IMPACT ON MISSION DESIGN DUE TO COLLISION AVOIDANCE OPERATIONS BASED ON TLE OR CSM INFORMATION

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Collision avoidance manoeuvres are considered for mission design and fuel budget allocation, and may have a relevant impact in particular orbital regimes. Current operations for collision avoidance are based on Two-Line-Elements (TLE) orbital data or the Conjunction Summary Message (CSM) data. This paper presents the most suitable approach for collision avoidance for several mission types when operations are based on TLE or CSM data, with a detailed analysis of the impact of the orbital accuracy of catalogue data and warning time–to–event on mission design in terms of fuel budget for collision avoidance activities and operational constraints imposed by the avoidance manoeuvres.

INTRODUCTION

Among the activities to be considered for mission design and fuel budget allocation, the approach for collision avoidance activities is addressed and may have a relevant impact on the mission service interruption and fuel budget allocation for some particular orbital regimes. Current operations for collision avoidance are based on Two-Line-Elements (TLE) orbital data provided by USSPACECOM (unique public catalogue of orbiting objects) or the data provided by the operational JSpOc service raising collision event warnings in the basis of the Conjunction Summary Message (CSM) data format. The most suitable approach for collision avoidance for a particular mission will be different if the operations are based on TLE or CSM data, mainly due to the knowledge of the orbital accuracy of those data sets.

The uncertainty associated to the miss distance is one of the most relevant aspects in the collision risk computation. Most of the algorithms computing collision risk approach the problem by translating the uncertainty of the orbits knowledge into the uncertainty of the miss distance. This determines the probability of having a real encounter by integrating this uncertainty into the projected collision volume of the two colliding objects. Therefore, it determines the operator capacity to identify risk events, discard false alerts and finally, avoid an eventual encounter. Manoeuvres are normally applied when the computed risk is larger than an Accepted Collision Probability Level (ACPL) for the mission. This ACPL value should be carefully defined considering the capabilities to reduce the risk (derived from the accuracy of the catalogues).

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One of the main problems associated to the computation of the collision risk derives from the lack of knowledge on the orbital data accuracy. TLE catalogue is not very accurate, and additionally, it does not provide an estimation of the accuracy for each orbit. Several studies have evaluated the uncertainties of associated to the TLE catalogue (e.g. Kelso et al.\textsuperscript{15}).

In this paper, the resulting data from one of those analyses is used to evaluate the most appropriate avoidance manoeuvre approach for operational missions when basing the collision risk avoidance activities on TLE data. This analysis of the accuracy of TLE data set is based on the comparison of the propagation of TLE data sets (by means of the standard SGP4 propagation) with operational precise orbits of some satellites, considering the propagation time. A brief summary of the mentioned accuracy results is also provided. As the TLE data sets are lacking of orbital knowledge information, some operators are approaching the collision avoidance activities in the basis of the so-called maximum risk associated to an encounter (mainly based on miss distance and encounter geometry). The paper addresses the impact on number of avoidance manoeuvres to be executed along mission lifetime when using this approach when compared with an approach based on estimated accuracy of TLE data.

Similar analysis was approached to characterise the accuracy provided by CSM data sets as a function of time to event. Again, the outcome of such analysis is used to evaluate the optimum avoidance manoeuvre approach when CSM data is used for collision avoidance operations. The results are compared with those from the analysis based on TLE data approach to point out the main benefits and drawbacks of the two operational approaches.

The paper intends to define general rules for defining collision avoidance schemes, depending on the orbital regime and object size, by proposing adequate ACPL over which a manoeuvre should be executed to effectively reduce the risk of the mission. Analysis of the impact of the warning time-to-event in the decision to perform a manoeuvre on the collision avoidance approach is also discussed. Application cases include missions in the most populated LEO orbital regimes, but also MEO and GEO regimes.

For this analysis, ESA DRAMA ARES tool is used, making use of the stored information on orbital accuracy for TLE and CSM data and the different manoeuvring criteria implemented in the tool.

**BASIS ON COLLISION AVOIDANCE AND MANOEUVRING CRITERIA DEFINITION**

The collision avoidance needs to be accounted in a mission design depends on the population of objects in the vicinity of the satellite at its nominal orbit, the knowledge of such population of objects, the spacecraft size (the large the satellite is, the larger the number of eventual encounters), and the criteria to manoeuvre.

