Risk reduction and collision risk thresholds for missions operated at ESA

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Abstract

Collision avoidance is common practice in satellite operations nowadays, e.g. the European Space Agency's (ESA) Space Debris Office provides a service to support operational collision avoidance activities for ESA's missions as well as missions of third party customers.

Since key data, such as the trajectories of both objects involved in a close approach around the time of minimum separation, are known only with limited precision it can't be known for sure whether a collision will occur or not.

Thus major ingredients to any collision avoidance strategy are criteria on when to execute an avoidance manoeuvre. Prime criterion is the collision risk since it encodes the main data of the close approach event (approach geometry and trajectory uncertainties), but of course operational constraints also have to be taken into account.

Many mission operators use 1/10000 as a risk threshold at least for missions in low Earth orbit and this figure seems to have become a quasi-standard which thus is presumably often applied without being scrutinized.

The aim of this paper is to present the approach on defining the threshold followed at ESA's spacecraft operations centre ESOC by the missions supported by the Space Debris Office and to discuss alternative approaches.

Keywords: collision avoidance, risk threshold, collision probability, close approach statistics, avoidance manoeuvre frequency, risk reduction

Introduction

Major space agencies started probabilistic collision risk analyses and avoidance activities some two decades ago. Following the Cosmos-Iridium collision in 2009, collision avoidance has become common practice in satellite operations for institutional and commercial operators.

Currently, ESA's Space Debris Office supports operational collision avoidance activities for ESA's missions Cryosat-2, Aeolus, the constellation of Swarm-A/B/C, seven Sentinels, as well as missions of third party customers (see Figure 1) and missions on highly eccentric orbits.

Whereas there are no international standards or requirements on how to perform collision avoidance operationally, two major aspects of any operational approach consist of:

1. Operational constraints and requirements, such as forbidden manoeuvre times/directions and/or limited delta-v (due to spacecraft) and times needed for the avoidance manoeuvre preparation and decision process (due to operations concept, e.g.

24/7 coverage of operations and decision taking staff, mission planning cycles, ground station coverage etc.).

2. Judgement of severity of close approach, i.e. criteria to decide which conjunctions shall be mitigated by an avoidance strategy. Since key data such as the trajectories of both objects around the time of closest approach are known only with limited precision it can't be known for sure whether a collision will occur or not.

For the latter, some operators in the past looked at predicted minimum separation, possibly weighted with the uncertainties of the secondary object. At ESOC, since the beginning of operational collision avoidance more than a decade ago, the prime criterion is the collision risk since it encodes the key data of the close approach event (nominal separations, approach direction and trajectory uncertainties).
Auxiliary information is also often looked at, e.g. age of tracking data and update frequency for the secondary's orbital information. For a recent description of the conjunction risk assessment process at ESOC see [1,2].

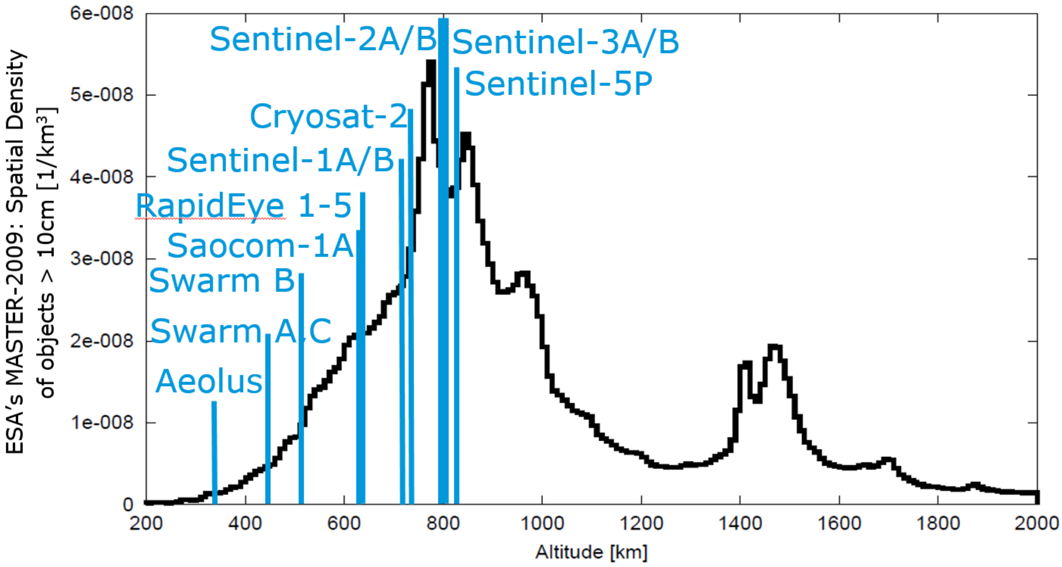

Figure 1 Missions in low Earth orbit covered by the ESA's Space Debris Office's operational collision avoidance service, their altitudes and background spatial densities.

