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Detection of orbital debris collision risks for the Automated Transfer Vehicle¹

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Abstract: In this paper, we present a general collision risk assessment method, which has been applied through numerical simulations to the Automated Transfer Vehicle (ATV) case. During ATV ascent towards the International Space Station, close approaches between the ATV and objects of the USSTRACOM catalog will be monitored through collision risk assessment. Usually, collision risk assessment relies on an exclusion volume or a probability threshold method. Probability methods are more effective than exclusion volumes but require accurate covariance data. In this work, we propose to use a criterion defined by an adaptive exclusion area. This criterion does not require any probability calculation but is more effective than exclusion volume methods as demonstrated by our numerical experiments. The results of these studies, when confirmed and finalised, will be used for the ATV operations.

1. Introduction

From early 2008, the Automated Transfer Vehicle (ATV) will be one of the ISS supply spaceships. After lift-off from Kourou aboard the Ariane 5 launcher and transfer to the ISS vicinity, the ATV will automatically dock with the Station's Russian service module. The ATV will be dedicated to provide the crew with food and materials, to provide the ISS with propellant gas and water, to raise up the ISS altitude by several reboosts, and finally to unload ISS waste for a final

¹ The ATV-CC project is supervised by ESA and developed by ATV-CC project team. This paper uses a lot of materials made available in the frame of work performed by ESA, the industrial design team, the ATV-CC project and the CNES Space Mechanics service. They are acknowledged for their contribution. The authors thank B. Corley and L. Howorth for their help and explanations on NASA methods. Thanks also to H. Klinkrad and H. Krag of ESOC for helpful comments on an earlier version of this work.

burning into the atmosphere. ESA's ATV is considered as the most complex space vehicle ever built in Europe, combining autonomous navigation capacities with strict human spacecraft safety requirements.

During the ATV ascent toward the ISS, the ATV Control Center (ATV-CC) and the NASA Johnson Space Center will monitor close approaches between the ATV and objects from the USSTRATCOM catalog. If a conjunction is detected and confirmed by collision risk analysis, then an avoidance maneuver can possibly be scheduled by the ATV-CC. In this paper, we will present the close approach detection process that has been designed for the ATV missions. It relies on an original risk criterion which is able to make good use of the close approach geometry.

Because of the ever-increasing amount of orbital debris, partially automated methods of collision risks analysis have been developed these last years [1,2,3]. Thus, dedicated algorithms screen the most current object catalog and provide to the user a batch of conjunctions that are potentially dangerous for the spacecraft of interest. These conjunctions are determined with respect to some pre-defined risk criterion. This risk criterion has to be carefully tuned : on the one hand, it has to be conservative enough to guarantee a high-level safety for the spacecraft despite the high uncertainty that may affect the debris position ; on the other hand, it has to ensure a reasonably low frequency of alarms. Indeed, any orbital debris alarm entails various additional operational activities to confirm the collision risk and to possibly prepare an evasive maneuver that might impact mission objectives. Therefore, the risk criterion has to establish a good trade-off between the collision risk reduction and the frequency of alarms. A risk criterion is usually defined through one of the following means :

- an *exclusion volume* surrounding the spacecraft is specified ; an alarm is raised each time an object penetrates the exclusion volume ;
- a *probability threshold* is set ; an alarm is raised each time the collision probability exceeds this threshold.

Motivation

NASA studies [4,5] show that the probability threshold method is theoretically better than the exclusion volume method in the sense that for any exclusion volume, there is a probability threshold with the same safety level while guaranteeing a lower alarm frequency. In other words, exclusion volume methods raise a higher number of false alarms. However, the probability threshold approach prerequisites that a covariance model is available for any cataloged object. As the USSTRATCOM catalog does not provide covariance data to the regular user, such a model is likely to be missing or rough for a number of objects. Therefore, we aim to design a risk criterion which does not rely on covariance and probability computation while being more effective than the exclusion volume method. To achieve this goal, we propose to use an *exclusion area* that is adaptive to each conjunction event – contrarily to exclusions volumes that are fixed within the vehicle local frame.