The size of the satellite and how populated the orbital regime is determines the so-called Annual Collision Rate (ACR). The ACR for a spacecraft with a cross section \( C_s \) from an object population within a given size threshold \([r_{\text{min}}, r_{\text{max}}]\) is usually computed by means of an analogy with the collisions among particles within the laws of kinetic gas theory:

\[
ACR = F_{r_{\text{min}}}^{r_{\text{max}}} \frac{C_s}{r^2} \]

where \( F_{r_{\text{min}}} \) is the flux of orbiting objects (number of object passages per unit area and year) with sizes in the defined range \([r_{\text{min}}, r_{\text{max}}]\).

The collision process follows Poisson statistics, so the probability of no impacts can be expressed as the complement of the probability of one or more impacts:
The flux provides the number of mean object passages per area and year, and does not take into account the size of the debris object. However, the area to be taken into account for the computation of the risk must be related to the size of the debris impacting the spacecraft (a collision occurs when an object passes near the spacecraft at a distance less than the sum of the two radii, assuming spherical objects). Thus, the total collision probability must be obtained by the addition of the contributions of all objects. 

$$ACP = P_{\text{i}} = e^{-ACR} \approx ACR$$ (2)

where $R_{sc}$ is the mean radius of the operating spacecraft and $r_j$ is the radius of each one of the population objects.

The Annual Collision Probability gives an idea of the risk of collision of the spacecraft with one of the orbiting objects. A spacecraft operator, thanks to the catalogued data provided by a surveillance system, cannot completely remove this risk. Firstly, because avoidance manoeuvres will only be performed for conjunctions with a foreseen risk larger than an allowed limit (Accepted Collision Probability Level, ACPL), and so a residual risk is left. Secondly, part of this risk intrinsically cannot be diminished, as it comes from objects orbiting the Earth which are not catalogued. The Annual Collision Rate due to the catalogued objects, and defines the maximum amount of risk that can be diminished by avoidance manoeuvres. The evaluation of the residual risk associated to the catalogued population is used to assess the appropriateness of the avoidance criteria.

If only those encounters with EMR over 40J/g are considered, then, we can also compute the $ACP_{c,\text{cat}}$ and $ACP_{w,\text{cat}}$, associated to the catastrophic risk only, both for the risk derived from the whole or the catalogued population.

**Manoeuvring Criteria**

The criterion to manoeuvre may be based on a defined minimum distance threshold. If any object is estimated to pass closer than this distance threshold, a manoeuvre is planned. This approach does only require the knowledge of the two objects positions at the estimated time to encounter. As the accuracy of the orbital prediction is not considered, the estimation of the effectiveness of the avoidance criterion is difficult. The threshold in the defined distance shall account for the typical uncertainties of the orbital information, so the threshold should be larger than the sum of the two expected position errors.

On the contrary, accounting for the orbital uncertainties leads to the definition of manoeuvring criteria in the basis of the level of risk associated to an encounter that forces the spacecraft to perform a manoeuvre to diminish that risk. This level of risk is known as the Accepted Collision Probability Level (ACPL). Accounting for the risk over which an encounter event is to be avoided allows estimating the amount of risk that the operator aims to diminish.

In the mission design phase, the approach shall not account for deterministic computation of object-to-object encounters but on statistical considerations on population.

Following figure shows the typical relationship between this ACPL value and the number of manoeuvres required for collision avoidance, and the associated residual risk (part of the collision risk that is not intended to be reduced). As it can be seen large ACPL values are associated to
very low number of estimated encounters along a year of mission. This is caused by the lack of capability of assigning a high risk to an encounter due to the level of knowledge of the predicted orbits. As it can be seen from the figure, the larger the uncertainty (TLE uncertainties are normally larger than those associated to orbital information used for CSM), the lower the opportunities to predict large risk encounters. No warnings are raised for ACPL larger than $10^{-3}$ in the case of large uncertainties (TLE case), whereas some encounters could be predicted with that estimated collision risk if more accurate orbits are considered (CSM case). In any case, the number of warning would be very low, and the capability of effectively reduce the risk would be small, as it can be observed in the left axis of the plot. Only a small fraction of the risk would be removed. In order to significantly reduce the risk (let us consider reduction of risk about one order of magnitude, fractional residual risk equal to 0.1) smaller ACPL values shall be considered. The larger the uncertainty of the orbital data is, the smaller the recommended ACPL value. Diminishing the ACPL down to very small values, in order to allow further reduction of risk is not always possible due to the enormous number of events that would be raised along a mission lifetime and the consequent fuel budget to be allocated for collision avoidance activities.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Manoeuvre Rate and Fractional Residual Risk as a function of Accepted Collision Probability Level for a LEO mission in the Sun-Synchronous orbital Regime when using CSM and TLE data}
\end{figure}

As already mentioned, as the uncertainty associated to the orbits of the catalogue may be unknown, and in order to provide a criteria based on collision probabilities instead of predicted miss distance, some operators consider the evaluation of the so-called maximum collision risk. A detailed analysis of the impact of using this maximum collision risk approach is provided for a mission in Sun-Synchronous orbital regime. The achievable risk reduction is similar in the two approaches at a cost of a very large number of manoeuvres or warnings when the maximum risk is considered.

