparent magnitude computed according to [5]. The target dimension information is retrieved from a 2008 catalogue covering up to approximately *Norad ID 40000*; all the remaining objects are assumed to have a normal distribution with mean and variance computed from the whole catalogue.

The simulation is carried out though SOPAC (Space Object PAss Calculator), a python library developed by *Politecnico di Milano* as the core of the SENSIT software suite, allowing to compute all the possible observation opportunities for a given sensor network. The library exploits NAIF's SPICE Toolkit for computations related to simulation geometry and TLEs for the propagation of satellites orbit with the Simplified General Perturbation model SGP4; the output is a list of windows, for each object, with the starting and ending epoch of visibility.

2.1. Sensitivity analysis

Here the sensor performance are evaluated in terms of total visibility time for all the computed windows and compared to the asset observation uniformity along its orbit. Furthermore, two additional parameters are identified as relevant for a space-based platform: non-visible objects and revisit time. 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 number of visibility windows and time, yet the considered catalogue is too limited for a significant inference.

The total visibility time is shown in Figure 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.

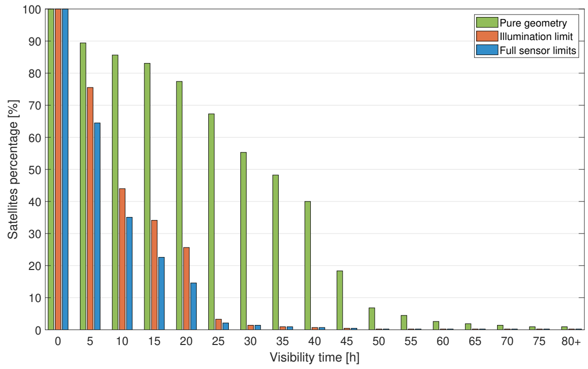

Figure 1: Total visibility time expressed in hours for three different sensor limits: pure geometry, only illumination and full sensor limits

The second relation is highlighted in Figure 2, with the total time related to RAAN and uniformity index. The latter is 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 about the quality of measurements taken for the specific target.

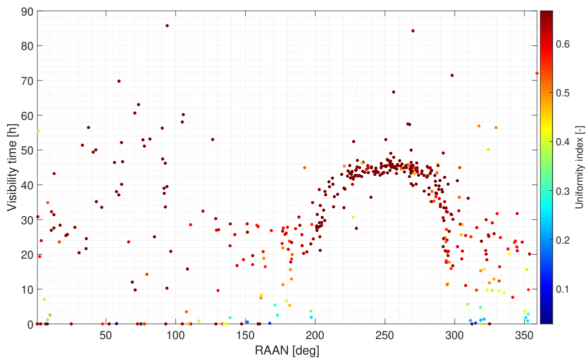

Figure 2: Total visibility time expressed in hours and RAAN as function of the uniformity index. Only the geometric constraint is applied

Objects with RAAN between 200 and 300 degrees are characterized by a higher time and higher uniformity index with no significant influence on the specific target initial conditions. This is an expected results 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 thy are strongly dependent on the initial relative position. Similar considerations can be made also for the number of visibility windows. It is worth noting that the maximum uniformity index is limited to 0.67, regardless of the type of

sensor; the reason probably lies in the geometry of this specific scenario and a longer simulation could lead to an increase of the index.
Concerning non-visible objects, Figure 3 reports RAAN and inclination of unseeing targets, with increasing sensor constraints. Out of the 43 identified 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. Concerning the inclination, no significant correlation is found, apart from the absence of objects below 50 degrees, though it may result from a lower number in the catalogue itself.

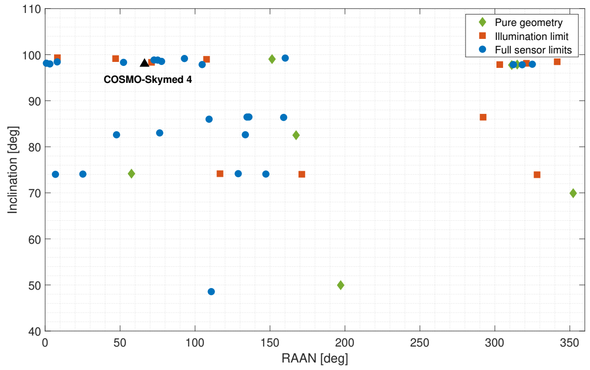

Figure 3: RAAN and inclination for non-visible objects with increasing limits: pure geometry, only illumination and full sensor limits

An important parameter when scheduling observations is the revisit time, the time between two consecutive passages. In Figure 4 the maximum and minimum revisit are highlighted as function of RAAN, with an upper limit of 3000 seconds.

