UNCONTROLLED DE-ORBITTING: AN ASSESSMENT OF ON-ORBIT COLLISION RISK AT END OF LIFE WITH RESPECT TO DE-ORBIT TIMES

Isabel Moore(1), Iliass Tanouti(2), Simon Wheeler(3)

(1) *Thales Alenia Space in the UK, Building 660, Bristol Business Park, Bristol, BS16 1EJ, UK, Email:isabel.moore@thalesaleniaspace.com*
(2) *Thales Alenia Space in the UK, Building 660, Bristol Business Park, Bristol, BS16 1EJ, UK, Email:iliass.tanouti@thalesaleniaspace.com*
(3) *Thales Alenia Space in the UK, Building 660, Bristol Business Park, Bristol, BS16 1EJ, UK, Email:simon.wheeler@thalesaleniaspace.com*

ABSTRACT

This paper examines a novel approach to selecting Low Earth Orbit (LEO) de-orbit strategies where the risk of collision during uncontrolled de-orbit (normally a 25 year de-orbit) is considered. The risk of collision is then reduced by a shorter de-orbit time with the subsequent impacts to satellite design discussed. De-orbit durations ranging from 5 to 25 years for a future LEO mission were studied. A complementary software package to the Debris Risk Assessment and Mitigation Analysis (DRAMA) tool was developed, allowing the calculation of the collision risk for an evolving orbit. Collision risk for the 25 year case is higher than 1/500. This risk is reduced by more than six times when de-orbit time is decreased to 5 years. Results suggest that the de-orbit time limit set for satellites performing an uncontrolled re-entry should be driven by adhering to an accepted de-orbit collision risk threshold.

1 INTRODUCTION

There are currently around 16,000 tracked objects on the Low Earth Orbit (LEO) region [1]. This represents an equivalent area of almost 20,000 m^2 and 4,000 tons of mass. These numbers are more than twice as high as they were in 1990. The international space community's concerns with regards to artificial satellite collisions and man-made debris have grown in the last decades [2]. Both research institutions and space agencies have conducted their own predictions on the evolution of the future space debris environment and developed debris mitigation guidelines [3][4][5][6][7]. The National Aeronautics and Space Administration (NASA) alongside the U.S Department of Defence (DOD) helped in developing the "U.S. Government Orbital Debris Mitigation Standard Practices" in 2001 [8]. Furthermore, the Inter-Agency Space Debris Coordination Committee (IADC) introduced the "Space Debris Mitigation Guidelines" in 2002 [9].

These mitigation guidelines have been revised regularly since they were first introduced at the beginning of the 21st century [10][11]. They advise on several aspects of debris mitigation: debris released during normal operations, minimization of on-orbit break-up potential, post mission disposal and prevention of on-orbit collisions. The amount of mission related and explosion debris has significantly reduced since these measures were adopted [12]. However, fragments arising from collisions have meant an increase in the total number of debris [12]. One of the most important aspects in avoiding congestion of the space environment is post-mission disposal. According to the guidelines, LEO satellites should be removed from orbit within 25 years after mission completion [11]. The 25 year rule is as a result of a number of studies [13] [14] [15] on the evolution of the number of objects in LEO conducted by space agencies and research institutions. By comparing different de-orbit times it was concluded that 25 years would be sufficient to stabilise the LEO region [16]. Hence, the focus has been on achieving compliance to these guidelines. For instance, in 2008, the European Space Agency (ESA) established its own "Requirements on Space Debris Mitigation for Agency Projects" [17] and following this the French government wrote the guidelines into law (2008), "Loi sur les Opérations Spatiales" [18]. This means any satellite built in France or launched from a French territory must be designed to comply with this law. However, the writing of these measures into legislation has been the exception and not the norm [19].

According to ESA's latest annual space environment report less than 20% of satellites "reaching end-of-life in the LEO protected region in a non-compliant orbit attempt to comply with the space debris mitigation measures" and only 5% of them do so successfully [1]. Recent studies suggest that LEO may have already reached a level of instability [20]. Results from the Italian Space Agency (ASI), ESA, the Indian Space Research Organisation (ISRO), the Japan Aerospace Exploration Agency (JAXA), NASA, and the United Kingdom Space Agency (UKSA), indicate that even with 90% compliance to current mitigation measures,

Proc. 1st NEO and Debris Detection Conference, Darmstadt, Germany, 22-24 January 2019, published by the ESA Space Safety Programme Office
Ed. T. Flohrer, R. Jehn, F. Schmitz (http://neo-sst-conference.sdo.esoc.esa.int, January 2019)

the debris population will experience an increase of about 30% in the next 200 years [21]. This growth is expected to be predominantly driven by catastrophic collisions. With the current levels of impact flux, about five events per year can be expected, which includes a catastrophic event every 5 to 9 years [21]. This could lead to the effect known as Kessler syndrome [22]: a cascade of collisions started by a single catastrophic event, which can culminate in a very dense debris distribution that makes the use of some LEO regions unsafe.