**Theoretical Formulation for deterministic collision avoidance computation based on ACPL**

Several formulations for the collision risk associated to a near-miss encounter are available in literature. Most of them make use of the Gaussian three-dimensional probability function for both objects involved in the encounter (Afriend and Akella, 2000; Frisbee et al., 1999; Foster,
The density function that gives the probability of finding an object at a distance \( \delta r \) from its nominal position is:

\[
 p(\delta r) = \frac{1}{\sqrt{(2\pi)^3 \det(C)}} e^{-\frac{1}{2} \delta r^T C^{-1} \delta r} \tag{1}
\]

where \( C \) is the covariance matrix associated to the position determination uncertainty of the object. During an encounter (due to its short duration) the object’s motion can be considered rectilinear, the uncertainty in velocity is negligible and the position uncertainty for both objects can be considered constant.

The most extended way of computing the collision probability for an encounter makes use of the density function of the so called miss-vector, which has an associated error covariance matrix given by the sum of the matrices of the two objects (since the object uncertainties are not correlated). The obtained three-dimensional problem can be reduced to a two-dimensional problem \( (2, 3, 4, 5, 6) \) in the B-plane (perpendicular to the approach velocity between the objects involved in the near-miss event). Then, the probability of collision for an object-to-object encounter is computed as:

\[
 P = \frac{1}{2\pi \sqrt{\det(C)}} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-\frac{1}{2} \delta r^T C^{-1} \delta r} \, dy \, dx \tag{2}
\]

where \( R \) is the sum of the two object radii (both objects are assumed to be spherical), while \( \delta r \) is the vector between each point in the integration area (circle of radius \( R \); \( x \) and \( y \) define a point in that area) and the point in the B-plane where the near-miss is foreseen.

An approximate value of the collision probability can be obtained by assuming that the function to be integrated in previous equation is constant over the integration area, and equal to the value at the centre. If the area is too large, or the involved uncertainty matrix is too small, this assumption can become false.

The decision to perform an avoidance manoeuvre is related to the defined Accepted Collision Probability Level (ACPL). The spacecraft operator defines this collision probability value. If the risk associated to an event is larger than this value, then a manoeuvre must be performed. Otherwise, no avoidance manoeuvre needs to be carried out.

**Theoretical Formulation for non-deterministic collision avoidance computation**

Computation of the conjunction probability between an operational satellite and an object included in the catalogue makes use of the theory presented in previous section. The assessment of collision risk over the whole life for mission analysis and S/C design, on the other hand, requires a non-deterministic formulation. This formulation must be related to the deterministic algorithms and make use of similar concepts. Thus the deterministic algorithms are used together with the average flux of an object crossing the altitude band of the spacecraft orbit.

**Manoeuvring Rate in the basis of ACPL.**

The flux can be obtained for several groups of objects within the debris catalogue. The groups are specified by orbit characteristics that define the orbit determination uncertainty behaviour. Each of these orbit groups provides a flux over the spacecraft orbit and an associated mean impact velocity direction. Thus, a mean conjunction event can be described. This mean conjunction event is defined by the characteristics of the B-plane. Among them, the directionality with respect to the spacecraft velocity vector (given by the impact directionality) and the combined covariance
matrix for the miss-vector. The different values of the direction of the impact velocity define several B-planes. ARES computes the actual velocity of every mean-encounter, so no need of assumption on the encounter velocity is required to impose the catastrophic collision requirement.

Once their covariance matrices are translated to the B-plane reference system, the combined covariance matrix can be obtained. By means of the deterministic formulation, the collision risk associated to each point of the related mean B-plane is computed. Those points with an associated collision risk larger than the \( ACPL \) define an area \( (\text{manoeuvring area}) \) composed of those points that would involve an avoidance manoeuvre. The number of avoidance manoeuvres, related to each one of the debris object groups, is then dependent on the size of that area and the associated flux, caused by the catalogued objects \( (F_j' \text{ in the following}) \). The total manoeuvre rate \( M_A \) is the sum of the number of avoidance manoeuvre rates over all the catalogued groups.

\[
M_A = \sum_j A_{\text{enc}} \int_{A=0} F_j' dA \tag{4}
\]

The risk associated to the catalogued objects may also be divided in the same orbit groups, thus, equation (3.) can be written in the following way:

\[
ACP_c = \sum_j F_j' C_s = \sum_j \int_{A=0}^\infty PF_j' dA \tag{5}
\]

