DOI: 10.13009/EUCASS2022-4507
9TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Analysis of conjunctions between two satellites with no communication

Romain Lucken⋆† *and Alexis Petit*⋆
and Sacha Redel and Florent Deleflie
and Emanuel Ramirez and Jesus Salgado and Maria Ramirez

⋆*Share My Space*
32 Boulevard du Port, 95032 Cergy-Pontoise, France

Observatoire de Paris, Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE)
UMR CNRS 8028, 77 Av Denfert Rochereau, 75014, France

Quasar Science Resources
C/Faraday 7, P1, D1.6d, 28049 Cantoblanco, Madrid, Spain

romain.lucken@sharemyspace.space · alexis.lucken@sharemyspace.space
sacha.redel@obspm.fr · florent.deleflie@obspm.fr
emanuel.ramirez@quasarsr.com · jesus.salgado@quasarsr.com · maria.ramirez@quasarsr.com
†Corresponding author

Abstract

Space traffic management is becoming increasingly more complex with the growing number of maneoeuvring satellites particularly in low Earth Orbit (LEO) due to the race for large constellations of communication satellites. One of the major challenges for CNES[1] and the EU SST[2] specifically is the analysis of the collision risk when a conjunction that involves one of these satellites is scheduled. Sample analysis showed that about 40% of the close approach conjunctions with active satellites involve a secondary object with some manoeuvre capability, while this figure was rather below 10% a few years ago. This evolution is partially due to the deployment of more than 2,000 Starlink satellites over 2020 and 2021. In some cases, satellite operators can share their ephemerides and coordinate their actions to minimize the collision risk. However, in most cases, the behavior of the secondary object is unknown. The purpose of this work is to identify patterns of life of the secondary object to reduce the risk of collision.

A conjunction is mainly characterised by a time of closest approach (TCA), a miss distance, a relative velocity, and uncertainty in position at TCA which allows to compute a probability of collision. Recent studies discussed the realism of uncertainties and proposed solutions to reassess the collision risk.[3–5] These works impact the decision making process that precedes a collision avoidance manoeuvre. However, if a manoeuvre is performed by the secondary satellite between the prediction date and the TCA, the risk assessment can turn out to be inaccurate. More importantly, some dangerous events can also be missed or detected just a few hours before TCA. In general, the whole process of orbit fitting and trajectory forecast becomes inaccurate when the secondary objects performs regular frequent station-keeping manoeuvres.

To tackle this issue, secondary objects with manoeuvre capability are treated separately from the passive objects. First, a list of such objects is maintained on a daily basis using satellite databases. Secondly, the two-line elements (TLE) data of these objects is analyzed to determine how often station keeping manoeuvres are realized. This step is based on filtered differences on the orbital elements[6] and yields a first time interval where each manoeuvre occurred, as well as an estimate of the manoeuvre Delta-V. Then, an estimate of the thrust capability and thrust direction of the secondary satellite is determined using a method based on forward and backward orbit propagation of the special perturbation (SP) orbital data from the US Air Force. The uncertainty on the object position comes mainly from the uncertainty related to the time and duration of the manoeuvres, and the Gaussian assumption is not valid anymore. Hence, we define an exclusion volume at each date whose bounds are defined by the extreme manoeuvre scenarios that would be possible for the secondary satellite. In order to avoid a collision, the primary satellite should keep out

DOI: 10.13009/EUCASS2022-4507

of this exclusion volume, at any epoch. In this paper, we describe each of these methods in details and present simulation results for a limited set of primary objects in LEO.

1. Introduction

Nowadays, the automation of the collision risk management is not possible because of blocking points due to the necessity of human interventions. A general framework for communication between operators does not exist although it is crucial for decision making, and to predict the intention of the secondary satellite to perform or not a manoeuvres before the time of closest approach (TCA) of a conjunction.

In this paper we describe the Share My Space's work to improve the process of collision risk management. These results were obtained in the framework of the EUSST. A consortium including Share My Space, the Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE) and Quasar Science Resources, was mandated by the Centre National d'Études Spatiales (CNES) to study blocking points for space traffic management automation and to propose a simulator of such a system to this end. The goal is to identify the performance of this aforementioned system regarding assumptions like priority rules or the success of algorithms to converge towards the best solution.

In Section 2 two algorithms to characterise the manoeuvre capacity of a satellite from historical state vectors are provided. They are used to build a database of historical manoeuvres whose purpose is to find pattern-of-life for manoeuvre prediction. In Section 3, a simulator of collision risk management based on a decision tree is described with the processing of historical CDM of the satellite SMOS as application case. Finally in Section 4, we draw some conclusions.

