Low-thrust strategies and implications in the perspective of space debris mitigation for large constellations

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Abstract

The planned future generation of large constellations of satellites in orbit around the Earth considers the application of low-thrust devices for the various phases of the mission. This choice is mainly due to the advantage of reducing the launch mass, possibly increasing the payload mass, while keeping advanced maneuvering capabilities.

The aim of this work is to address the operational aspects and the implications related to the collision avoidance during the whole lifecycle of a satellite. We focus on the existing proposals for large constellations, taking as study cases the OneWeb constellation located at 1200 km of altitude and the Starlink constellation located at 550 km of altitude. We develop a software suite to generate realistic conjunction events between a satellite of the given constellation and the space debris environment, considering the orbit raising, the operational phase and the decommissioning phase of the mission. In case of a collision risk above a well-defined threshold, we fit the best parameters (orientation, and thrust duration) defining a collision avoidance with a low-thrust. The final goal is to provide the main features expected for the collision avoidance maneuvers of the proposed future missions.

1 INTRODUCTION

Since a few years the space traffic is drastically increasing. The popularity of smallsats (satellites with a mass lower than 500 kg) and the reduction in the launch cost allow a wider number of entities, in the institutional and private sectors, to deploy satellites or constellation of satellites, leading to a complex management of the space traffic. In particular, the large constellations of satellites, involving several hundreds and even thousands of satellites, exacerbate the difficulties. The most important threat is the risk of collision between functional satellites and space debris, but also among satellites of different operators.

The deployment of the large constellations has already started at the beginning of the year, with the launch of 10 satellites of the OneWeb constellation on-board of a Soyuz on February 27, 2019, and the launch of 60 satellites of the Starlink constellation on-board of a Falcon 9 on May 24, 2019. Space X envisages to deploy 400 satellites before May 2020, and 1584 in total before 2024. Hence, the space traffic is already increasing with unprecedented consequences. The orbit injection of the group of OneWeb satellites was performed at 1000 km of altitude and they have not crossed regions of high density (mainly located at 800 km of altitude). It was different for the group of Starlink satellites injected at 440 km and aimed to reach an operational altitude of 550 km. A satellite has already experienced a close approach with the ESA’s satellite Aeolus on Monday, 2 September, 2019\textsuperscript{1}.

In this context, it appears that the number of close approaches with a high collision risk will continuously increase and new strategies have to be developed for collision avoidance. Each maneuver implies a cost in propellant, thus reducing the orbital life of the satellite, but a collision could threat all future space activities for every space actors. Here, we will investigate the

\textsuperscript{1} https://www.esa.int/Our_Activities/Space_Safety/ESA_spacecraft_dodges_large_constellation
collision risk for the OneWeb and the Starlink constellations and we will suggest the optimal maneuver associated.

The collision avoidance maneuvers (CAM) are planned by the operator after an assessment of the risk, on the basis of the Conjunction Data Message (CDM) provided by the US 18th Space Control Squadron. Such message contains the dynamical state vectors of both objects involved, the covariance matrices, the time of closest approach, and the miss distance. Then, when a satellite operator is warned of a conjunction, it assesses the collision risk and decides whether to apply a CAM [1]. We propose to simulate similar data, to assess the collision risk, and the number of CAM needed, and the characteristics of the CAM expected during the complete satellite mission.

First, in Section 2 we introduce a software based on the CUBE algorithm to assess the long-term collision risk of a OneWeb and a Starlink satellite with the background environment of space debris. The same software provides individual close approach events which are analyzed. In Section 3 we propose to apply a heuristic algorithm fitting the CAM reducing the collision risk. Finally, in Section 4 we draw some conclusions.

2 THE COLLISION RISK INSIDE LARGE SATELLITE CONSTELLATIONS

Long-term collision risk

We are interested in the risk assessment for constellations with different configurations in term of altitude, inclination, total number of satellites, and number of orbital planes. We developed a software based on the CUBE algorithm developed at NASA/JSC [2].

Our software detects close approaches between a satellite and the background population of space debris, which is produced by evolving in time an initial population of objects larger than 10 cm, extracted from the ESA MASTER population. The long-term evolution is performed by means of the SDM model considering a reference scenario where launches, in-orbit explosions (2-3 per year until 2028) and collisions are considered [3].

By detecting close encounters with the filter approach of the CUBE algorithm, we can infer information about the relative distance, collision probability, but also about energy-to-mass ratio and the location of the potential collision. The results of the simulations will yield important constraints to the orbit design of a given constellation, like the number of CAM needed given a collision probability threshold.