The rest of the paper is organized as follows. Section 2 reviews the various risk criteria employed for space debris detection, in particular the exclusion volume and probability threshold methods. Section 3 introduces our exclusion area as an approximation of the probability threshold method. Section 4 provides simulations showing the very good behaviour of our exclusion area compared to various exclusion volumes.

2. Risk criteria for orbital debris detection

2.1 Debris detection processes review

Most space debris detection processes are iterative and involve several risk criteria. The risk criteria to be used mainly depend on the quality of positional data currently available. Thus, the ISS debris avoidance process is initialized by the USSTRATCOM screening on the entire catalog over a 72 hours window. Any conjunction within a $\pm 10 \times \pm 40 \times \pm 40$ km box is notified to NASA. The box dimensions are radial x downtrack x crosstrack i.e. defined in a UVW vehicle centric frame. If after additional orbit numerical processing, the event falls into a $\pm 2 \times \pm 25 \times \pm 25$ km box, then covariance information for both objects are included and collision probability is assessed if some stability criterion is met. Avoidance maneuvers are considered if the conjunction falls within a $\pm 0.75 \times \pm 25 \times \pm 25$ km “pizza box”. Similarly, ESA's approach combines a $\pm 10 \times \pm 25 \times \pm 10$ km exclusion ellipsoid completed with a collision probability assessment [3].

The approach developed at ATV-CC includes an exclusion area for initial screening and a collision probability assessment. The operational procedure of debris avoidance also involves data exchanges with NASA Johnson Space Center each time a conjunction is detected. In this paper, we will focus on the design of the risk criterion for initial screening.

Two competing quantities have to be balanced when designing such a criterion :

- the *alarm frequency* e.g. the number of alarms per year ;
- a measure of the *residual collision risk* e.g. the ratio between the annual collision probability with some debris avoidance strategy and the annual collision probability without any debris avoidance strategy.

An effective risk criterion has to establish a good trade-off between alarm frequency and collision risk reduction.

2.2 Exclusion volume vs. probability threshold method

To optimize the risk criteria used in operational procedures for the ISS and the Space Shuttle, Foster and Frisbee [4] propose to assess the efficiency of various exclusion volumes and probability thresholds. The efficiency is defined in terms of annual maneuvers and *fractional residual risk*. The fractional residual risk is defined relatively to the no-maneuver strategy : an exclusion volume showing a 0.5 fractional residual risk divides by 2 the annual collision probability associated to the no-maneuver strategy. It is assumed that each detected risk is eliminated by an appropriate maneuver.

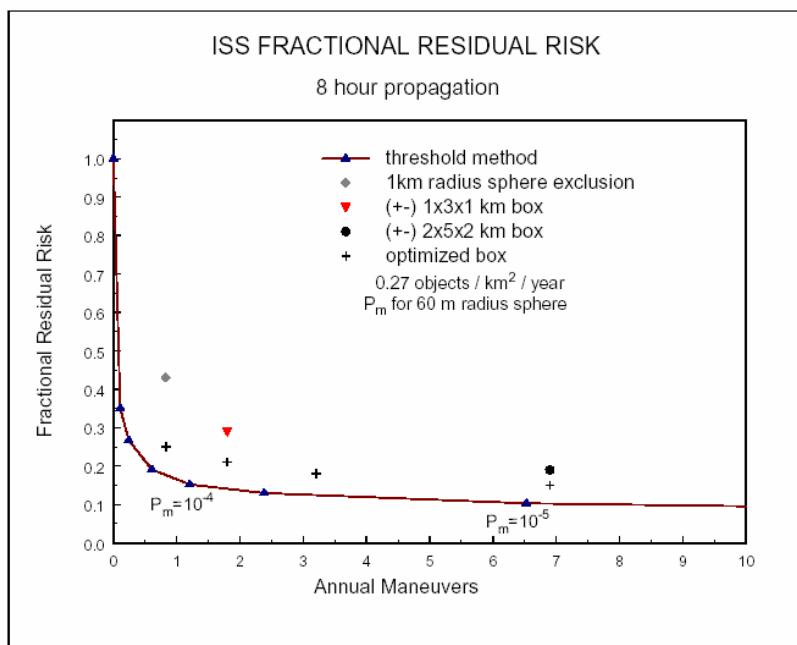


Figure 1. Fractional residual risk for ISS for 8-hour propagation, *in Foster and Frisbee [4]*