Many mission operators use 1/10000 as a risk threshold, at least for missions in low Earth orbit, and this figure seems to have become a quasi-standard which thus is presumably often applied without being scrutinized. The aim of this paper is to present the approach on defining the threshold followed at ESOC by the missions supported by the Space Debris Office and to discuss alternative approaches.

In order to analyse potential reaction thresholds, ESA's ARES ("Assessment of Risk Event Statistics" within the DRAMA tool suite) tool [3,4] is used. It allows the estimation of the overall collision risk as well as the annual frequency of close approaches with collision risks above accepted levels selected by the user, as a function of spacecraft size as well as the quality and age (time to event) of the orbit information. It is thus possible to trade-off ignored risk vs. avoided risk via selecting the risk threshold, at the cost of a number of manoeuvres required because of the frequency of events having a higher risk than the selected threshold.

In this paper we summarize the features of ARES and its recent upgrades, discuss sensitivity to key parameters, present the ESA approach including exemplary results and discuss possible alternative and future approaches.

Close approach statistics

Key ingredients to the computation of the collision risk for a given close approach event are the approach geometry, i.e. separations and approach direction, as well as the uncertainties in the two object's trajectory and the sizes of the two objects [5,6].

For a statistical assessment of possible reaction thresholds and their associated costs (in terms of avoidance manoeuvre frequency) during the design phase of a spacecraft one thus needs

- A statistical model of the (debris) environment the mission is operating in
- A statistical model of the performance of the space surveillance system providing regularly updated trajectory data on catalogued objects
    - Model needs to provide uncertainties (as function of prediction time) as well as catalogue coverage (minimum size)
- A method to evaluate the frequency of close approaches and their collision risks for a mission operating in this environment supported by this surveillance system.

This is the task of ESA's Assessment of Risk Event Statistics (ARES) tool, which is part of ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) suite [3,4]. DRAMA is the tool recommended by ESA to be used in early design phases of a project to assess debris-related aspects, like collision avoidance statistics, impact and damage assessment, disposal orbit design and re-entry analysis.

The space debris population, which is the essential input for most analyses, is provided to DRAMA/ARES through ESA's reference model MASTER (Meteoroid And Space debris Terrestrial Environment Reference [7]).

Uncertainty information for all orbital regions has been analysed from a large set of Conjunction Data Message (CDMs) provided by the US Space Surveillance Network [8].

The ARES tool allows to assess the annual rates of close approaches between an operational spacecraft and tracked objects in Earth orbits above a collision risk threshold along with the associated Δv and propellant mass for collision avoidance manoeuvres if that threshold is adopted.

ARES also provides figures of the yearly collision risk for the cases where no collision avoidance is in place as well as for the scenario where all risk for the close approaches above the threshold is mitigated. This allows computing the risk reduction and the remaining (ignored/accepted) risk due to the catalogued population achieved by implementing this threshold. ARES also allows to compute the remaining risk, which includes the risk due to the objects of the population which are not catalogued because they are too small to be tracked regularly with the assumed surveillance system. Thus the remaining risk is the residual (ignored) risk plus the practically unavoidable risk due to the uncatalogued part of the population.

Sensitivity to key parameters

In this section we discuss the influence of key parameters on the frequency of events above a given threshold (i.e. frequency of avoidance manoeuvres if this threshold is adopted) and the associated risk contributions (i.e. risk reduction if these events are avoided).

As mentioned above the collision probability computation for any close approach event heavily depends on the approach geometry, i.e. separation and approach direction, as well as the uncertainties in the two object's trajectory at the time of closest approach and the sizes of the two objects.

The uncertainties in the objects' positions result from the uncertainty during the orbit determination (at OD epoch) and its propagation to the time of closest approach (TCA). The first contribution is a function of the surveillance and tracking system (i.e. sensor quality and geographical network distribution) and its data processing chain[1] whereas the increase in uncertainty until TCA depends mainly on the time between TCA and the last OD. Both contributions of course depend also heavily on the orbital regime.

Catalogue accuracy

The influence of the catalogue accuracy is exemplified in Figure 21 showing risk reduction and avoidance manoeuvre frequency for high and low accuracy catalogue data for a spacecraft operating in the dense LEO regime near 800 km altitude on a polar orbit. It can be seen that for the accurate data almost all risk can be mitigated at a moderate cost of few manoeuvers per year (risk thresholds between 10^{-4} and 10^{-3}) whereas for the low accuracy catalogue the number of avoidance manoeuvres is prohibitive or the risk reduction is below 50%.