2. Characterisation of the secondary object

2.1 Diversity of the missions

The number of active satellites has significantly increased these last years with the diversification of missions and propulsion modes. It is common to see a large batch of satellite injected in a same orbital plane at low altitude followed by a phase of orbit raising over several months before reaching their nominal orbit. At the end of their life, they are decommissioned and again, their perigee is lowered to lead to a reentry, however crossing a large range of orbits. During the operational phase of the mission, satellites perform station-keeping manoeuvres to maintain a nominal altitude or right ascension of the ascending node which drifts naturally due to external forces like atmospheric drag or Earth oblateness. In GEO, control of the longitude position and inclination is also required by manoeuvre of station-keeping. For satellites using chemical propulsion, manoeuvres are sparse twice a month in GEO, less in LEO, but for the new generation of satellites using station keeping, several manoeuvres per day are expected.

Characterisation of pattern-of-life for satellites, i.e. the knowledge of their manoeuvre planning over time, is crucial for the collision risk management. An unexpected manoeuvre occuring before the time of closest approach leads to wrong computation of the ephemeride of the secondary object, and consequently to a wrong assessment of the collision probability.

Several sources of data are available to extract historical manoeuvres. Two are provided by the 18th Space Defense Squadron (SDS):

- Two-line element (TLE) sets are public data available through the 18 SDS plaform (www.space-track.org), and they contain mean orbital elements of an object in the TEME frame. The TLE are in the public domain and their accuracy is limited. They are provided for about 22,000 non-classified objects by the US Air Force, and updated at a variable rate, typically 12 hours.

- SP vectors are generated by 18 SDS using the Special Perturbation theory and contain osculating elements of an orbiting object. The positions and velocities of the objects are given in TEME frame and generated once a day. The state vector epoch can vary from an object to another.

From this data, we propose to extract following manoeuvres:

- Hohmann transfert and station-keeping: changes in longitude, semi-major axis or inclination.

- Electrical orbit raising, decommissioning: long term change in semi-major axis.

DOI: 10.13009/EUCASS2022-4507

2.2 Manoeuvre extraction from TLE

2.2.1 Method

Kelecy et al.[6] proposed to detect orbital manoeuvres by time series analysis of mainly three orbital elements: the semi-major axis a, the inclination i, and the eccentricity e. Let X be one of these 3 orbital elements. The TLE contain a series of data $(X_1, X_2, ..., X_i, ..., X_n)$ at epochs $(t_1, t_2, ..., t_i, ..., t_n)$. The filtered differences used for manoeuvre detection are estimated at the epochs $(t_{i+1/2})_{i<n}$ defined by

$$t_{i+1/2} = \frac{t_i + t_{i+1}}{2} \tag{1}$$

for each time step $i + 1/2$, we define left and right regression polynomials $L_{i+1/2}$ and $R_{i+1/2}$ on a number of points N_L and N_R with degrees d_L and d_R respectively. More precisely:

- $L_{i+1/2}(t)$ is the polynomial of degree d_L that fits t_k with X_k for $i - N_L + 1 \leq k \leq i$.
- $R_{i+1/2}(t)$ is the polynomial of degree d_R that fits t_k with X_k for $i + 1 \leq k \leq i + N_R$.

The degrees used by Kelecy are $d_L = 0$ (local average) or $d_R = 1$ (linear regression) and the amount of data used is $N_L = 5$ and $N_R = 6$. Therefore, the method rather consists in a regression than an interpolation. The filtered difference is then:

$$\Delta_{i+1/2} = R(t_{i+1/2}) - L(t_{i+1/2}) \tag{2}$$

The standard method proposed by Kelecy is to assume that manoeuvres are detected when $\Delta_{i+1/2}$ is greater than a certain threshold value which is proportional to the standard deviation of the $(\Delta_{i+1/2})$ time series over the considered time interval σ. The time interval is the full period of interest for manoeuvre detection, between a few months and a few years. Typically, the threshold value is taken at 3σ. Kelecy already noticed that there was no universal threshold value and that there could be either many false detections if the threshold was too low or many missed events if the threshold value was too high. **The original idea that we developed was to relate the value of the thresholds to higher moments of the distribution of the $(\Delta_{i+1/2})$ series.**
Instead of using always 3σ as threshold value, we use $c_{crit}\sigma$, where c_{crit} is defined by the statistical moments of the distributions of these series.

2.2.2 Detection results

In order to test MANEXT TLE performance, the 31 LEO and 31 GEO satellites for which we had reference manoeuvres have been tested separately. We define the score as the ratio between the number of correct detections and the total number of samples:[1]

$$SCORE = \frac{TP + TN}{TP + TN + FP + FN} \tag{3}$$

The confusion matrices results for LEO and GEO satellites are presented in Figure 1. The trend is that the score of detection increases when the manoeuvre frequency decreases. The high score of detection obtained for one satellite comes mainly from the fact that when no manoeuvre occurred for a given TLE sample, it is correctly predicted by the algorithm. In other words, the number of true negatives (TN) is high. However, the ratio of detected manoeuvres among the real manoeuvres is not always very good (sometimes below 50%). This is partially due to delay in the TLE: the peak observed in the time series of the filtered differences is shifted with respect to the manoeuvres. This time shift effect also causes false positives. In some cases, false positives also come from mere errors in the TLEs that are difficult to detect a priori.