Figure 2 presents results comparing the probability threshold method (line curve) with different exclusion volumes (isolated points). It shows the better efficiency of the probability threshold method compared to exclusion volumes. For instance, the 10^{-4} probability threshold exhibits smaller risk and lower maneuver rate than the $\pm 1 \times 3 \times 1$ km box. However, some optimized exclusion volumes perform nearly as well as the probability threshold. These optimized volumes are “hockey pucks” approximating ellipsoids. Similar charts have been generated for various propagation durations, showing the superiority of the probability threshold method for both ISS and Space Shuttle.

2.3 Probability computation and debris positional accuracy

Foster and Frisbee study demonstrates the theoretical superiority of the probability threshold over the exclusion volumes. Nevertheless, a collision probability assessment requires accurate covariance for the spaceship and for the debris. Indeed, a small variation in covariance can yield a large variation in probability. This is illustrated by Figure 2 which represents

the collision probability as a function of the combined positional error of ATV and debris. One can see that there is a maximum when the combined positional error is near the *miss distance* i.e. the predicted minimal distance between the ATV and the debris. For positional errors smaller or greater than this maximum, the collision probability quickly decreases.

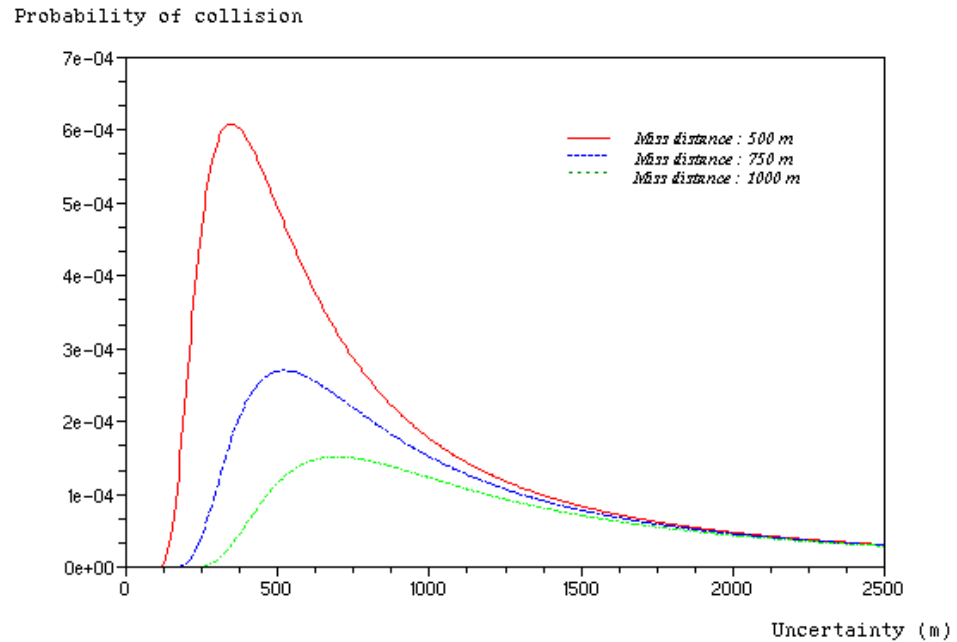


Figure 2 : Probability of collision vs. combined uncertainty for various miss distances. ATV radius : 10 m. Debris radius : 10 m. Spherical covariances.

Therefore, any collision probability computation requires highly reliable covariance data to be meaningful. Unfortunately, this requirement is not always fulfilled for the debris covariance. Indeed, the measurement characteristics uncertainties - depending on sensor type and measurement frequency - are not accessible to the regular user of the USSTRATCOM TLE catalog. This problem can be overcome to some extent: Legendre et al. [6] have proposed to assess TLE accuracy on the basis of pairwise comparisons of successive TLE from CELESTRAK website. Their work shows that a single Gaussian law is too rough to represent the TLE error and recommends the use of a Gaussian mixture for better fitting. However, any a priori model of TLE error is unable to capture events like changes in the measurement process or space vehicle maneuvers. Consequently, our risk criterion for initial screening does not rely on collision probability computation. Collision probability becomes really reliable later in the debris avoidance process when the conjunction has been confirmed.