Our software performs a time and space sampling of the circumterrestrial system. The original idea is to express the collision rate between two objects $i$ and $j$ over a period of time

$$N_{tot} = \int_{t_{begin}}^{t_{end}} P_{i,j}(t) dt = \int_{s=0}^{L} \int_{t-s}^{t} P_{i,j}(t) dt ds,$$

where $P_{i,j}$ is the collision rate, $L$ the number of time intervals between $t_{begin}$ and $t_{end}$, and $t_s$ the date at the beginning of the time interval $s$. The collision rate is computed on the basis of an estimation of the flux using the gas theory. Here, we propose to use a more accurate method giving the collision probability with the Foster method [4]. In other words, for each time interval we compute the collision probability as follows:

- First, a comparison between apogee and perigee of a pair of objects allows to exclude a collision risk in a low computation time.
- Second, we discretize the 3-dimensional space in cubes of 10 km $\times$ 10 km $\times$ 10 km.
- Third, once two objects are found within the same cube, we compute the collision probability by propagating the dynamical state of both objects involved until the time of closest approach, we project the sum of the covariance matrices over the $b$-plane, and we integrate the probability density function over the projected cross-sectional area.
The orbit of the satellite is computed beforehand with an orbit propagator taking into account the geopotential zonal harmonics $J_2$ up to $J_5$, the Moon, the Sun, the solar radiation pressure, the atmospheric drag with the DTM2013 model, and the different maneuvers. We implemented the CUBE algorithm to detect the close approaches between the background population and the satellite as a target. Each event characteristics like the epoch, the initial condition of the target and the chaser, their mass and cross-sectional area are stored in a file. Moreover, the Foster method allows to obtain the relative distance at the time of the closest approach and the collision probability. The flowchart is represented in Fig. 1.

![Flowchart](image)

Figure 1: Flowchart to assess the collision risk during the orbital life of a satellite. The CUBE algorithm is used as a close approach filter filling a realistic event database for an individual satellite.

In this way, for an individual satellite as a target we obtain an assessment of the collision risk with the evolution of the collision probability, but also a detailed description of the close approach events which can be carefully analyzed to determine the best strategies for collision avoidance maneuvers as explained in Section 3.

Application for a OneWeb and Starlink satellites

We compute the ephemeris of the target satellite of the given constellation at a time step of 300 seconds and we apply our software to assess the collision risk over the complete lifetime of the satellite including the orbit raising, the operational phase at the nominal altitude, and the decommissioning by lowering the perigee towards an atmospheric reentry. The operational orbit inside the constellation and the manoeuvres are given in Tab. 1. The parameters used for the CUBE algorithm with the physical characteristics of the satellites are summarized in Tab. 2. In Fig. 2 we plot the evolution of the perigee and apogee of the satellite, and the evolution of the cumulative collision probability. We see a change of the trend during each phase because the satellite crosses regions with a different density of space debris. Moreover, the collision probability of a Starlink satellite increases faster after 2021 and at the end the collision
Table 1: Altitude of injection, operational altitude and inclination, and apogee/perigee of the decommissioning orbit for the satellite constellations OneWeb and Starlink.

<table>
<thead>
<tr>
<th>Name</th>
<th>Injection [km]</th>
<th>Operational altitude [km]</th>
<th>Inclination [deg]</th>
<th>Decommissioning [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OneWeb</td>
<td>500</td>
<td>1200</td>
<td>87.9</td>
<td>1100×250</td>
</tr>
<tr>
<td>Starlink</td>
<td>300-350</td>
<td>550</td>
<td>53</td>
<td>550×300</td>
</tr>
</tbody>
</table>

Table 2: Parameters used for the CUBE algorithm and physical characteristics of the target satellite (OneWeb and Starlink).

<table>
<thead>
<tr>
<th>Name</th>
<th>OneWeb</th>
<th>Starlink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte-Carlo runs</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Time step [s]</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Cube size [km]</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Mass of the target [kg]</td>
<td>145</td>
<td>227</td>
</tr>
<tr>
<td>Cross-section area of the target [m²]</td>
<td>3.14</td>
<td>3.14</td>
</tr>
</tbody>
</table>

The probability is one order of magnitude higher than the OneWeb satellite. In Fig. 3, we assess the number of collision alerts as a function of the probability threshold for the complete lifetime of the both satellites. We see that we can expect more close approaches with a high collision probability for the Starlink satellite.

3 COLLISION AVOIDANCE MANEUVERS

We are interested in the way to determine the CAM in case of close approach. Previously, we have described an algorithm generating close approaches between a satellite during its orbital life and the space debris environment. Now, we investigate solutions to reduce the collision risk and we draw the characteristics of the CAM expected.