2.3 Manoeuvre extraction from SP vectors

2.3.1 Method

The MANEXT SP algorithm is based on two main processes: manoeuvre detection and characterisation. The algorithm takes as input osculating elements at epoch given by either SP vectors, SP ephemeride or optical observations and generates temporal windows. These windows are defined as the time interval between two consecutives orbital element sets. For a given set of SP vectors $\{SP_1, SP_2, ..., SP_n\}$, the detection process performs the computation of a metric δ associated to each temporal window. For a given pair $\{SP_i, SP_{i+1}\}$, the metric is calculated by Eq 4, with

[1] TP=True positives, TN=True negatives, FP=False positives, FN=False negatives.

DOI: 10.13009/EUCASS2022-4507

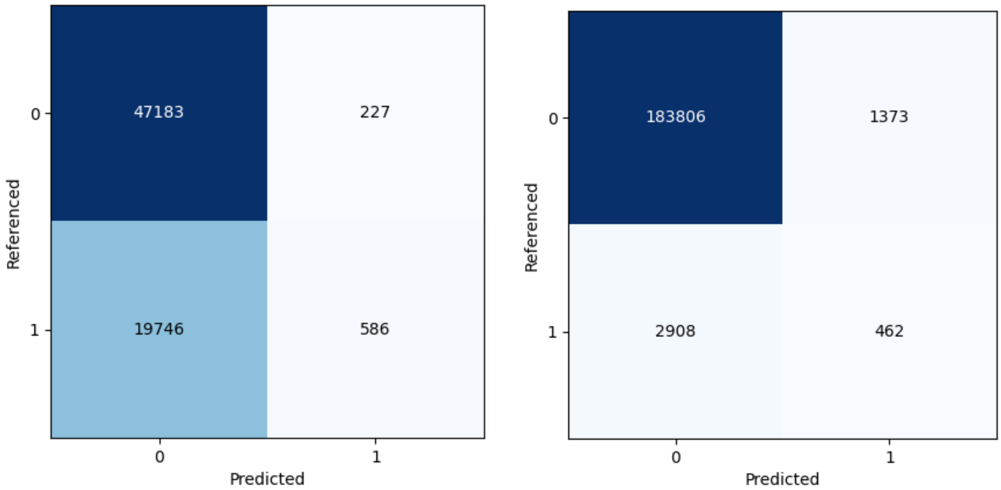

Figure 1: Global confusion matrices for LEO (31) and GEO (31) satellites of interest.

$(x_{i+1}^{ref}, y_{i+1}^{ref}, z_{i+1}^{ref})$ the position vector given by SP_{i+1} and $(x_i^{prop}, y_i^{prop}, z_i^{prop})$ the position vector of the state at epoch t_{i+1} propagated from the initial conditions given by SP_i.

$$\delta_i = \sqrt{(x_{i+1}^{ref} - x_i^{prop})^2 + (y_{i+1}^{ref} - y_i^{prop})^2 + (z_{i+1}^{ref} - z_i^{prop})^2)} \tag{4}$$

Each metric gives an indication on the relative distance between a real observation (second state) and a propagated state which should match approximately, taking into account the propagation error, the real observation if no manoeuvre was performed in the temporal window. From the set of calculated metrics $\delta = (\delta_0, \delta_1, ..., \delta_{n-1})$, outliers detection can be performed using a fixed threshold σ defined as the standard deviation of the metric distribution. A temporal window is considered as manoeuvred if $\delta_i > \sigma$.

Then the characterisation process can be applied on each manoeuvred temporal window and result(s) in the estimation of the epoch, the direction and the magnitude of the manoeuvre. For a given temporal window $\{\mathrm{SP}_i, \mathrm{SP}_{i+1}\}$, the two states are cross-propagated to generate a pre- and post-ephemeride. The equations of motion are integrated numerically with high fidelity force models to have an accurate estimation of the manoeuvre parameters. The TCA and the minimum relative distance at TCA or miss-distance, are computed from the two ephemerides using a linear algebra method called Conjunction Assessment. Through Chebyshev Polynomials (CATCH).[7] The TCA corresponds to the epoch of the manoeuvre and the delta-V and direction are estimated by projecting the velocity vector of one of the two states at TCA in the local orbital frame (TNW) defined by the other at TCA. Finally, the extraction process ends by storing the parameters of the detected manoeuvres in a database which will be used by the SST system.