3. Defining an exclusion area in the conjunction plane

3.1 Projecting the probability computation into the conjunction plane

Although we do not explicitly compute a collision probability for our initial risk criterion, its design is inspired from principles that have been proposed in the framework of probability computation. In this paragraph, we present a brief overview of these principles. The reader can refer to [7] for a more substantial presentation of collision probability calculation.

Eliminating the time of conjunction

Several studies propose to reduce the problem to two dimensions by eliminating the dimension along the relative velocity vector. The idea for reducing the problem into a two-dimensional problem is that we are interested in whether the

collision will occur rather than when it will occur. Thus the uncertainty along the relative velocity vector is eliminated along with the time conjunction factor.

The probability computation can be thereby simplified by reducing the uncertainty ellipsoid to an ellipse. To guarantee the correctness of the probability computation under this simplification, some assumptions have to be verified, in particular the relative velocity vector has to be large enough so that covariances can be supposed to be constant around the time of conjunction [5].

Representation in the conjunction plane

The conjunction plane is perpendicular to the relative velocity vector and contains the miss-vector ATV-object at the time of closest approach. The ATV and object covariances are supposed to be described by uncorrelated 3-dimensional Gaussian distributions ; they are summed to form a combined error ellipsoid that is centred at the ATV and then projected onto the conjunction plane (see Figure 3). After this projection, the collision probability can be determined through a double integral calculation over the projected ellipse, assuming for instance that ATV and the object collision cross-sections are circular.

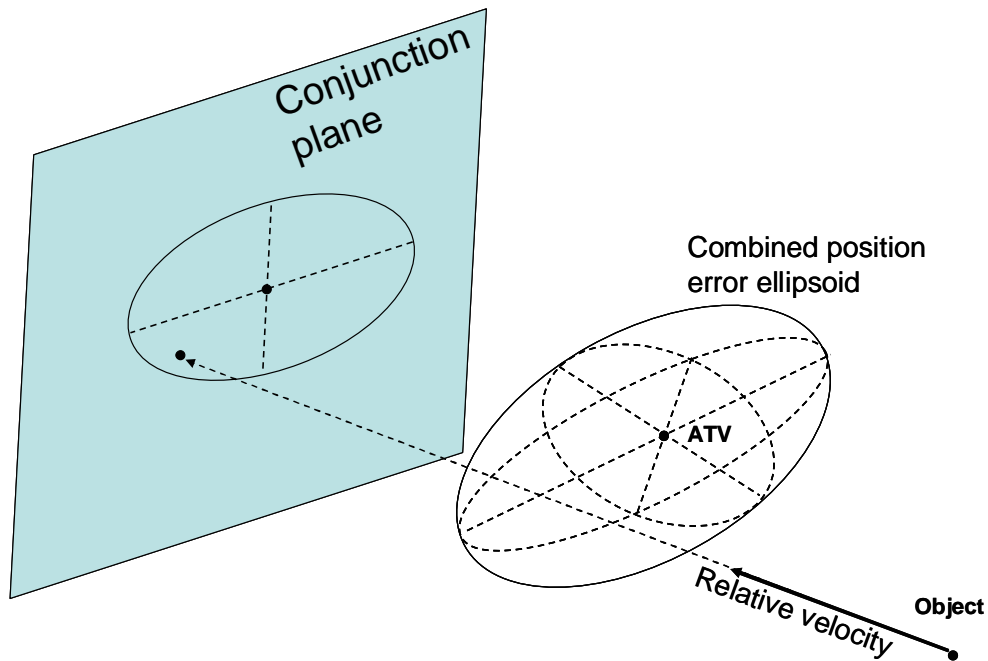


Figure 3 : Close approach projection into the conjunction plane

3.2 ATV-CC exclusion area

The exclusion area used by ATV-CC is oriented to roughly approximate the orientation of the projected error ellipsoid in the conjunction plane, without explicitly manipulating covariances. The idea is that the largest uncertainty errors are along ATV and object velocities. We define an ATV-centred frame (c_1, c_2) in the conjunction plane as follows :

- c_2 is perpendicular to the debris (and ATV) velocity vector
- c_1 is perpendicular to c_2

Thus projected along-track errors are along c_1 (see Figure 4, upper diagram).