Management of the collision risk with low thrust maneuvers

The collision risk is managed by space operators and has become a daily task. Space surveillance networks generate hundreds of collision alerts per week for possible close encounters between two catalogued resident space objects. Assuming the collision avoidance maneuver is performed on the basis of a collision probability threshold, we propose to compute the maneuver needed to reduce the risk. A maneuver is defined by the magnitude, the direction, and the duration of the acceleration which can be constant or not. The design of a CAM implies different requirements for the optimization in terms of miss distance, collision probability, propellant consumption, or service interruption. Several studies have been conducted to compute the relative motion, with an analytical or semi-analytical approaches, due to an impulsive [6] or continuous low-thrust maneuver [7]-[8]. These different approaches are interesting in terms of computational cost. Moreover, they showed that a thrust along the tangential vector is close to the optimal strategy to maximize the miss distance.

In this paper, we focus only on a tangential low-thrust strategy, aimed to modify the semi-major axis and the eccentricity. If the maneuver is performed sufficiently in advance of time of the closest approach, a low thrust is enough to reduce the collision risk. Nowadays, the electric thrusters are popular because they provide a low thrust with a very high specific impulse $I_{sp}$ and thus, they allow to save propellant.

We propose to assess an optimal maneuver defined by a set of parameters in order to reduce the collision probability $P_c$ below an acceptable threshold. In Tab. 3, we provide the orbital elements and physical parameters of two objects involved in a close approach obtained by the simulation introduced in Section 2 for a OneWeb satellite. The target is a OneWeb satellite and the chaser a space debris of the background population.
Figure 2: We plot in red the evolution of the perigee and apogee of a OneWeb (top) and a Starlink (bottom) satellite. The satellites perform the orbit raising, station-keeping maneuvers during 5 years, and decommissioning maneuvers lowering the perigee towards an atmospheric reentry. We plot the evolution of the cumulative collision probability obtained with our implementation of the CUBE algorithm (in black).

In Fig. [4], we show the consequences of a thrust oriented along the tangential vector on the collision probability. By varying the duration of the maneuver (limited by the period between the beginning of the thrust and the time of closest approach), the magnitude ($10^{-4}$, $10^{-5}$, and $10^{-6}\text{m.s}^{-2}$), the direction (positive or negative), and the time between the beginning of the thrusting and the time of closest approach (4 and 8 orbital periods), we obtain the sensitivity of the collision probability to the maneuvers. In the right column of Fig. [4] we see that a thrust in
the positive direction of the tangential vector leads the collision probability first to increase until a maximal value, and then to decrease. On the other hand, in the left column of Fig. 4, the thrust in the opposite direction leads to a decreasing in collision probability. Indeed, the change in the semi-major axis leads to a modification of the mean motion and the temporal evolution of the mean anomaly. In other words, as the evolution of the collision probability is oppositely correlated with the miss distance at the time of closest approach, the relative position change after the low-thrust maneuver leads to a change in collision probability. In our study case, a thrust in the positive direction first leads the two objects closer to each other at the time of closest approach, reducing the miss distance. Later on, after a minimum, their separation distance starts to increase. In Tab. 4, we give the variation of the orbital elements and the relative distance at the moment of the time of closest approach. Moreover, note that the post maneuver state shall be determined as soon as possible after the maneuver and the satellite should be brought back to the operational orbit at the earliest convenience. Note that these kind of operations would strongly benefit from an on-orbit autonomous navigation system to alleviate the burden on the ground control.

The process of CAM design presented so far can be applied to any conjunction events. The flowchart is given in Fig. 5. We read the conjunction events stored in a database and we apply a heuristic algorithm as the simulated annealing, by exploring the space of CAM parameters and finding the best one minimizing the collision probability [9]. First, we propagate both objects backward in time over several orbital periods. Second, we compute a new trajectory until the time of the closest approach, by applying a low-thrust maneuver for the initial set of CAM parameters, and a modified set (varying the thrust duration, and the direction). Third, we compute the collision probability with the Foster method for both set of CAM parameters. Then, we keep the CAM parameters that minimize the collision probability, and we iterate the process until the new collision probability is below a given threshold. At the end, we save the final CAM
Table 3: Orbital elements and physical parameters of the target (a OneWeb satellite) and the chaser objects (a space debris of the background environment) involved in the close approach.