2.3.2 Detection results

The results of the detection of manoeuvres based on SP data are presented in this section for 17 LEO and 24 GEO satellites. As the historical SP data was available only from 2018 a less number of reference manoeuvres have been analyzed compared to the TLE method. The confusion matrices for the two orbital regimes are presented in Figure 2. The overall score of detection for LEO satellites reaches 97.3%. According to the confusion matrix, when no manoeuvre occurs during the time span between two SP vectors, the algorithm is able to well characterize the temporal windows as it does not have difficulties to correctly propagate the trajectories. When a manoeuvre is detected, it is correct about 60% of the time. However, Sentinel-1A and Sentinel-1B contribute for more than a half in the false detections. If we remove these two satellites, we see that the precision of the algorithm reaches 80%. For GEO, the mean score of detection is around 63%, which is lesser than the one obtained with LEO satellites. However, this score is largely lowered by some satellites for which the score of detection is below 20%. We see that the highest detection scores are obtained when the satellite performs 1 or 2 manoeuvres each month. This is the case of the METEOSAT fleet or some of the INMARSAT fleet (3rd generation) with chemical propulsion. Conversely, the worst scores are mostly obtained by satellites with a high number of manoeuvres performed each month. SES 4 and all the INMARSAT 5 satellites have a score below 20% which are mostly due to the high frequency and not only to the type of propulsion as SES 4 has chemical propulsion and INMARSAT 5 fleet all have electrical propulsion. Although a lot of manoeuvres are missed

DOI: 10.13009/EUCASS2022-4507

by the algorithm for these satellites, there are not a high number of false positive. Accordingly, the algorithm is correct about 90% of the time when a manoeuvre is detected.

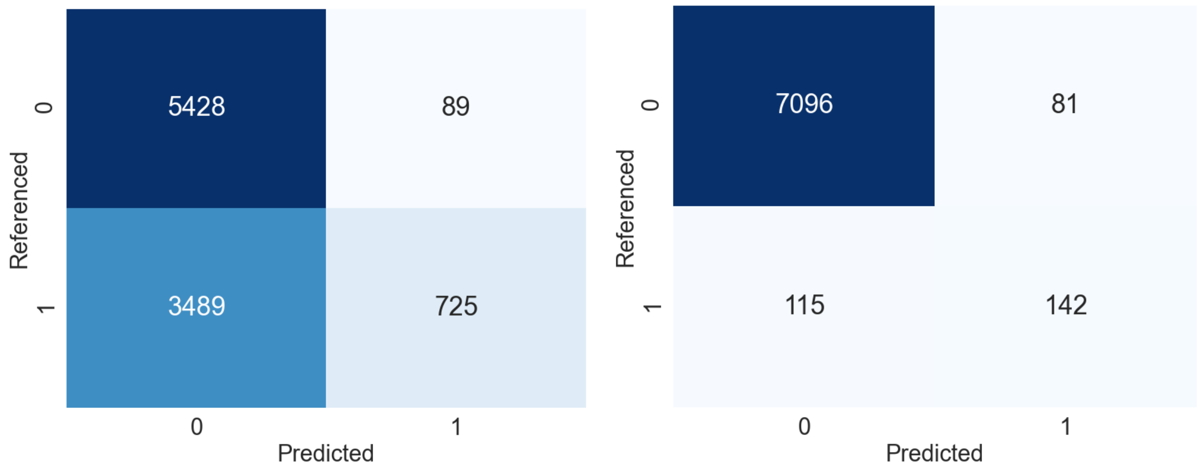

Figure 2: Global confusion matrices for LEO (17) and GEO (24) satellites of interest.

3. Automated collision risk management

3.1 Decision tree

Increasingly more CDM are received by satellite operators or Middle Man services like CARA and CAESAR respectively in the US and France.[1] They have to deal with thousands of CDM on a daily basis, assessing the collision probability, and designing collision avoidance manoeuvres if required. The large fleets of satellites and the intensification of the space traffic will exacerbate this trend.

In order to investigate how an automated process can deal with this flow, a simulator has been implemented based on a decision tree composed of 3 main blocs. The first one proceeds with the reading and storage of the CDM file and provides a first insight of the collision risk. The second one is related to the classification of the secondary object and to the prediction of a potential manoeuvre. The third one performs the design of multiple collision avoidance manoeuvre scenarios (CAM) to mitigtate the risk.

3.1.1 CDM reading and risk assessment

The first step of the decision tree is described by the Figure 3. It reads the CDM file and performs a first assessment of the collision risk. The CDM is checked to be sure the information is relevant (state vectors and covariances). If an ephemeride of the primary object is available (for example an ephemeride operator obtained using GNSS measurement) the CDM is recomputed by performing a screening one versus all. If a conjunction is returned by the new screening, the CDM associated is taken as reference, otherwise it is the received CDM. If the received CDM is not taken as reference, the O/O and the CA provider are notified.