The ATV-CC exclusion area dimensions are defined in this conjunction frame (see Figure 4, lower diagram) :

- the distance d_1 w.r.t. to ATV center of gravity in the conjunction plane
- the distance d_2 w.r.t. the c_1 axis

There are two main differences compared to exclusion volumes defined in a vehicle local :

- the ATV-CC exclusion area is adaptive as the (c_1, c_2) conjunction frame is defined for each conjunction event
- the time of conjunction factor is eliminated as the conjunction is projected in the conjunction plane

The dimensions of the ATV-CC exclusion area are the following: $d_1 = 30$ km and $d_2 = 5$ km. They have been determined considering the observed dispersions for a number of debris relevant for the ATV mission (see next section).

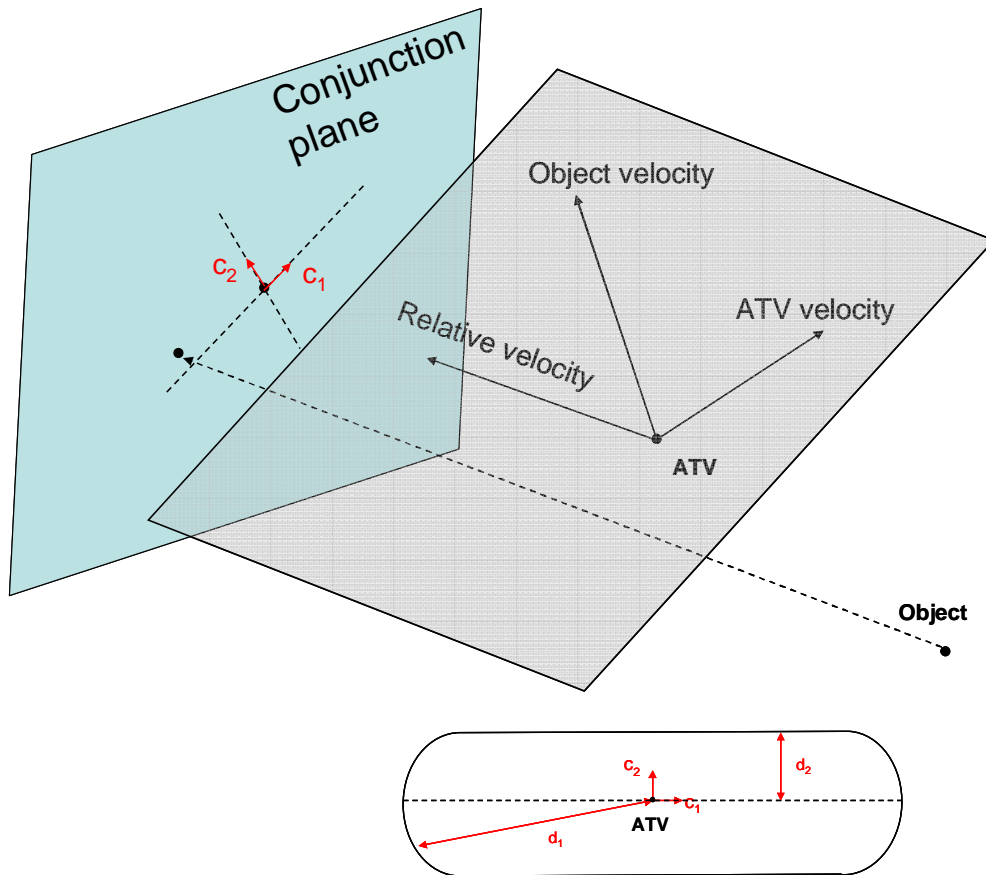


Figure 4 : Definition of the ATV exclusion area in the conjunction plane

4. Experiments

The design of our exclusion volume is based on a Monte-Carlo study that has been performed to generate a large batch of randomized ATV trajectories. For each trajectory, close approaches have been screened in order to assess their frequency and to gather statistics about the most frequent debris and other parameters of interest.