The integral operations in former equation can be split in two parts: the first part associated with the manoeuvring area, and the second covering the rest of the space.

\[
ACP_c = \sum_j \left[ \int_{A=0}^{A_{\text{enc}}} PF_j' dA + \int_{A_{\text{enc}}}^{\infty} PF_j' dA \right] \tag{6}
\]

**Risk Reduction and Residual Risk.**

The first term in previous equation is associated to the reduction of risk related to the avoidance strategy. The second term represents the existing risk that is not intended to be reduced. The ratio between these two quantities and the total risk associated to the catalogued objects are known as the fractional risk reduction and fractional residual risk, respectively. They provide information on the appropriateness of the avoidance strategy.

As explained before, \( ACP_c \) does not provide the value of the total risk, but the risk due to catalogued objects. Thus, the residual risk is the amount of risk that could be avoided, but it is not. If the total remaining risk is required, \( ACP_w \) has to be used: subtracting the risk reduction from \( ACP_w \), the total remaining risk is obtained. A fractional remaining risk can also be obtained by normalizing the remaining risk with the total \( ACP_w \).

**Catalogue data**

TLE and CSM are the source of data for the operational collision avoidance activities, but an estimated population is needed for the analysis of collision avoidance requirements on mission design. The assessment of the number of near-miss events and avoidance manoeuvres, during the lifetime of a satellite, requires the knowledge of the object population that can cause conjunction
events. The population provided by the MASTER-2009 environment model for objects larger than 1 cm in size is used within the ARES software package described in this paper.

MASTER provides a semi-deterministic population of natural and man-made objects for a reference epoch. Natural objects are discarded for collision avoidance manoeuvres computations. MASTER provides data on the whole orbiting population, but avoidance manoeuvres are dependent on that part of the population that can be tracked. Thus, the incompleteness of the catalogue must be taken into account by introducing a correcting function to consider only population data over the cataloguing size limit.

Several cases are executed, considering catalogue coverage at different levels, to evaluate the impact on mission design of the catalogue performance in regards to object coverage.

As already mentioned, a main issue related to risk reduction is the uncertainty in the orbital data. The orbit determination uncertainty of the population objects, together with the orbit determination of operating spacecraft play an important role in the risk associated to each near-miss event. The orbit determination uncertainty of the spacecraft and population objects is handled in terms of the associated error covariance matrices. In the case of the debris objects, the covariance matrices are dependent on the type of orbit. ARES provides suitable covariance data for different orbital regimes and orbital information data sources (TLE or CSM). Next section provides some information on the uncertainty associated to those orbital data sets, and how this information is obtained for ARES.

Accuracy of the Orbital Data Sets

ARES provides position uncertainty information for the debris populations. Two kind of covariances are provided: based on TLE accuracy and based on JSpOC CSM accuracy. These covariances were the result of an extensive study described in Domínguez-González, 2013. In that reference:

- CSM typical uncertainties were obtained by averaging the CSM-provided covariance matrices as a function of the time to event.
- TLE typical uncertainties were obtained by comparing a large number of precise (post-processed) reference orbit arcs with the orbit arcs predicted by TLEs.

![Figure 2. Example of U, V and W position errors as a function of TLE age](image-url)
Figure 2 shows the TLE-type position uncertainties for an example satellite, as a function of the SGP-4 propagation interval. For each orbit regime, uncertainties from several satellites are averaged. The results for the most common orbit regimes are shown in figures 8, 9 and 10. ARES users can use the pre-computed covariances for the debris population and (optionally) for the spacecraft determination.

In addition to this, it is possible to define arbitrary scaling factors for the covariances, and even use a custom covariance set.

ANALYSIS ON DIFFERENT ORBITAL REGIMES

The analysed cases are related to three LEO orbits, a GEO and a MEO case. The three LEO case cover the two populated regimes at 800 (SSO like) and 1400 km altitude respectively and a low orbit at 400 km altitude (ISS like orbit).

For any of the orbital regimes, collision avoidance analyses are considered in the basis of TLE and CSM approach. For the case of TLE (and due to the lack of knowledge of the accuracy of the orbital TLE data), the impact of using a realistic accuracy of the data sets or driving the manoeuvring criteria by the maximum collision likelihood is also addressed.

The catalogue coverage is considered to be 10 cm for the LEO orbital regime and 100 cm for the GEO and MEO case. Analysis of improved catalogue in terms of catalogue coverage is provided in dedicated section, to address the scalability of the conclusions for improved surveillance systems. In regards to the accuracy of future surveillance systems, analysis will be reported in a future paper.