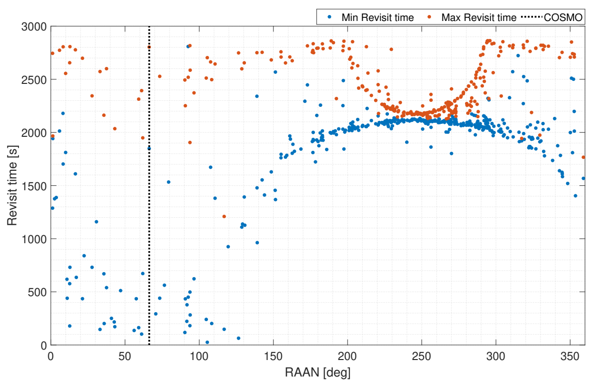

Figure 4: Maximum and minimum revisit time zoomed in. Only geometric constraint is applied

At around 250 degrees, the two values are almost coincident at approximately 2000 seconds. On the other hand, satellites with RAAN similar to the asset can reach even lower values of minimum revisit time, though they are more spread, with values of maximum time reaching up to 1 full day without observations.
Predictably, the maximum visibility range is weakly affected by the illumination requirement and close to the geometrical limit also when the specific sensor is enforced, with a few very small objects visible only when closer than 5000 km.
Considering that the asset is located in a Sun-Synchronous orbit (SSO), it is important to verify the visibility of the other objects in the same region of space. However, no significant correlation is found, apart from a lower percentage of satellites with uniformity index greater than 0.55.
Finally, the influence of Sun separation is negligible for the considered scenario and time window. In particular, the distribution of the angular distance between the Sun-asset and the asset-target vectors is rarely below 80 degrees, likely due to the observer orbital plane being almost perpendicular to the Sun direction, close to the Autumn equinox.

3. Methodology

The conjunction events are searched in the 8 days after the statistical analysis, from the 8th to the 16th September, and summarized in Table 1. In order to ensure a sufficiently high accuracy, the TLEs propagation is kept under a week by updating the set every two days, such that at least one is available for each satellite.
Measurements are simulated according to the camera frame defined above up to one day before the conjunction, such that time can be set aside for computation and scheduling of a potential CAM. The optical sensor provides right ascension and declination every 60 seconds, computed exploiting SPICE's *recrad*, to which is summed a Gaussian noise of zero mean and variance equal to the sensor accuracy squared. The latter is set at 0.01° for both measurements, to account for lower performance of an onboard sensor, as well as possible mounting errors; no cross-correlation is considered, leading to a diagonal observation error matrix.

Object	TCA	Distance [km]
Elektron 1	09/09 13:29	2.75
Falcon 1 (r/b)	09/09 20:05	0.88
Fengyun 1C (deb)	10/09 03:51	2.85
Cosmos 1408 (deb)	13/09 04:41	4.69
Fengyun 1C (deb)	14/09 01:13	4.21
Cosmos 2252 (deb)	14/09 06:45	4.89

Table 1: Identified nominal conjunction events. Acronyms *r/b* and *deb* refers respectively to *rocket body* and *debris*.

3.1. Nominal trajectory

Since the proposed filtering method is based on the linear, minimum variance Least Squares, the nominal trajectory with respect to which deviations are referred, must be computed. The propagation should be close to the real motion to ensure that the adopted filter provides sufficiently accurate results with a single iteration. Therefore, the best compromise is found bypropagating directly from the TLEs using SGP4, allowing to keep a low computational time. The contribution of the State Transition Matrix (STM) is much less sensible to inaccurate orbit modeling and a simple J2 effect can be implemented without excessively diminishing the estimation accuracy.
The B-plane is defined with the reference states at the nominal TCA, so the method here presented is strongly dependent on the *a priori* information available, since the real conjunction epoch cannot be determined, as typically done in a sequential filter.