4.1 Method

To have a representative sample of conjunctions events, we have used a Monte Carlo approach that generates conjunctions between a randomized ATV trajectory and objects from the USSTRATCOM catalog. This has been done for various ATV altitudes, providing a list of 8606 simulated conjunctions between the ATV and catalogued objects.

To assess the collision risk reduction of various criteria, we used a database containing observed errors between pairs of TLE over several years (see [6]). We selected deviations separated by a 48 hours duration, which is coherent with the frequency of updates performed by USSTRATCOM for low-altitude TLEs. Thus, for each object, hundreds of observed errors are available.

We measured the collision risk reduction by introducing a *probability of detection* for each risk criterion based on these catalogued objects errors (ATV positional error is neglected). From each conjunction, we derive a collision event by setting the miss distance to zero while keeping the ATV and debris velocities. Each observed TLE error is considered as a conjunction associated to this collision event. For this collision event, the probability of detection for some risk criterion is the ratio between the number of raised alarms and the number of observed TLE errors. In Tables 1 and 2 of §4.2.3, we provide the probability of detection over all collision events derived from the whole list of simulated conjunctions for a given TLE.

4.2 Results

4.2.1 Comparison of probability threshold and exclusion area in the conjunction plane

Figure 5 represents generated conjunctions on a 20 km radius for an ATV at 400 km altitude. It shows that a probabilistic criterion can reasonably be approximated by an appropriate exclusion area in the conjunction plane. The collision probability was assessed on the basis of the mixture of Gaussian laws described in [6].

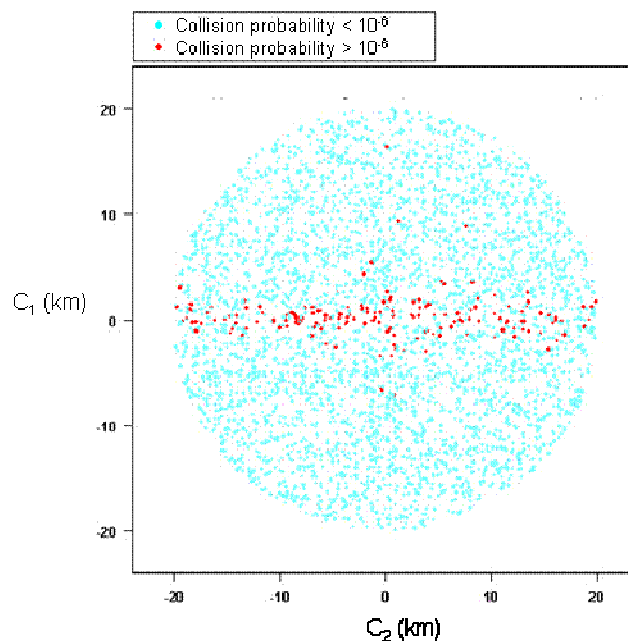


Figure 5 : Repartition of the most dangerous conjunctions events in the (c_1, c_2) frame

4.2.2 Representation of close approaches in the conjunction plane

Figures 6, 7 and 8 represent conjunctions for objects 11332, 25063 and 28185 in the conjunction plane. They also show the ATV-CC exclusion area along with the projection of 2 exclusions UVW boxes.

The ATV orbit is quasi-circular and the largest part of observed conjunctions involves objects on quasi-circular orbits. For this kind of conjunctions (e.g. Figures 6 and 7), the c_2 axis is almost along the radial direction and the projection of UVW boxes are -almost- rectangles. It should be noted that even if the debris is inside the projection of a UVW box into the conjunction plane, the debris may be outside this box. For instance, the $\pm 10 \times 25 \times 10$ km box does not raise an alarm for the conjunction depicted by Figure 7 because of the inclination of the box with respect to the conjunction plane.