All the analysed cases are based on the same satellite size with radius 2m. This assumption is considered in order to allow comparison of risk at different regimes. Analysis of the scalability of the conclusions for other satellite sizes is addressed in a dedicated section at the end of the paper.

DISCOS data is used for analyzing the typical size of satellites at different orbital regimes. This analysis is constrained on payloads only. DISCOS data has been filtered to provide diameter for all Payloads. For the sake of clarity, diameter wise groups are presented in next figures.

![Figure 3. Averaged object diameter versus orbit altitude for different size groups for Payloads as extracted from DISCOS database (20/11/2012). Left plot reaches up to 50000 km, whereas right figure focus on the LEO altitudes.](image)

Typical diameter ranges from 15 cm up to 10 m. A couple of cases can be found for objects larger than 10 m diameter. For low altitudes, it can be seen that small payloads exist. This is not the case for higher altitudes. At GEO regime, the average diameter for smaller satellites is 70 cm.
(although the number is very small). For MEO, an average of 2 m is found for small objects. One 50 cm object at 17000 km altitude is found.

The minimum object size found in DISCOS is about 10 cm derived from the limitation of the underlying TLE population. The number of objects at the different regimes and for different size types is also analyzed. For payloads, diameters larger than 1 m are dominant for GEO and MEO orbits, whereas for LEO regime, there is also a large number of smaller payloads.

Figure 4. Number of objects versus orbit altitude for different size groups for Payloads as extracted from DISCOS database (20/11/2012). Left plot reaches up to 50000 km, whereas right figure focus on the LEO altitudes

Summary of Annual Collision Rate associated to each orbital regime

Following figure provides a comparison of the global collision risk at the different orbital regimes analyzed in this paper. The global risk is consider for all objects in the population model down to 1 cm diameter size. It can be clearly seen that Sun-synchronous regime cumulates the highest risk due to the large population in that region. The second high risk is at the 1400 km altitude, whereas the risk at ISS orbital altitude is about one order of magnitude lower than the second one. Non LEO orbits, like GEO and MEO regimes have much lower collision risks. In particular, global risk at MEO is about 4 orders of magnitude lower than that at Sun-synchronous regime.

As the analysis in this paper is focused in the reduction of the risk for every mission, the provided plots along the document give fractional remaining risk, which is a relative risk over the natural and detected risk of the mission. There is no information on the absolute risk associated to every mission in the rest of the paper. The absolute risk can somehow be derived from the number of events encountered by each mission.

Additionally, the figure provides the amount of that risk that can be detected and then, eventually reduced if appropriate collision avoidance warning and maneuvering scheme is put in place. As already mentioned, two catalogue capabilities have been analysed in regards to the minimum size of catalogued objects (5cm and 10 cm diameters in LEO; 50 cm and 100 cm in high altitude regimes). It can be seen that there is a difference between the risk that can be detected for the two analysed catalogues in the LEO regime, but such a difference is not noticeable in the MEO and GEO cases. For the case of LEO, although there is a large part of risk that cannot be detected (that posed by the large amount of small debris), detecting down to 5cm objects allows to properly cover all objects that could be related to a catastrophic collision. Detailed analysis of the capability to reduce the risk of catastrophic collisions will be detailed in a later paper.
LEO at 800 km altitude (SSO like orbit)

The analysis of the most populated regime at about 800 km altitude, provides the following main conclusions in regards to eventual collision avoidance approaches for the TLE and CSM data sets.

Typical ACPL $10^{-4}$ is not a suitable value for collision avoidance schemes based on TLE data. The risk reduction capacity is almost null. This is due to the large uncertainties associated to TLE data sets (even for short time-to-event values. Large uncertainties impact on encounter events with low collision probability due to the lack of knowledge of the real position of the two involved objects.

For significant reduction of risk when using TLE data at reasonable time-to-event intervals, ACPL on the order of $10^{-6}$ (or lower) seems to be required. In those cases, a 90% of reduction of risk (fractional residual risk equal to 0.1) can be achieved when evaluating collisions one day ahead (about 10 warnings per year and mission). The reduction of risk is almost 90% when collisions are evaluated three days ahead but at a manoeuvre rate larger than 100 per year. Thus, the main conclusion from these results is the lack of feasibility of TLE for a proper collision avoidance approach. In any case, pre-warnning can be considered with TLE. As mentioned in former sections the use of Maximum risk algorithms leads to an even larger number of events.

In case of defining the collision avoidance in the basis of CSM data, and due to the better accuracy of the orbital information when compared with TLE, ACPL on the order of $10^{-4}$ allows to significantly reduce the risk. This is true for events estimated up to 3 days ahead. Even 5 days ahead events can be considered, but ACPL values down to $10^{-5}$ should be considered in such case.