3.2. Onboard relative orbit determination

The nominal relative motion, given by the difference between primary and secondary spacecraft states, allows to compute measurements and their deviation with respect to the real ones, computed from Python as described before. 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. This relation is showed in Equation (1).

$$\delta \boldsymbol{y} = \tilde{H}\Phi_T(t_{TCA}, t)\delta \boldsymbol{s}_{TCA} + \boldsymbol{\epsilon} \tag{1}$$

Here, $\tilde{H}$ represents the linear matrix mapping relative state and the corresponding measurement, while $\delta \boldsymbol{s}_{TCA}$ is the relative state deviation at the conjunction epoch, linked to the observation epoch by the state transition matrix $\Phi_t(t_{TCA}, t)$; $\boldsymbol{\epsilon}$ is the unknown observation error vector, to be minimized with the Least Squares method [6].
If the primary spacecraft motion is assumed to be perfectly known, then $\delta \boldsymbol{s}_{TCA}$ is equal to the target state deviation at the TCA, allowing to work in terms of absolute quantities, with Φ_t being the target STM. 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). The impact of the consider parameter, in this case the primary spacecraft state, is assessed by choosing not to estimate it, but rather use the a priori information to properly account for its uncertainty, modifying estimated state and covariance accordingly, as described in [6].
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 [2]. The probability of collision is thus computed according to the Chan formulation, truncated to the third order[1].

3.3. Ground-based analysis

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. The first two are monostatic radars, while the latter is a telescope, located in Spain and Italy respectively. The UKF is a sequential filter exploiting the Unscented Transform (UT) to predict mean and covariance of state and measurements, dropping the linear method of the Extended Kalman Filter to achieve a greater prediction accuracy, at the expense of higher computational cost. The dynamical model includes degree-two, order-two geopotential coefficients, Sun and Moon gravitational perturbations, drag and Solar Radiation Pressure. The values are tuned to produce similar results with respect to SGP4, though errors are still present and a process noise must be added to avoid divergent behaviours. Although in general it is defined at each filter step, a constant value is assumed [4]. The filter is initialized with state equal to the reference and covariance expressed in the UVW reference frame with standard deviation components $[10, 30, 10]$ m and $[0.5, 2, 0.2]$ m/s respectively.

4. Results

The results of the onboard relative orbit determination and conjunction analysis are here presented for the two closest events, involving Elektron 1 and Falcon 1 rocket body.

4.1. Elektron 1 conjunction

Launched in 1964 as part of the first multiple satellite program, Elektron 1 is a 300 kilograms decommissioned satellite, orbiting between 400 and 6000 kilometers of altitude, with an inclination of 61 degrees. In the considered time window, RAAN is about 256°, right in the middle of the high visibility region identified above. As expected, it is characterized by 122 windows with a very high visibility time of 47 hours and uniformity index of 0.67. Also the revisit time is particularly low, about 2000 seconds for the minimum and 5800 for the maximum, when all limitations are considered. Overall, a total of 786 measurments are available. The conjunction event is shown in Figure 5, computed considering the a priori state equal to the reference and standard deviation components in the UVW frame $[1, 3, 1]$ km and $[0.005, 0.02, 0.002]$ km/s respectively.

The estimated error resulting form the Least Squares is 40 meters and the square root of the covariance trace 270 m, of which 39 m are summed to take into account primary spacecraft uncertainty. The combined covariance is thus summating the computed one with the UKF result described below. Considering the miss distance of 2.75 km the probability of collision is effectively equal to zero.

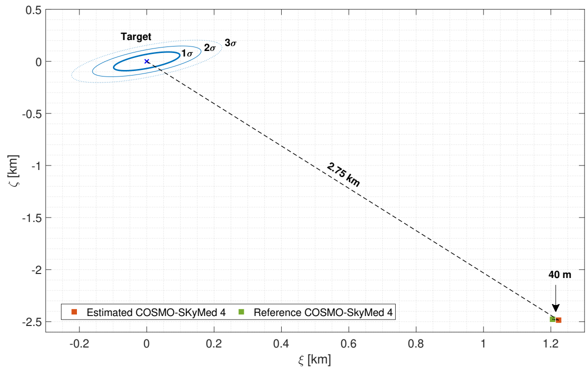

Figure 5: COSMO-SkyMed 4 and Elektron 1 projected onto the B-plane at the conjunction epoch. The combined covariance is centered at the target.

4.2. Falcon 1 conjunction

Falcon 1 upper stage from the last launch of 2009 still orbits in a quasi-equatorial orbit at 9° inclination at approximately 650 km of altitude. Although RAAN is equal to 329 degrees, the object is characterized by a higher number of windows, 165, of shorter duration, for a total time of only 16 hours. Due to the relative orbit inclination, also the uniformity index is particularly low at only 0.25; as a consequence, only 284 measurements are processed. Nevertheless, the revisit time is still ranging between 2000 and 5500 seconds.