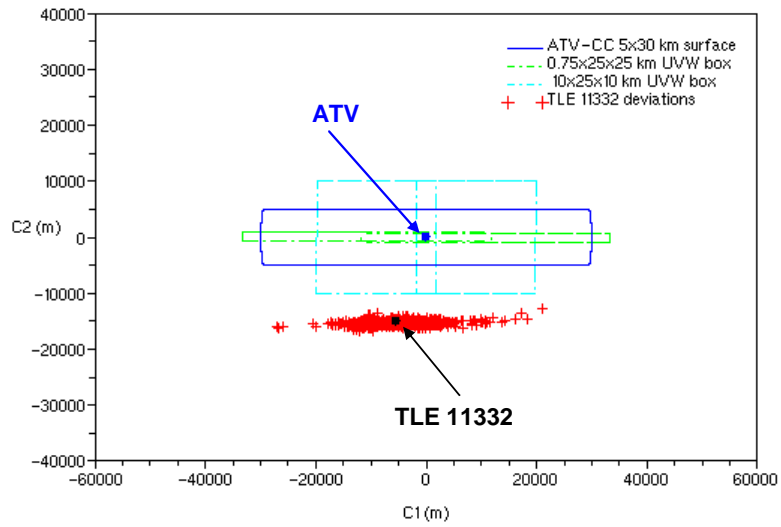


Figure 6 : Harmless conjunction with object 11332. None of the 3 risk criteria raise an alarm.

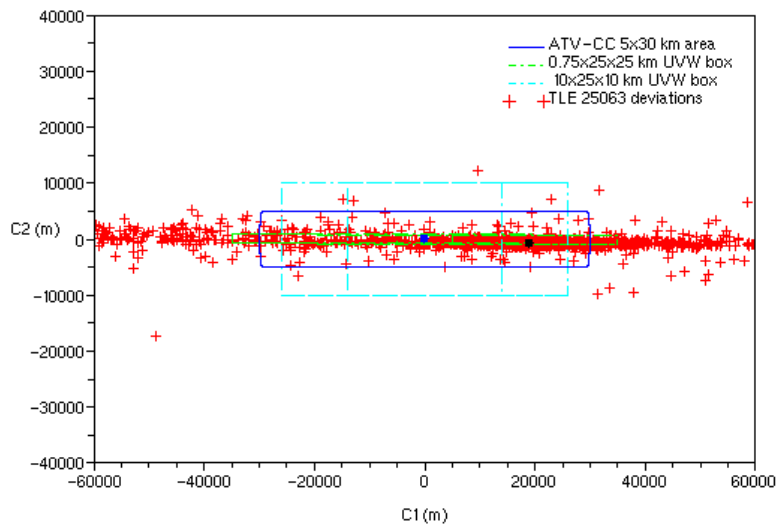


Figure 7 : Dangerous conjunction with object 25063. Only ATV-CC exclusion area raises an alarm.

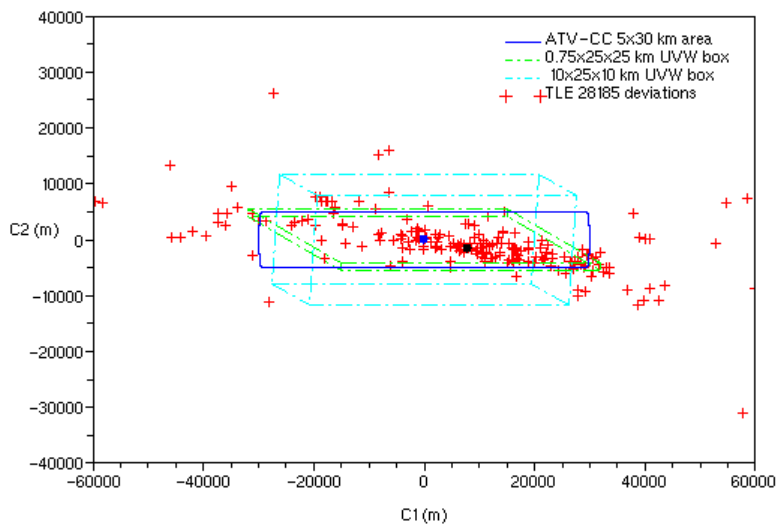


Figure 8 : Dangerous conjunction with object 28185. Only ATV-CC exclusion area and $\pm 10 \times 25 \times 10$ km box raise an alarm.