Using data relative to the shape of the objects which are stored in the database, collision risk is assessed by computing the maximal collision probability (PoC^*). If less than four CDMs have been received, the maximal collision probability is computed with a brute force method (interval of dilution [0.25, 4]). Otherwise, a statistical approach based on the Mahalanobis distance is used. If the PoC^* is below a threshold PoC_1, the conjunction is discarded, otherwive the O/O is notified and we continue to progress in the decision tree. Simultaneously, the simulator keeps track of the CDM relevant information by storing it in a database.

3.2 Classification of the secondary object

If the secondary satellite is able to perform manoeuvre the situation becomes more complex because its predicted trajectory can be inaccurate. In the worst case, if both satellites move without coordination, it could lead to an increased risk and a potential catastrophic collision. A coordination with the operator of the secondary object can sometimes fail. Moreover, it requires human action which can be time consuming. In Figure 4, the second bloc is described. An

DOI: 10.13009/EUCASS2022-4507

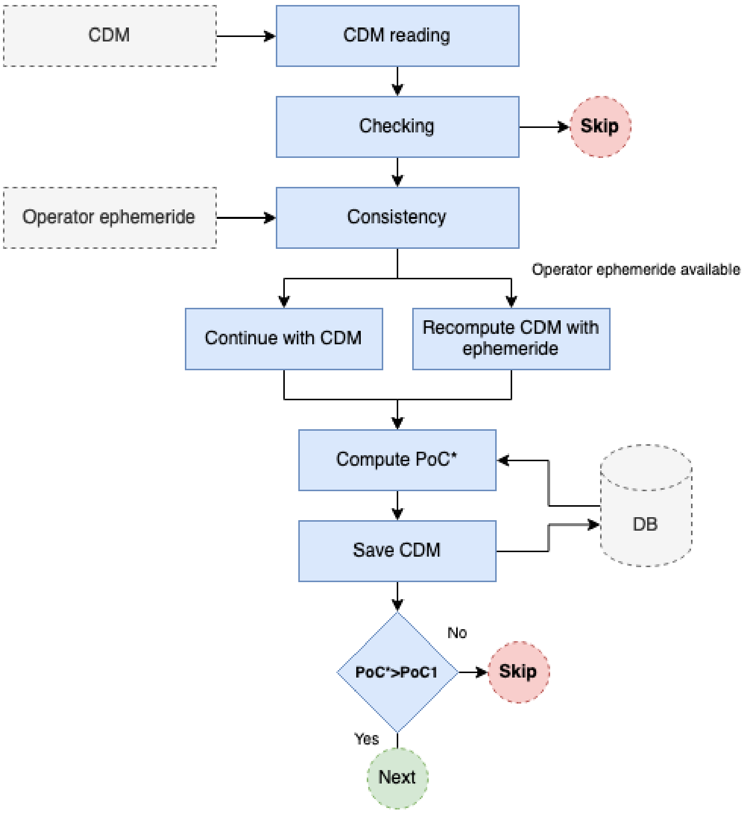

Figure 3: The first bloc of the decision tree read a CDM and compute the maximal collision probability. If the maximal collision probability is above a given threshold, the process goes to the next bloc.

automated process is proposed to characterise the secondary object using historical data leading to a knowledge of its capacity to perform manoeuvres, and in the best case to anticipate the next manoeuvres if a pattern-of-life is reliable.

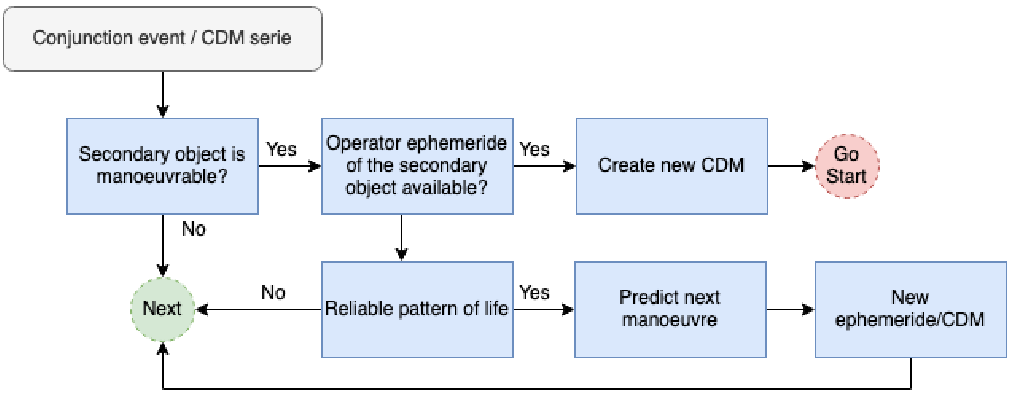

Figure 4: The second bloc of the decision tree characterises the manoeuvre capacity of the secondary object involved in the conjunction. If a reliable pattern-of-life is available in the database, a future manoeuvre before TCA can be anticipated.