<table>
<thead>
<tr>
<th></th>
<th>Targer</th>
<th>Chaser</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$ [km]</td>
<td>7578.883</td>
<td>7363.768</td>
</tr>
<tr>
<td>$e$</td>
<td>$2.524\times10^{-3}$</td>
<td>$2.759\times10^{-2}$</td>
</tr>
<tr>
<td>$i$ [deg]</td>
<td>87.900</td>
<td>98.220</td>
</tr>
<tr>
<td>$\Omega$ [deg]</td>
<td>217.263</td>
<td>117.669</td>
</tr>
<tr>
<td>$\omega$ [deg]</td>
<td>119.203</td>
<td>257.248</td>
</tr>
<tr>
<td>$M$ [deg]</td>
<td>338.865</td>
<td>194.197</td>
</tr>
<tr>
<td>Area [m$^2$]</td>
<td>3.14</td>
<td>0.011</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>145</td>
<td>0.357</td>
</tr>
</tbody>
</table>

Table 4: Variation of the orbital elements and of the position of the target due to the maneuvers for a maneuver applied before 4 orbital periods, in direction opposite to the tangential vector, with a magnitude of $10^{-4}$ m.s$^{-2}$.

<table>
<thead>
<tr>
<th></th>
<th>$\delta a$ [m]</th>
<th>$\delta e$</th>
<th>$\delta i$ [deg]</th>
<th>$\delta \Omega$ [deg]</th>
<th>$\delta \omega$ [deg]</th>
<th>$\delta M$ [deg]</th>
<th>$\delta r$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>67.48</td>
<td>9.03$\times10^{-6}$</td>
<td>-2.38$\times10^{-7}$</td>
<td>2.73$\times10^{-6}$</td>
<td>-1.25$\times10^{-2}$</td>
<td>-6.92$\times10^{-3}$</td>
<td>2867.33</td>
</tr>
</tbody>
</table>

parameters obtained in the database for the given conjunction event.

**CAM design process applied for OneWeb and Starlink**

The process of CAM design described previously is applied for each conjunction event expected during the orbital life of a OneWeb and a Starlink satellite, with a collision probability above $10^{-7}$. In Fig. 6, we plot the distribution of the CAM as a function of the collision probability computed for a given conjunction event and the thrust duration needed to lower it below a threshold of $10^{-7}$. The process of CAM design is performed for a constant thrust magnitude of $10^{-4}$ and $10^{-5}$ m.s$^{-2}$, and for an ignition time of 12 and 24 hours before the time of closest approach. We show that a maneuver performed 24 hours before the time of closest approach needs less thrusting time than a maneuver performed 12 hours before. However, for a thrust with a magnitude of $10^{-4}$ m.s$^{-2}$ the thrusting time stays limited up to 950 seconds (or 15 minutes) although for a magnitude of $10^{-5}$ m.s$^{-2}$, the thrusting time reaches up to 2500 seconds (or 42 minutes). The distribution for the Starlink and OneWeb constellations are similar but more Monte Carlo runs are needed to obtain a more significant outcome.

**4 CONCLUSIONS**

In the context of the deployment of large satellite constellations we are interested in the assessment of the collision risk and the strategies to perform collision avoidance maneuvers. The large number of satellites involved leads to the impossibility to perform conventionally the operation from the ground and part of the process should be performed on-board. In this paper, we introduce a software developed to assess the long-term collision probability and filling a database of realistic conjunction events between a satellite as a target and the space debris of the background environment. The collision risk of each event is analysed and a CAM is proposed if the probability of collision is above a given threshold. Then, we use a heuristic algorithm to fit the parameters of an optimal collision avoidance maneuver (assuming a tangential thrust and a
constant magnitude, and controlling the thrust duration) for a given conjunction event. Applying
the algorithm of the CAM design to each conjunction event previously generated, we characterize
the typical CAM parameters expected for a satellite of the OneWeb and Starlink constellation.
Our investigations can be extended to other satellite constellations like Telesat or Kuiper located
at different altitudes. New assessments with a higher number of Monte Carlo runs need to be
performed in order to fill our database with a significant number of close approach events to infer
accurate statistical information.

The CAM design using low-thrust is the subject of several studies in recent years. Numerical,
semi-analytical, or analytical methods have been proposed to obtain fast computations. Using
the conjunction events of our database, a comparison of the different methods will be performed
to assess their computational cost, efficiency, and accuracy. Then, it will be possible to design the
best algorithm for CAM computed on-board a satellite system in an autonomous way.

ACKNOWLEDGEMENTS

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Regione Toscana project Giovanisi (www.giovanisi.it).
Figure 5: Flowchart to design collision avoidance maneuvers (CAM) from conjunction events obtained with our implementation of the CUBE algorithm and stored in the database.

REFERENCES


Figure 6: Duration of the collision avoidance maneuvers as a function of the collision probability for each conjunction event generated for the complete lifetime of a OneWeb and a Starlink satellite, for different thrust magnitudes ($10^{-4}$ and $10^{-5}$ m.s$^{-2}$), and different ignition time of the thrust before the time of closest approach (12 and 24 hours).