Even larger prediction times can be considered (7 days) for risk reduction about 90%, at the cost of larger number of warnings up to 5 events per year, when 5 days prediction allows to keep the manoeuvre rate in 2 manoeuvres per year. Pre-warning can be considered with larger times (7 days). It has to be accounted that JSpOc policy on the prediction times consider normally up to 5 days timeframes for LEO missions.
In the case of TLE-based collision avoidance approaches, it is sometimes considered the maximum risk associated to an estimated event geometry. This is caused by the lack of uncertainty information associated to the orbital data provided by TLE. In this case, the warning, or manouevring criteria is based on the use of a covariance matrix that maximises the risk associated to that geometry. This approach leads to a number of events which is much larger than that associated to the real uncertainties. As it can be seen from following figure, significant risk reductions are achievable but at the cost of a large number of manoeuvres. About ten events per month would be raised with this approach, no matter the prediction time considered (as the real covariance is not considered for evaluation of the risk). The reduction of risk would be equivalent to that obtained with the approach of considering the real error associated to the orbits.

![Manoeuvre Rate and Residual Risk for different ACPL values and time-to-event values for the case of a LEO mission in Sun-Synchronous orbit (TLE based approach)](image)

Figure 6. Manoeuvre Rate and Residual Risk for different ACPL values and time-to-event values for the case of a LEO mission in Sun-Synchronous orbit (TLE based approach)
Figure 7. Manoeuvre Rate and for different ACPL values and time-to-event values for the case of a LEO mission in Sun-Synchronous orbit (TLE based and maximum risk approach, left plot) and Manoeuvre rate and Residual Risk for the maximum collision risk and nominal risk for TLE based collision warning approach (right plot).

Figure 8. Manoeuvre Rate and Residual Risk for different ACPL values and time-to-event values for the case of a LEO mission in Sun-Synchronous orbit (CSM based approach)
LEO at 1400 km altitude

For this altitude band, and similar to the former SSO case, ACPL $10^{-4}$ is not a suitable value for collision avoidance schemes based on TLE data for an orbit at the second population peak in LEO. The risk reduction capacity is almost null. Risk reduction up to a 90% is achieved for ACPL on the order of $10^{-6}$ or lower. For a 3 days ahead warning, 90% of risk reduction is achieved with about 20 manoeuvres per year, being 50 manoeuvres if warning is raised five days in advance.

For the case of CSM driven collision avoidance approaches, the risk reduction can be considered with ACPL between $10^{-4}$ and $10^{-5}$ (with warnings of one up to three days) and ACPL on the level of $5 \times 10^{-6}$ for 5 days ahead collision evaluation. Larger prediction times provide small reduction of risk unless going to a very small ACPL value.

The number of annual warnings raised per mission for the different prediction times ranges from 1 case for a 10 years mission lifetime (prediction one day in advance) to one manoeuvre per year when the estimation is done five days in advance.

![Manoeuvre Rate and Residual Risk for different ACPL values and time-to-event values for the case of a LEO mission in a 1400 km altitude orbit (CSM based approach)](image)

Figure 9. Manoeuvre Rate and Residual Risk for different ACPL values and time-to-event values for the case of a LEO mission in a 1400 km altitude orbit (CSM based approach)

LEO at 400 km altitude (ISS like orbit)

Finally, for the low altitude in this paper, the analysis provide results similar to former LEO missions, but with a lower number of manoeuvres due to small number of objects crossing these altitudes. Very small ACPL values are required when basing the collision avoidance approach on TLE, leading on large number of collision warning events for prediction times larger than one day.

For the case of CSM-based avoidance schemes, prediction times up to 5 days can be considered with a short number of events. In this CSM case, for one day ahead events, ACPL of $10^{-4}$ allows an appropriate reduction of risk, with a very short number of events (one in ten years of mission). Behavior in regards to risk reduction, prediction times feasibility and TLE vs. CSM approach is similar to that already reported for all LEO missions.
Figure 10. Manoeuvre Rate and Residual Risk for different ACPL values and time-to-event values for the case of a LEO mission in a 400 km altitude orbit (CSM based approach)

GEO case

Dynamics of the GEO orbits is different to that in LEO, impacting on a lower increase of orbits uncertainty along time. It has to be considered anyway, that the uncertainties at short prediction times at this orbital regime are larger than those at LEO due to the differences in observation capabilities. Additionally, it has to be accounted that short prediction times feasible at LEO may not be appropriate for a GEO mission due to the orbital period being much larger at this regime.