The pattern-of-life allows to estimate the date of the future manoeuvre and the characteristics of the manoeuvres (in-plane, out-of-plane, magnitude). If a reliable pattern-of-life is available and the date of the predicted manoeuvre is before the TCA, a new ephemeride is computed propagating the orbit and including the expected manoeuvre. This ephemeride will be used in the next bloc to exclude manoeuvre scenarios.

DOI: 10.13009/EUCASS2022-4507

3.2.1 Collision avoidance manoeuvre

In an operational framework, one has to define priority rules to regulate space traffic. Considering two objects, the priority and thus the decision to manoeuvre belongs to the satellite that has propulsion capacity if the other doesn't have any. If both are able to manoeuvre, priority rules become more complex.

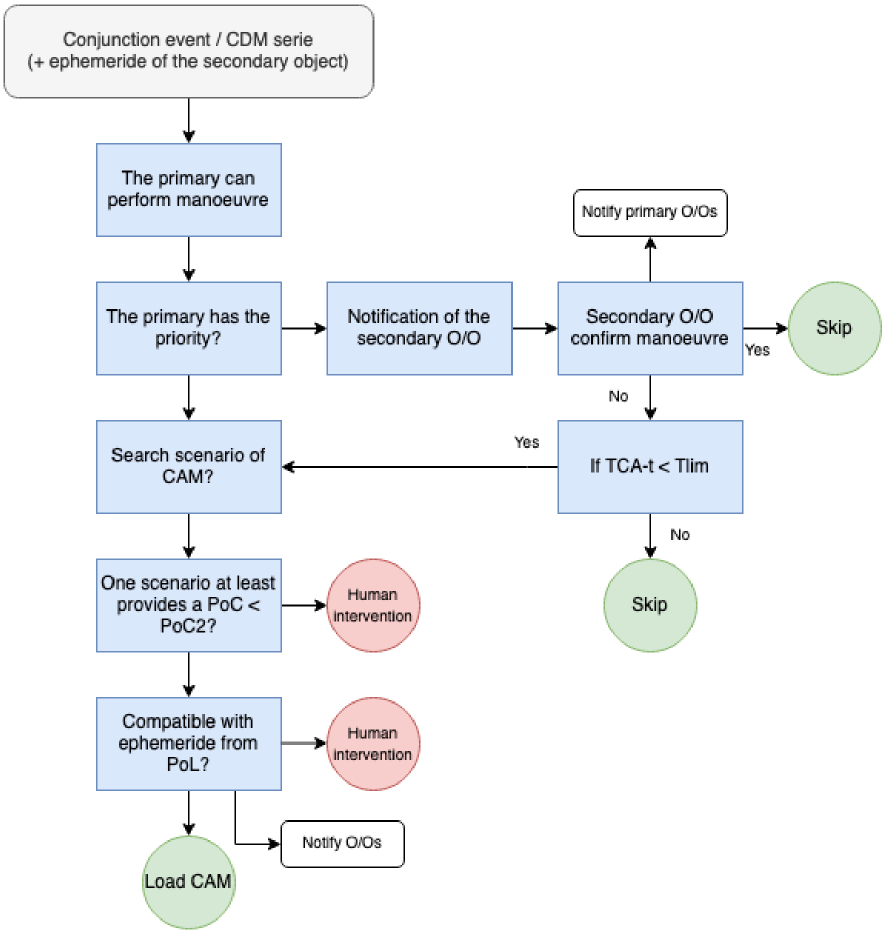

Figure 5: The third bloc of the decision tree deals with the priority rules and searches the collision avoidance manoeuvres that reduce the collision probability.

The priority rules for STM system will be defined in the future to prevent problematic cases as for example experimented by ESA and Space X in 2019[2]. In the simulator, a priority of the primary or the secondary is an option in the configuration file, but module given the priority following rules can be implemented.

If the primary object must perform manoeuvre, pre-defined CAM scenarios will be computed. A scenario is defined by the type of manoeuvre (tangential or radial), the magnitude of the ΔV, the time before TCA. The date of the manoeuvre before TCA is counted in a odd number of half-period and the ΔV should lead to a radial separation of 100 m. If no manoeuvre reducing the risk is found, a human intervention is required. Moreover, if the secondary object is able to manoeuvre, and if a reliable pattern-of-life allows to predict a manoeuvre before TCA, then the virtual ephemeride provided by the bloc 2 has to be considered for the conjunction assessment. The decision to proceed with a CAM is taken several hours before TCA (it depends on the communication capacity). Before the deadline, next CDM are expected to update the decision. If the priority rule leads the secondary object to perform a manoeuvre, notification towards the owner/operator is sent, and a confirmation of the decision to manoeuvre is expected. Past a given delay without answer, the primary executes the CAM.