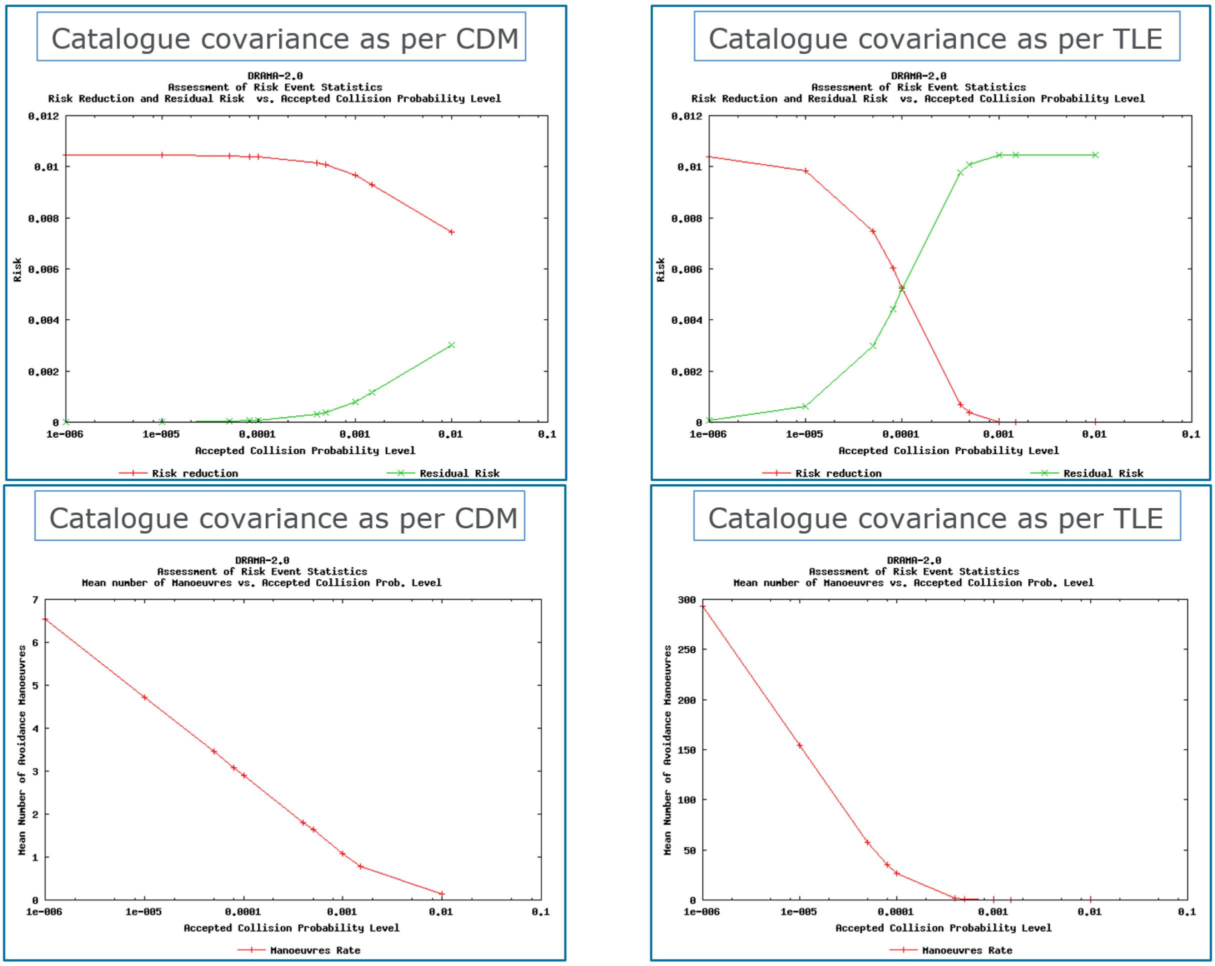

Figure 2 Risk reduction (top row) and avoidance manoeuvre frequency (bottom row) for high accuracy catalogue data (CDM, left column) and low accuracy catalogue data (TLE, right column).

[1] And of the active satellites' operational orbit determination performance in case of use of mixed data sources (i.e. operational data for the active satellite and catalogue data for the conjunction partner).

Time to close approach event

Figure 32 shows the effect of the time between catalogue or OD update and TCA for an example of two days between catalogue update and TCA (right column) and half a day for a large satellite in polar orbit at about 600 km altitude. The effect is less dramatic than for the previous example however operationally significant, e.g. at a threshold of 10^{-4}, 1.7 manoeuvres per year suffice to reduce the risk by more than 98% if a reaction time of 0.5 days is used, whereas for 2 days this threshold leads to 3 manoeuvres reducing 95% only. If this 95% risk reduction would be the requirement and 0.5 days a feasible reaction time then a threshold of $5{\cdot}10^{-4}$ would be enough at a cost of 0.8 manoeuvres per year only.