In the case of TLE data sets, significant reduction of risk is only achieved for small ACPL values, producing about a warning per if warnings are raised one day in advance to the event (too short for any reaction to be considered). Suitable ACPL values would lay in between $5 \cdot 10^8$ and $10^7$, well below the normal values used in current operations for most of the GEO missions. It is definitely clear that TLE-based strategies for collision avoidance at this regime are not recommended. On the contrary, CSM data allows a good reduction of risk with ACPL in between $10^5$ and $10^4$ for short and medium prediction times. $10^5$ is recommended for prediction times of five or seven days. Larger warning times would require very small ACPL values. The number of events raised for a suitable warning time of seven days would be about one in a 10-year mission. It must be noted, that these results are associated to a 2 m radius spacecraft.

Figure 11. Manoeuvre Rate and Residual Risk for different ACPL values and time-to-event values for the case of a GEO mission (CSM based approach)
MEO case

Missions at this altitude have a very different behaviour when compared to the former ones. The number of objects crossing this orbital regime is much lower than those at LEO or GEO. Then, the number of warnings raised for both TLE and CSM data sets is much lower. Then, the allocation of Delta-V budget required for collision avoidance manoeuvres would also be small.

It has to be accounted, that a low number of events impact on the risk-reduction. This effect can be observed in figures showing the difficulty to reduce the risk unless very small ACPL values are considered. With this approach, the satellite is manoeuvred at almost any risk, in order to cumulate opportunities to reduce the overall risk. Thus, it may be considered that the residual risk criteria (diminish the risk over the mission by one order of magnitude) may not be adequate for defining the ACPL of a mission for cases where the annual collision rate is not large.

For CSM data, and prediction times of 5 days, a constellation would encounter 1 event after cumulating 1000 years of flight. Thus for a 30 satellite constellation, this would mean about a warning in 30 years of operations of the set of satellites. Those events correspond to ACPL values on the order of $10^{-5}$.

![Figure 12. Manoeuvre Rate and Residual Risk for different ACPL values and time-to-event values for the case of a MEO mission in GNSS constellation type orbit (CSM based approach)](image)

SCALABILITY OF THE RESULTS

Some additional simulation cases have been considered for evaluating how the former results can be translated to other missions in these regimes. The main aspects impacting on the number of events for a mission is the number of objects in the vicinity of the satellite and the size of the spacecraft. The larger the satellite is, the higher the likeliness to encounter objects posing a risk of collision. Several satellites sizes will be considered for this comparison.

In regards to the number of objects, the collision risk depends on the number of debris in the population, but the collisions that can be avoided depend on the number of objects that are catalogued, and thus, their orbits can be estimated. As the former analysis has addressed the impact of the number of objects as a function of the orbital regime, we address in this section the impact of an improved catalogue in regards to the number of catalogued objects (by improving the observable diameter of objects at different altitudes).

All simulations in this section are related to two days prediction times. As it has been discussed before, the prediction time may be different for some orbital regimes, but a common value is considered to allow comparison of results.
Impact of Spacecraft size

As already mentioned, the number of events encountered by a mission largely depends on the size of the satellite. Former analysis was executed for a 2 m radius size satellite. In this section, a small satellite (0.5 m radius), a medium 1 m and larger 5 m size cases are also considered. The objective of this analysis is to demonstrate that a risk reduction criterion imposes similar approaches for the recommended collision avoidance scheme. Figures for TLE Analysis are not reported as the results scale similarly for both TLE and CSM cases.

The obvious result from the analysis is related to the larger number of collision warnings associated to larger satellite sizes. Apart of that, it can also be observed that for larger objects, it seems that larger ACPL values allow reducing the risk. This fact can be related to the larger global risk that can be easily achieved by addressing some high risk cases. On the contrary, for smaller objects the risk is only reduced by addressing even the low risk encounters. This is translated into an almost unique risk reduction – manoeuvre rate for all satellite sizes for the low risk cases. Due to similarities of the LEO cases, the figures for the 400km case are not included in the document.

Impact of Catalogue Coverage

This section is devoted to analysis the impact on the collision avoidance scheme to be put in place for different missions, when the catalogue coverage performance is improved in regards to the size of observed and catalogued objects, and then the number of eventual colliders that can be identified. Former analysis focus on catalogue of debris of about 10 cm diameter in LEO regime and 100 cm size in the high altitudes of MEO and GEO. Additional simulation cases are considered for a catalogue of objects down to 5 cm diameter in low orbits and 50 cm in high altitudes.

Figure 13. Manoeuvre rate and fractional residual risk for different spacecraft sizes at LEO regime
No significant impact on number of events to reduce the risk when improving the cataloguing capacity (coverage-wise) in higher orbital regimes. If objects are catalogued down to 50 cm instead of the current 1 m coverage, the number of warnings and risk reduction capacity are similar for GEO and MEO missions. This is mainly caused by the short number of small objects estimated to exist at those regimes.