[2]https://www.esa.int/Safety$_{S}ecurity/ESA_{s}pacecraft_{d}odges_{l}arge_{c}onstellation$

DOI: 10.13009/EUCASS2022-4507

3.3 Simulator of a SST system

The decision tree is implemented in a simulator processing historical CDM respecting the timeline of the conjunction events, i.e. the CDM are processed following a chronological order in a similar way to the operations. In Figure 6, the flowchart of the simulator is described. The choice of CDM series (ID of the primary satellite, the considered period of time) is done with the help of an indexation table. Parameters are provided by a configuration file. The simulator is connected to a database containing catalog objects (name, Norad ID, Cospar), data relative to operators/owners for each satellite, mass and dimension of each satellite, and during the processing, CDM will be stored. The simulator reads each CDM and processes them following the decision tree described previously. For each action taken, or output of the decision tree, an entry in a log file is created. A script of post-processing will extract statistical information from the log file to build a metric about the automation as described in the next subsection.

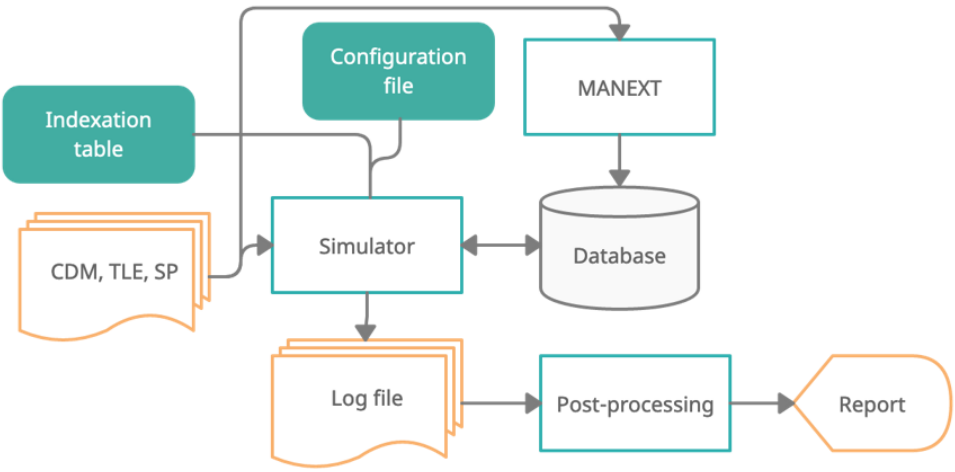

Figure 6: Flowchart of the simulator dealing with CDM to assess conjunction risk and make the decision to perform a manoeuvre or not. The simulator interacts with a database of space objects data in particular a table of historical manoeuvres and pattern-of-life computed with the MANEXT tool.

3.4 Application case

Historical CDM can be processed by the simulator. The CNES provided to Share My Space a set of CDM for the LEO satellite SMOS (36036). Information on its orbit is given in Table 1.

Elements	Value
Altitude [km]	763.439
Eccentricity	0.00086
Inclination (deg)	98.438
RAAN (deg)	103.811
Argument of perigee (deg)	94.638

Table 1: Orbital elements of SMOS

As the satellite is orbiting in a high object density region, the period intervals studied have been reduced to 5 months from 2021-01-01 to 2021-05-31. Due to its orbit, SMOS has the highest number of conjunction events therefore it is involved in a lot of CDM. Hence, a filter has been applied to only account for conjunctions with a miss distance lesser than 5 km. Using this filter still leads to 312 events with 7541 CDM to process for this period. The distributions of the miss distances and of the PoC* are given in Figure 7. During this period, 11 events, with 84 CDMs, have a PoC* above the standard threshold of 1.10â4 thus leading to a CAM design. These events have been analysed more closely to output metrics resulting from the autonomous system. The Figure 8 shows the number of CAM design and the number of CAM design automatically computed, the number of human actions required, the number of CAM finally planned and uploaded. The reason for human action requirement is the failure of the implemented algorithm to find a CAM reducing the risk below the safety threshold. It shows the critical aspect of this feature for automation process.