4.2.3 Compared efficiency of risk criteria

Tables 1 and 2 synthesize the efficiency of various risk criteria for a number of objects as explained in §4.1. Table 1 contains some of the most frequently observed objects. All of them are on quasi-circular orbits. Table 2 contains two highly eccentric objects. Our Monte-Carlo approach does not allow us to precisely assess the frequency of alerts for these highly eccentric objects as such conjunctions are very rare. These objects were selected to assess the efficiency of our exclusion area when the c_2 axis is not aligned with the radial direction.

TLE #	11332		25647		25063	
	Probability of detection	Number of alerts / year	Probability of detection	Number of alerts / year	Probability of detection	Number of alerts / year
3 km sphere	0.44	0.2	0.24	0.3	0.08	0.7
10 km sphere	0.86	5.5	0.63	3.7	0.23	4.9
±10x25x10 km box	0.92	3.6	0.78	6.7	0.28	10.1
NASA "pizza box" ±0.75x25x25 km	0.98	0.4	0.93	0.4	0.33	1.4
NASA "hockey puck" ±5x30 km	0.99	3.6	0.94	5.0	0.37	7.5
ATV-CC ±30x5 km area	1.00	3.6	0.99	5.0	0.39	7.5
USSTRATCOM ±10x40x40 km box	1.00	7.6	0.97	9.8	0.42	11.1

Table 1: Compared efficiency of risk criteria for some of the most frequent objects on ATV orbit.

TLE #	26405		28185	
	Probability of detection	Number of alerts / year	Probability of detection	Number of alerts / year
3 km sphere	0.41	<0.1	0.05	<0.1
10 km sphere	0.87	<0.1	0.24	<0.1
±10x25x10 km box	0.92	<0.1	0.32	<0.1
NASA "pizza box" ±0.75x25x25 km	0.94	<0.1	0.26	<0.1
NASA "hockey puck" ±5x30 km	0.96	<0.1	0.68	<0.1
ATV-CC ±30x5 km area	0.97	<0.1	0.71	<0.1
USSTRATCOM ±10x40x40 km box	0.97	<0.1	0.79	0.1

Table 2: Compared efficiency of risk criteria for highly eccentric objects.

4.3 Discussion

As suggested by Figures 6 to 8, the probability of detection greatly depends on the considered object. For instance, object 25063 which is affected by a very large along-track uncertainty, has a probability of detection which is never greater than 0.42 for all risk criteria. On the contrary, object 11332 is detected with a probability greater than 0.99 by the three most conservative criteria.

The various risk criteria have very different efficiencies: the sphere is very ineffective compared to other criteria. Moreover the 3 km-radius is almost useless to detect debris with large uncertainty.

The ±10x25x10 km box is not effective compared to NASA "pizza box" for quasi-circular debris even if both are boxes oriented in the UVW ATV-centric frame. Indeed, the velocity of circular objects could be along any direction in the local horizontal plane. Therefore, the dimensions ratio of the "pizza box" is much more appropriate for the ATV context.

The ATV-CC is very effective compared to the USSTRATCOM box: its collision detection capacity is nearly the same while reducing by half the number of alerts. It is also slightly more effective than a "hockey puck" of the same dimension as it has the same alert frequency while ensuring a slightly higher safety level.

5. Conclusions and future work

We propose to use an adaptive exclusion area in the conjunction plane rather than an exclusion volume in the vehicle orbital frame. This exclusion area is able to filter conjunctions more efficiently by focusing on the really dangerous ones, as demonstrated by our experimental results. Moreover, it does not require any probability computation so that it is not affected by debris covariance issues.

An interesting direction to extend this work would be the use of a statistical model of the debris flux for the ATV orbit. This would allow us to generalize our results to the whole catalogued debris population. A related topic of interest is the design of debris avoidance manoeuvres. Besides the debris detection process, the conjunction plane representation could be useful to design such manoeuvres. Some preliminary studies have shown the interest of such an approach for choosing an appropriate avoidance manoeuvre and for post-manoeuve analysis in terms of predicted miss vector.

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