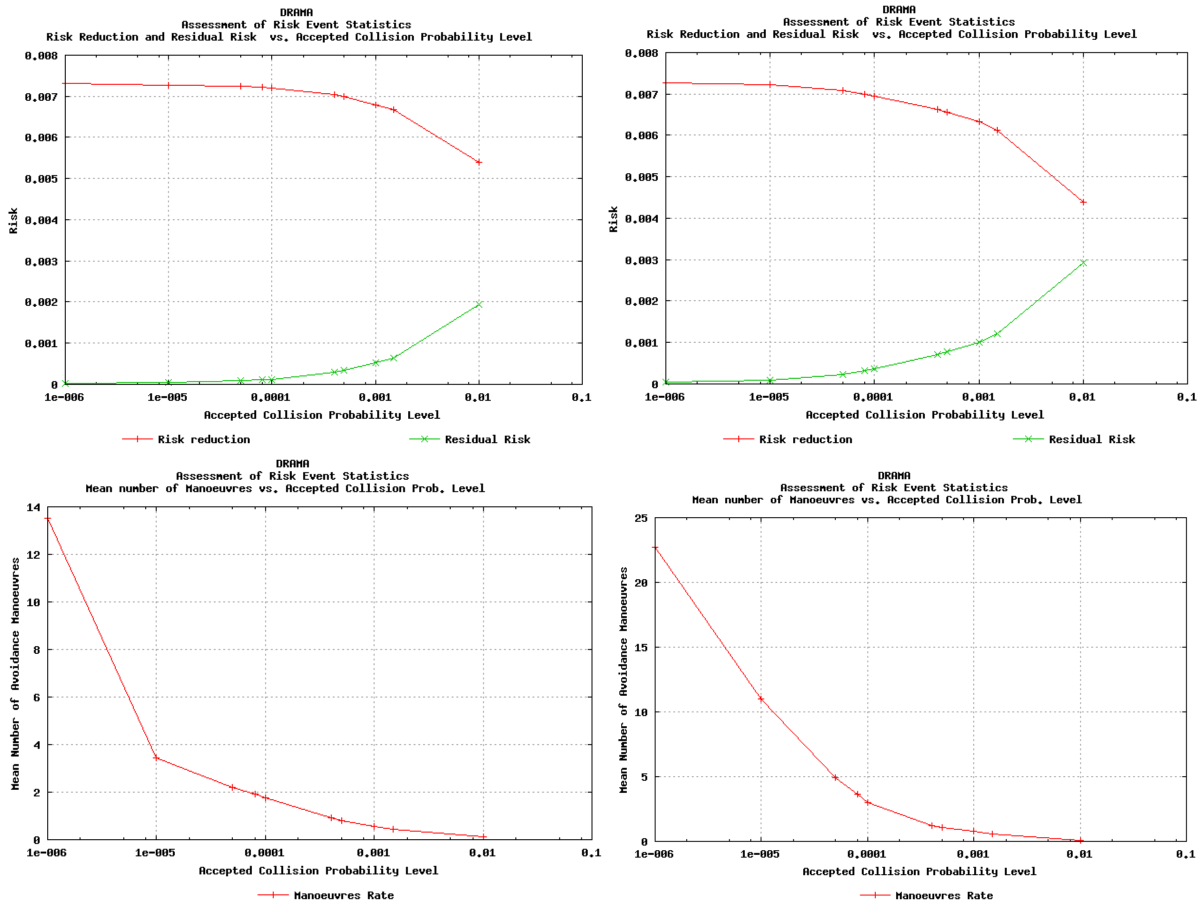

Figure 3 Risk reduction (top row) and avoidance manoeuvre frequency (bottom row) for 0.5 days (left column) and 2 days between catalog update and TCA (right column).

Object size

The size of the objects involved in a close conjunction is another key driver for the collision probability. Whereas the sizes of the catalogue objects are given by the environment model, the operational satellite is a configuration item. Figure 4 shows risk reduction and avoidance manoeuvre frequency for spacecraft differing about a factor 3 in span (thus an order of magnitude in area).