DOI: 10.13009/EUCASS2022-4507

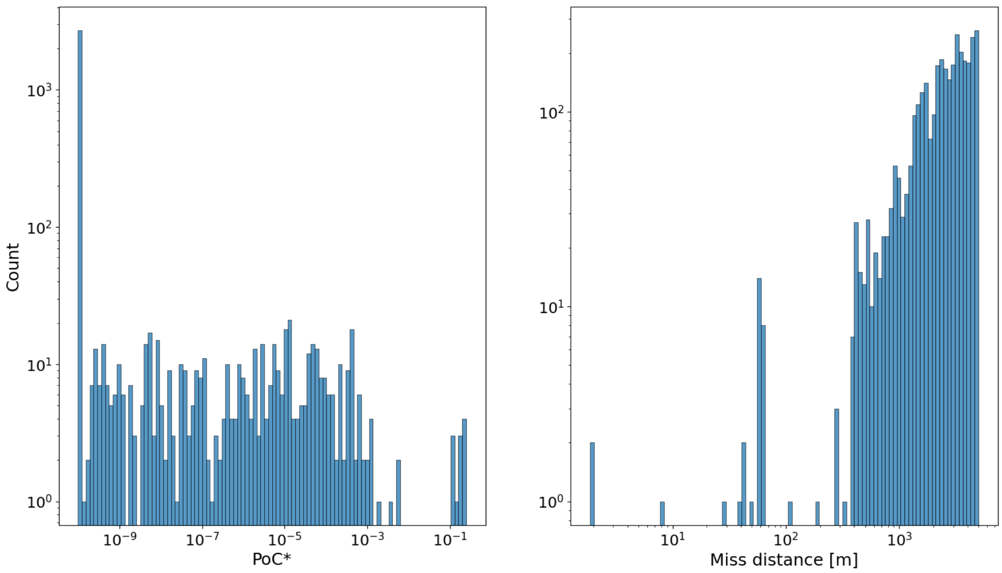

Figure 7: Distribution of the PoC* and miss distance of the conjunctions of SMOS between 2021-01-01 to 2021-05-31.

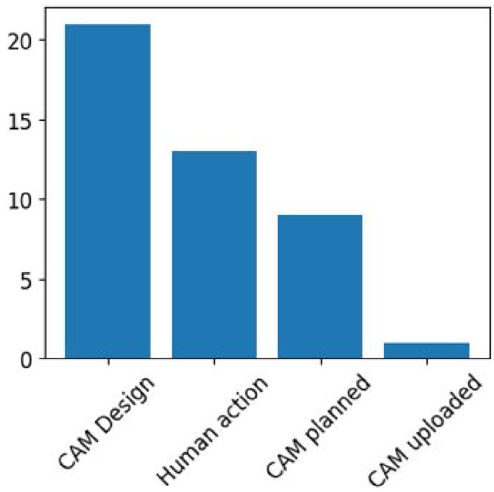

Figure 8: Number of actions related to collision avoidance manoeuvres simulated for SMOS using chemical propulsion.

4. Conlusions

The consortium led by Share My Space has developed new tools for collision risk management particularly based on the characterisation of the manoeuvring capacity of the secondary object involved in a conjunction. The purpose is to anticipate manoeuvres to avoid human intervention in case of failure with communication between operators. The detection of historical manoeuvres was demonstrated with historical TLE series and SP vectors series. The first one is well-known to contain large uncertainties and is not suited to detect manoeuvres of low order of magnitude. But the algorithm is fast and well suited for high thrust (chemical) manoeuvre detection like station-keeping, longitude change, or orbit raising. The use of SP vectors gives an accuracy able to determine the epoch, direction, and magnitude of the manoeuvre. However, only one SP vector is available per day and if more than one manoeuvre occurs then, it is not well detected. A solution will be to include additional data like optical measurements.

The database of historical manoeuvres is used by a simulator of space traffic management developed in this study. A decision tree was drawn and implemented to show how the anticipation of a manoeuvre by the secondary object using reliable pattern-of-life can be helpful to design collision avoidance manoeuvres if communication between operators failed. More effort has to be done to predict manoeuvre with a high level of confidence, for example by including automatic observation requests of the secondary object before TCA.

DOI: 10.13009/EUCASS2022-4507

5. Acknowledgments

The EU SST activities have received funding from the European Union programmes, notably from the Horizon 2020 research and innovation programme under grant agreements No 952852, No 785257, No 760459, No 713630 and No 713762, and the Copernicus and Galileo programme under grant agreements No 299/G/GRO/COPE/19/11109, No 237/G/GRO/COPE/16/8935 and No 203/G/GRO/COPE/15/7987.

References

[1] M Moury and L Newman. Middle man concept for in-orbit collision risk mitigation: Caesar and cara examples. In *SpaceOps 2014 Conference*, page 1637, 2014.

[2] P Faucher, R Peldszus, and A Gravier. Operational space surveillance and tracking in europe. *Journal of Space Safety Engineering*, 7(3):420–425, 2020.

[3] M D Hejduk and L C Johnson. Approaches to evaluating probability of collision uncertainty. *NASA Technical Reports (Presentation)*, 2016.

[4] S Laurens, P Seimandi, J Couetdic, and JC Dolado. Covariance matrix uncertainty analysis and correction. In *68th International Astronautical Congress*, 2017.

[5] A B Poore, J M Aristoff, Joshua T Horwood, R Armellin, William T Cerven, Y Cheng, C M Cox, R S Erwin, J H Frisbee, M D Hejduk, et al. Covariance and uncertainty realism in space surveillance and tracking. Technical report, Numerica Corporation Fort Collins United States, 2016.

[6] T. Kelecy and K. Hamada. Satellite maneuver detection using tow-line element (tle) data. In *AMOS*, 2007.

[7] Elad Denenberg. Satellite closest approach calculation through chebyshev proxy polynomials. *Acta Astronautica*, 170:55–65, 2020.