On the contrary, for the LEO orbits, the number of warning events is (roughly) multiplied by a factor of five. With this, even the CSM approach (at two days prediction time) imposes 5 manoeuvres per year for a mission at the very populated 800 km altitude, which would impact on fuel budget and mission interruption, but still could be addressed.

**Figure 14.** Manoeuvre rate and fractional residual risk for different spacecraft sizes at MEO and GEO regime

**Figure 15.** Manoeuvre rate and residual risk for the case of SSO orbit with catalogues down to 5 cm and 10 cm diameter size, for TLE and CSM approach
COMPARISON WITH REAL WARNING RATES

Collision warning activities carried out by ESA for the missions operated in ESOC provide an extensive data set for comparison of the real warning rate and the predicted rates by ARES. Collision warning activities are done routinely by ESOC in the basis of the ESA tool CRASS\textsuperscript{14}. CRASS estimates the eventual encounters among operational spacecraft and objects in the TLE catalogue. The warning rates generated by CRASS for ENVISAT have been analysed and classified as a function of the associated collision risk in order to compare the results with those coming from ARES. The collision risk algorithm implemented in CRASS is the Alfriend\&Akella’s one, so compatible with the approach implemented in ARES. Additionally, from April 2009 onwards, maximum risks are also computed by CRASS. The warning rates raised by Alfriend\&Akella algorithm are analysed for years 2008, 2009 and 2010. For the case of warning rate raised by maximum collision risk, year 2010 is compared with ARES estimates.

The warning rates analysed for ENVISAT are considered for events 1.5 and 2.5 days before the event. This data are compared with a mean 2 days before the event case in ARES.

Following figures provide the comparison between the obtained predicted warning rate with ARES and the observed real rate. Indication of the risk reduction for the different ACPL is also provided. ARES prediction are executed in the basis of a catalogue of objects down to 5cm and 10 cm diameter size. At ENVISAT orbital regime, it is expected that most of the 5cm objects are included in the TLE catalogue, especially those coming from the recent break-ups. 5-cm diameter fragments coming from all fragmentations may not be included as it is not possible to track them back to their originator. As it can be observed from the figures, the predicted warning rate for 2008 and 2009 (assuming catalogued objects down to 10 cm diameter) fits very well with the real warning rate encountered along the operations of the satellite. For the case of year 2010, the real warning rate is more similar to the estimated rate in the basis of a 5 cm cut-off catalogue, which may be related to the recent 5-cm fragments being included in the catalogue. Regarding the maximum risk, the fit is also good, except for the case of large ACPL values due to a limitation of the ARES software. In order to limit the run-time and RAM budget of the software, limitations are imposed to the number of steps in which some integrals are computed. This has an effect on extreme cases as the maximum collision risk one and with large ACPL values. The impact on real estimations is not considered important as normal ACPL for operations are well below 0.0005 where the difference in the results are more noticeable.

From this analysis of the warning rate for ENVISAT, and accounting for the maneuvering decision criteria which was settled at $10^{-5}$ during the years analysed here we can conclude that the capability to reduce risk is good allowing a reduction of about 90% of the risk.
The number of manoeuvres for ENVISAT along these years has not been that large as indicated by these warning rates. First, the warning rates are considered about 2 days before the event, and some events are discarded at very late prediction times in order to reduce the fuel consumption and service interruption associated to this type of manoeuvres. Additionally, CRASS (and so the ARES configuration for these cases) is run in a conservative approach considering the maximum span of ENVISAT (26 m), leading to a very large number of warnings. For every encounter, additional analysis was done to in order to estimate the real need of manoeuvre execution.

CONCLUSIONS

The work here reported shows the viability of analyzing the expected collision warning rates to be encountered by a mission along its mission lifetime. This expected warning, and eventually manoeuvre, rates shall be considered in the mission design and fuel budget calculation to ensure appropriate reduction of risk posed by the orbital debris to a satellite. The method here presented is compared with the encountered warning rates raised during several years of operations of ESA
ENVISAT satellite. This comparison reports a good match, which allows to validate the tool and the conclusions for the presented data along the paper.

For different orbital regimes, recommendations on the most suitable accepted collision probability levels (ACPL) are provided. These ACPL values are defined to significantly reduce the risk to the mission. The risk reduction capability is very much dependent on the accuracy of the catalogue utilized to identify eventual collisions. Approaches based on CSM data are recommended against the TLE based approach. Some approached based on the maximum risk associated to envisaged encounters are demonstrated to report a very large number of events, which makes the approach not suitable for operational activities.

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