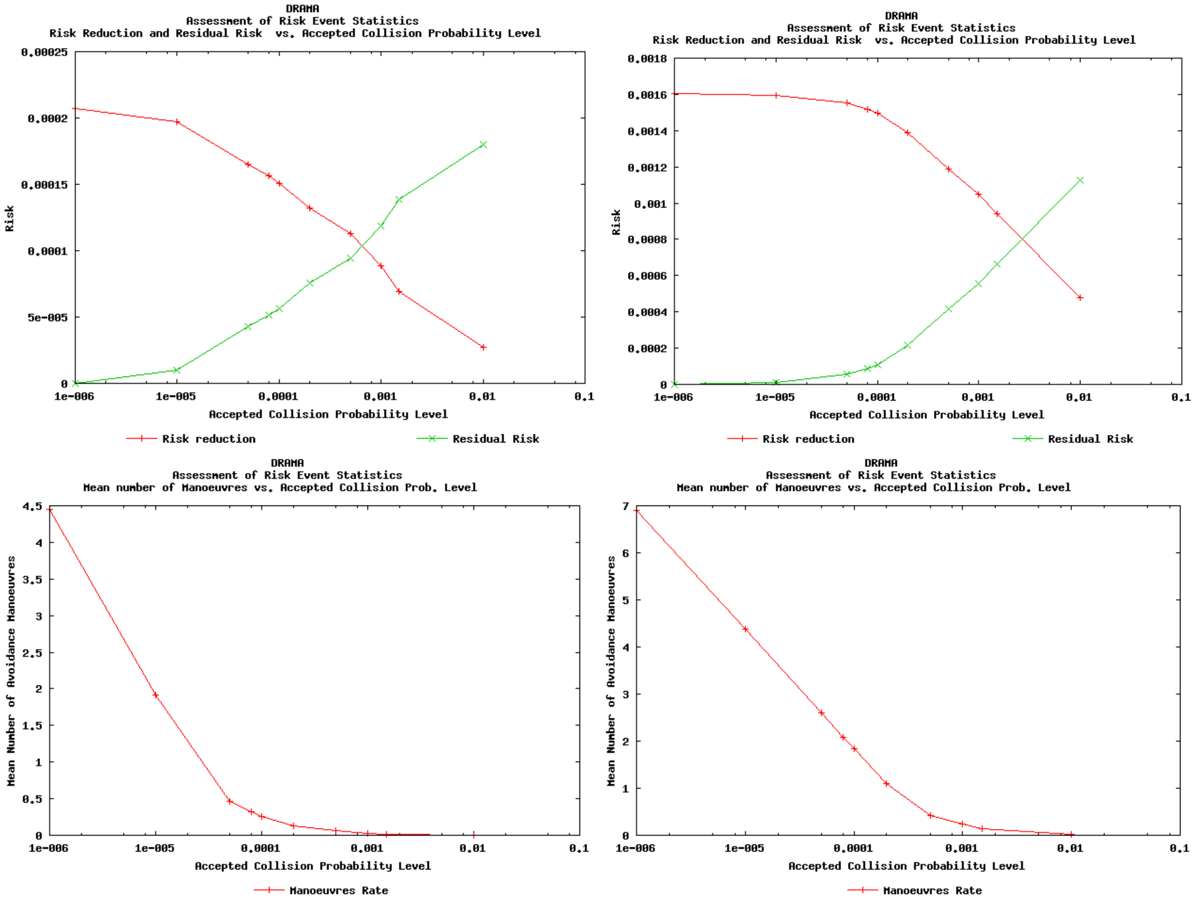

Figure 4 Risk reduction (top row) and avoidance manoeuvre frequency (bottom row) for small (left column) and large spacecraft (right column).

When looking at the risk reduction (relative, also called fractional) as a function of avoidance manoeuvre frequency the two configurations are very similar (as one should expect, see Figure 5), however the corresponding collision probability levels are shifted significantly.

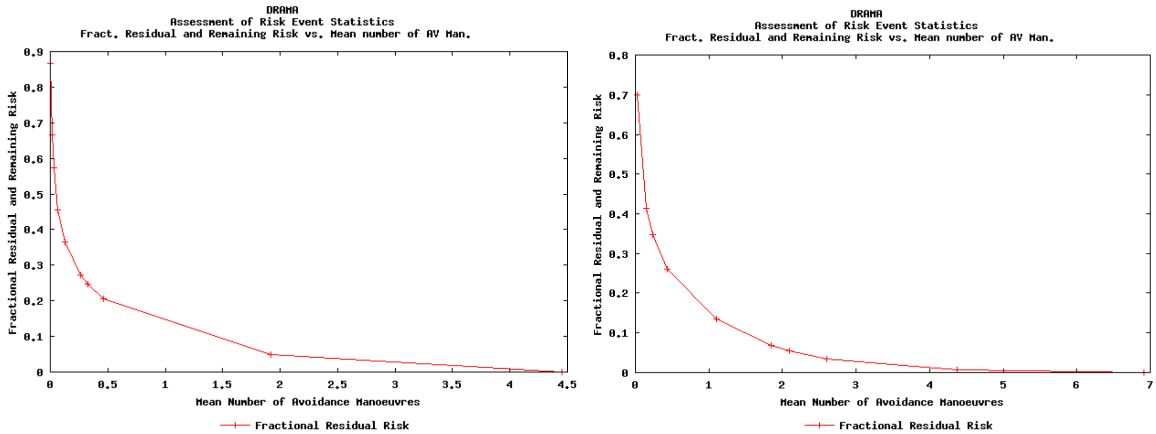

Figure 5 fractional (relative) risk reduction as a function of avoidance manoeuvre frequency for small (left) and large spacecraft (right) for the same configuration as Figure 4.