As highlighted in Figure 6, the estimated error is only 23 m, with a covariance of 76 m computed from the Least Squares, and 120 m added from the CCA, with the same a priori information of Elektron 1. Once again, the probability of collision is equal to zero, though the miss distance is now much closer, at 871 meters.

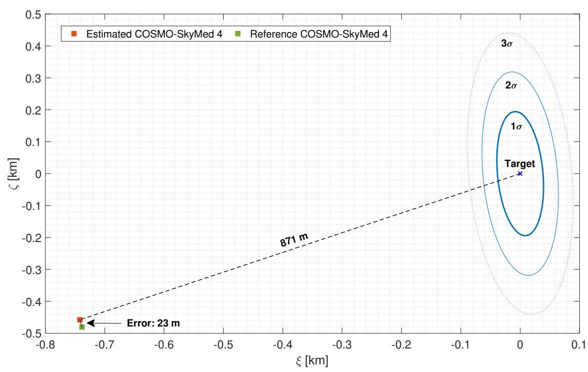

Figure 6: COSMO-SkyMed 4 and Falcon 1 projected onto the B-plane at the conjunction epoch. The combined covariance is centered at the target.

4.3. Ground-based analysis and comparison

The ground-based analysis is performed for all the three objects involved. Considering a minimum elevation of 20 degrees for all the stations, Falcon 1 cannot be observed and a fourth sensor, identical to S3TSR, is located in French Guyana for this specific case only.

In Figure 7, the square root of the covariance trace and the positional error are plotted for the asset spacecraft, though similar trends are identified also for the other two objects.

The final values are 33 and 23 meters respectively for COSMO, 27 and 22 for the Elektron and 110 and 120 for Falcon 1. The latter results lies in correspondence of a spike, though the steady-state values are actually comparable to the asset.

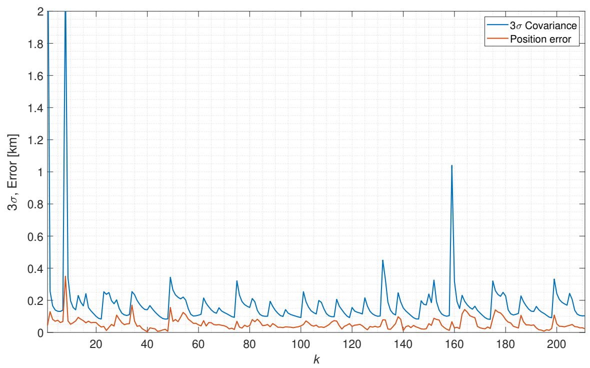

Figure 7: Covariance and error for COSMO-SkyMed 4 function of the processed measurements. The former is expressed in terms of 3σ, where σ is the square root of the trace of the positional component only.

As expected, the UKF results are slightly better, especially in terms of covariance; however, the difference in computational time is considerable, with the Least Squares providing results in few seconds, while the ground-based analysis requires at least 30 minutes, depending on the amount of measurements. 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. The estimation accuracy reaches the final value when approximately half of the available windows are processed, allowing more time for mission related tasks or CAM design. Nevertheless, the Least Squares requires accurate reference trajectory propagation for consistent results; multiple iterations may be required if smaller errors are needed.

5. 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. Elektron 1 results were slightly worse, probably due to lower accuracy of J2-propagated STM when dealing with low perigee and high eccentricity orbit. 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 autonomous initial orbit determination and threat detection, allowing to reduce the burden on ground infrastructure and improve the sustainability of human activities in space.

References

[1] F Kenneth Chan et al. *Spacecraft collision probability*. Aerospace Press El Segundo, CA, 2008.

[2] Andrea De Vittori, Maria Francesca Palermo, Pierluigi Di Lizia, and Roberto Armellin. Low-thrust collision avoidance maneuver optimization. *Journal of Guidance, Control, and Dynamics*, 45(10):1815–1829, 2022.

[3] ESA. *ESA's Space Environment Report*. Techincal Report, ESA, 2022.

[4] Eduard Gamper, Christopher Kebschull, and Enrico Stoll. Statistical orbit determination using the ensemble kalman filter. *Acta Astronaut*, pages 22–24, 2018.

[5] Alessandro Morselli. High order methods for space situational awareness. 2014.

[6] Bob Schutz, Byron Tapley, and George H Born. *Statistical orbit determination*. Elsevier, 2004.