Local debris environment

The (debris) environment obviously has a very strong influence on the close approach statistics, however it is out of direct control of any operator of a satellite. Indirectly the operator however influences the environment he sees by

- Selecting the nominal trajectory, in particular altitude

- The active mission lifetime (the environment changes with time)
- The environment catalogue (completeness and size limit) supporting collision avoidance operations (of course this doesn't change the environment the spacecraft moves through but only the part of it which is accessible for operations).

In view of the large variation of the spatial density of the debris population with altitude, it is no surprise to see strong effects as function of altitude – see Figure 6 for an example. However, the altitude not only affects the spatial density of the population, but also the capabilities to track objects (lower objects are easier to detect with radar due to the stronger signal returned, however regular catalogue maintenance is more difficult due to worse coverage) and predict their orbits (due to variability/uncertainty in air drag especially). As a consequence, the risk level without a collision avoidance process is higher at the higher altitude (around 720 km altitude in the right plot), however falls off more rapidly with lowering risk threshold than at lower altitude (at around 520 km altitude on the left). In the example the residual risk at a threshold of 10^{-4} is lower for the higher than for the lower spacecraft not only in relative terms but also in absolute and this even at a lower manoeuvre rate (1.8 per year versus 2.9 per year).

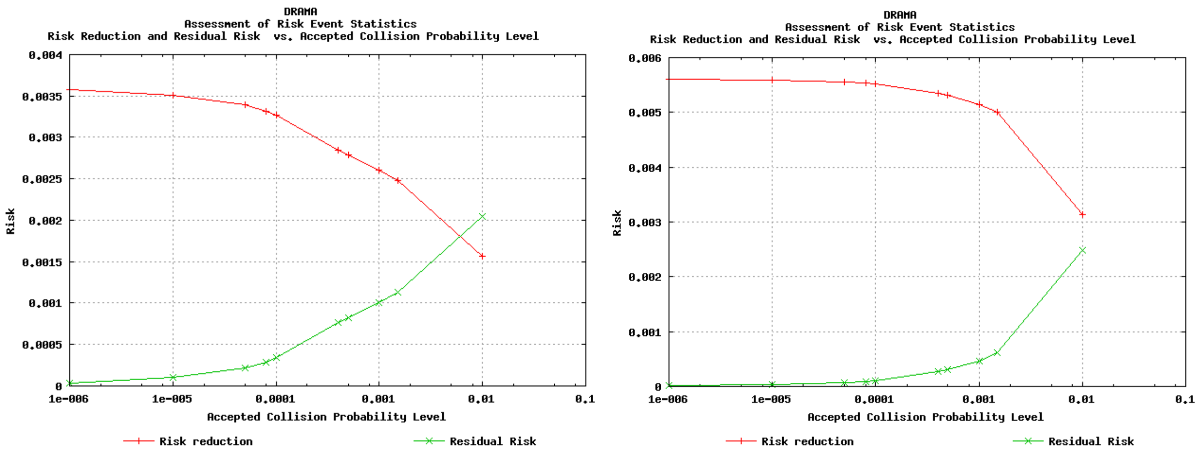

Figure 6 Risk reduction for spacecraft in low (520 km, left) and high (720 km, right) altitude.

So far the debris population increases with time[2] and this is reflected by the environment model (MASTER) also in the future. The expected increase is in the order of 10% over mission lifetimes in the order of 5 to 10 years, resulting in a similar increase of high risk events and thus avoidance manoeuvres and relative risk reduction for a fixed risk threshold. This quasi-steady increase of the predicted debris population is however a result of an averaging over long-term simulations in a Monte Carlo fashion. Therefore a single major break-up event may lead to a larger increase in the population than predicted by the model. Due to the stochastic nature of such events they can be taken into account only after the fact or as a hypothetical worst-case analysis. The MASTER model is regularly updated by ESA, but in ARES the user can also add debris clouds for which a dedicated population has been created.

[2] There are occasionally a few years where this trend is outbalanced by the 11 year solar cycle which leads to a faster cleaning of the environment around the solar maximum due to increased air density/drag.

Threshold selection

When defining a collision avoidance strategy for a particular mission, one typically is faced with a given debris environment, surveillance system and operational orbit (altitude essentially). The time needed between a decision to perform an avoidance manoeuvre and the time of closest approach needs to be established taking into account the operations concept e.g. staff coverage for manoeuvre preparation (during weekends/night time), ground station coverage, duration of satellite operations to reach manoeuvre readiness status (slews, mode changes etc.), time needed between manoeuvre execution and time of closest approach, etc. For most recent missions operated at ESOC this is about 1 day[3].

Once the size of the satellite is established the statistical analysis of risk reduction and manoeuvre frequency as a function of the risk threshold can be performed.

Most collision risk algorithms (and in particular those used in statistical tools such as ARES) treat the conjunction objects as spheres and consider a collision to occur if the centre of the spheres get closer than the sum of the two radii. As shown above, the statistics is very sensitive to the size (i.e. radius) of the object thus this parameter has to be selected carefully.

There are several ways how this can be done ranging from conservative to some sort of "realistic" in average sense: The typical approach at ESOC is conservative and using the smallest sphere encompassing the satellite and centred in the centre of mass of the satellite, i.e. there are no appendages like antennae or solar panels "sticking out" of the sphere. Less conservative approaches used by some operators use spheres of smaller size thus accepting that for some close approaches the collision risk is underestimated while (hopefully) on average the computed collision risks are more realistic. There are various ways to do this, e.g. by not requiring the centre of the sphere to coincide the centre of mass.
Other approaches attempt to use spheres having the same frontal area as some kind of typical or maximum frontal area of the actual spacecraft with its complex geometry. This requires a tool, such as the DRAMA module CROC ("Cross Section of Complex Bodies", see Figure 7 for an example), to model the complex geometry of an actual spacecraft and derive the projected area as a function of a viewing direction. This allows finding the maximum area and the area averaged over "all" viewing directions. Such an average, however, is not the average over the approach directions of the conjunctions experienced as these directions are not evenly distributed in the body-fixed frame of the satellite and thus this average may not be a good approximation of a typical frontal area. Instead, one may use the environment model e.g. MASTER, to obtain distributions of approach angles and on-orbit location of the flux (Figure 8) which together with an attitude law may allow defining typical approach directions in the body frame and thus the typical area[4] presented to the incoming debris.

[3] This is the rough time when the decision to start command generation is taken – the first warning is usually issued 1 to 2 days earlier and often a later a final go/no-go decision (but no other modification of the strategy) can be taken.
[4] This may be further complicated by rotating parts of the spacecraft such as antennae or solar panels.

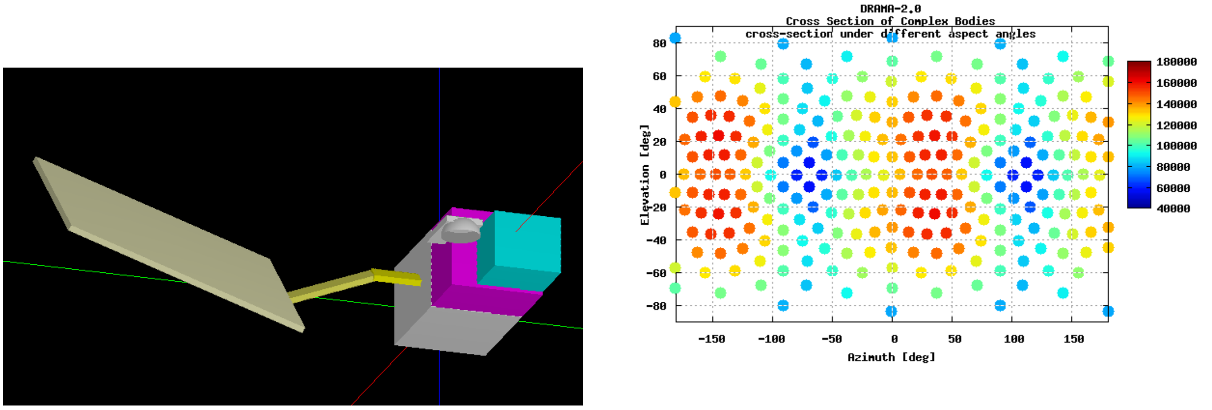

Figure 7 Example of spacecraft model and distribution of cross sections as computed by DRAMA module CROC

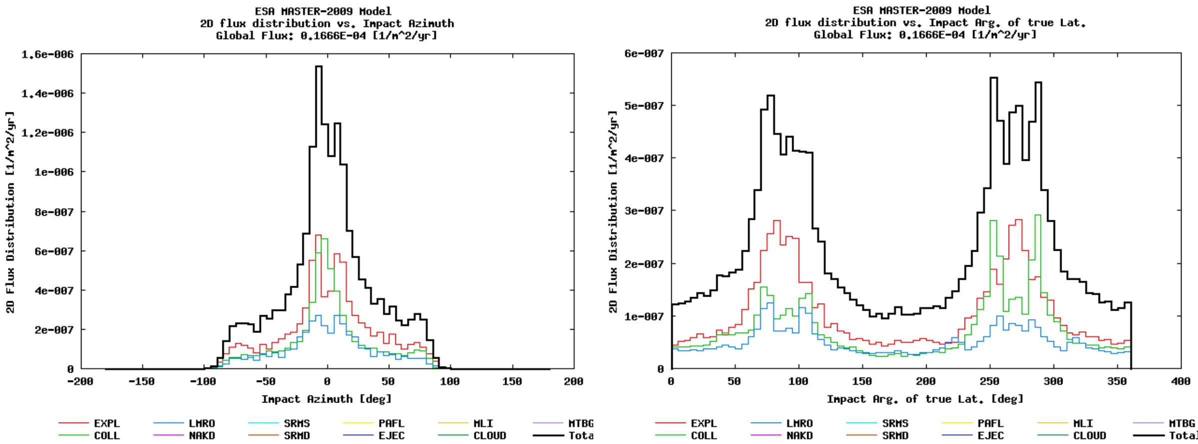

Figure 8 Distribution of the impact azimuth angle (left) and argument of latitude (right) of the flux imparting on a spacecraft in polar orbit near 800 km altitude

It is stressed here that during actual operations algorithms used for the computation of collision risk should be consistent with those used in the statistical analysis otherwise the expected frequency of avoidance manoeuvres may significantly differ from the real one. At least potential differences and their consequences shall be known and understood.

The actual risk threshold selection can in principle be seen from two perspectives: The risk may be a priori given by the mission owner[5] and the analysis aims at deriving the expected avoidance manoeuvre frequency (thus checking the feasibility of the a priori threshold). In this approach the a priori threshold should be given with a way to compute it - see size discussion above. An alternative approach consists of aiming at a certain risk reduction, i.e. reducing the overall collision risk (yearly or over mission lifetime) to an acceptable level. Such an acceptable level may be defined absolutely or in relative terms, e.g. a risk reduction by an order of magnitude (i.e. of 90%) may be aimed at. The latter is the typical approach for ESOC's missions where the necessary threshold is selected with some robustness, i.e. the ARES analysis is run several times varying the time to event, the catalogue accuracies and the mission time (end date) aiming to achieve 90% in all or at least most of these cases. For ESOC's missions the number of manoeuvres is typically not a hard constraint – at least for the current environment and risk reductions. However the trade-off could also be performed with a constrained manoeuvre number or delta-v budget, i.e. the threshold could be driven by the

[5] This approach is somewhat questionable since many other risks of mission loss are poorly computable and thus difficult to compare to the risk of mission loss due to a collision.

manoeuvre rate and avoiding the conjunctions above the threshold is then the most efficient risk reduction achievable.

With the upcoming introduction of the new S-band fence into the US space surveillance system the catalogue is expected to increase significantly (by an order of magnitude roughly). Sticking to the past risk thresholds would thus lead to far more avoidance manoeuvres, which for many missions is unfeasible. In principle, the approach should be to redo the above analyses using such an enlarged catalogue and establish new (higher) thresholds. While methodologically correct, applying higher thresholds is somewhat unsatisfying.

Possible improvements, at least for operators currently using conservative approaches with large spheres for spacecraft with large and/or asymmetric appendages, would be to use complex spacecraft shape and attitude models. Computationally this may, however, be far reaching for the large statistical analyses needed. Intermediate approaches using some simple encompassing shapes such as ellipsoids or boxes and some simple attitude law for them (potentially fixed in one of a few available frames) might be doable though.

Another approach discussed in the collision avoidance community is to ignore high risk conjunctions (i.e. to accept the risk due to them) with small fragments, based on the reasoning that collisions with such fragments may not cause catastrophic collisions or even trigger mission loss. This may however be considered doubtful at least for the fragments catalogued by the S-band fence. In case an owner would be willing to risk mission loss but still limit the effect of a collision on the environment the criterion of catastrophic collision (i.e. kinetic energy of the fragment related to the satellite mass above 40 J/g) may be used as a threshold to accept collision risks (but note that the fragment mass is not known but can only be roughly estimated from radar cross sections). Alternatively collision consequence indicators such as ECOB [9,10] may be used.

Conclusions

Collision avoidance is common practice in satellite operations nowadays and many mission operators use 1/10000 as a risk threshold for implementing an avoidance manoeuvre at least for missions in low Earth orbit. This figure seems to have become a quasi-standard which thus is presumably often applied without being scrutinized.

In this paper we have discussed approaches to select and justify risk thresholds based on statistical assessments of manoeuvre rates and risk reduction which can be expected when selecting a certain threshold. Sensitivity of these quantities to key parameters affecting the collision risk computation has been analysed. Many of these parameters are driven by the mission and its concept of operations (e.g. orbital altitude, time needed between decision on avoidance manoeuvre and time of closest approach). However, the modelling of the satellite's size, more precisely its radius when modelled as a sphere, is a configuration item having a strong influence on the risk reduction and manoeuvre frequency for a given risk threshold. It is thus of high importance to have consistent assumptions on the spacecraft model during actual operations and when performing the statistical analysis establishing the threshold.

We have presented ESA's approach on this modelling as well as the DRAMA/ARES software tool supporting these analyses. We have also discussed possible future enhancements in view of the expected growth in the catalogued population mainly due to the improved tracking capabilities via the US S-band fence.

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