Amid the growing debate in this area, questions are raised about whether new regulations should be implemented. A synthesis of the current knowledge about space debris and the current and future debris mitigation guidelines is necessary as countries are currently developing their own space sector regulations. International guidelines are also being revised, with the third edition of ISOISO 24113 - Space debris mitigation requirements due for release in early 2019, with further restrictions on de-orbit amongst other mitigation measures [23].

Collision risk whilst the satellite is operational is considered from the early stages of mission design. A portion of the propellant budget is allocated for performing collision avoidance manoeuvres (CAMs). However, the collision risk for a de-orbiting satellite performing an uncontrolled de-orbit is not. At this point the satellite is completely uncontrolled and therefore has no capacity for avoiding a collision with another defunct satellite or any other piece of space debris. It is paramount that mission designers start to consider the collision risk during the de-orbit phase to prevent further debris generation. Furthermore, even active satellites are at risk and a clear example of this is the defunct Kosmos-2251 satellite colliding with and destroying the functioning Iridium 33 satellite [24]. The collision increased the number of trackable debris by more than 1600 pieces. Hence, this paper looks at defining the on-orbit collision risk of a satellite during the de-orbit phase and minimising it by considering shorter de-orbit times than the standard of 25 years.

2 METHODOLOGY

2.1 Reference Mission

In order to conduct a meaningful study the work presented in this paper is based on a real mission which is currently in Phase A and for which Thales Alenia Space (TAS) in the UK are the prime contractor. The 500 kg class satellite is designed for Earth observation and has an operational lifetime of 4 years. This class of satellite was ideal for the study as often they consider an uncontrolled de-orbit and so had already incorporated the 25 year rule into the design. This meant it was simple to compare the baseline against the adjustments necessary to meet lower de-orbit times. It is also the type of mission for which new regulations would impact most significantly.

The satellite's operational orbit is a Sun-synchronous orbit at approximately 830 km with Local Time Descending Node (LTDN) 09:30. The operational orbital elements of the mission are given in Table 2-1. The satellite embarks a hydrazine monopropellant propulsion system. During its lifetime it requires approximately 16.5 kg of fuel for all other mission aspects, excluding the End of Life (EoL) manoeuvre. The parameters for the orbit, the satellite's size and mass, as well as the Specific Impulse (I_{sp}) considered for the thrusters at EoL have all been taken directly from this phase A project, so the paper is truly representative of a current and typical LEO mission.

Table 2-1. Orbital parameters of reference mission.

Orbital parameter	Value
Semi-major axis (a)	7195.605 km (corresponding to a 29 day repeat cycle)
Eccentricity (e)	0.001165
Inclination (i)	98.701^o
Right Ascension of the Ascending Node (Ω)	62.4731 + 0.98564735*N
Argument of Perigee (ω)	90.0^o

2.2 Software

2.2.1 DRAMA

A key toolset used in this study is ESA's Debris Risk Assessment and Mitigation Analysis (DRAMA) software. This is the standard suite of tools used by European industry to support debris mitigation analysis.

There are five tools which make up DRAMA and these are outlined in Table 2-2.

Table 2-2. DRAMA toolset and corresponding functionalities.

ARES	Assessment of Risk Event Statistics To consider the possible requirements for collision avoidance manoeuvres during a mission.
MIDAS	MASTER (-based) Impact Flux and Damage Assessment Software To model the collision flux and damage statistics for a mission.
OSCAR	Orbital Spacecraft Active Removal To analyse the disposal manoeuvre performed by a space system at the end of its useful lifetime.

CROC	Cross Section of Complex Bodies To compute the cross-section of a self-designed complex body.
SARA	Re-entry Survival and Risk Analysis Combines two tools for the re-entry (SESAM) and risk (SERAM) analysis: SESAM Spacecraft Entry Survival Analysis Module To model the re-entry of a space system into the Earth's atmosphere. SERAM Spacecraft Entry Risk Analysis Module To assess the risk on-ground of objects surviving re-entry.

Initially OSCAR was used to generate the evolving orbital parameters over the whole de-orbit phase; the time between completion of the EoL manoeuvre and re-entry into the Earth's atmosphere (with a 5% margin). The parameters inputted to OSCAR for this study are given in Table 2-3.

Table 2-3. Defined inputs used in OSCAR tool.

Parameter	Value
Starting orbit	Given by parameters in Table 2-1.
End of Life Date	01.07.2030
Mean Anomaly	0
Cross-sectional area	$4.825497 m^2$
Mass	448.6 kg
Specific Impulse	196.4
Solar Activity	Latest prediction by ESA

These values were taken from the reference mission. The reference satellite was considered to be tumbling so the cross-sectional area was calculated to be 4.83 m^2 using CROC. The latest predictions method was used for the solar activity since most of the de-orbit strategies used span over 11 years which is the solar activity cycle.

The following parameters were outputted by OSCAR to represent the spacecraft's evolving orbit throughout de-orbit with a time step of two days (this was considered sufficient to give representative results):

- Date
- Mean Julian Date
- Semi-major axis
- Eccentricity
- Inclination
- Right Ascension of the Ascending Node (RAAN)
- Angle of Perigee (AoP)
- Mean Anomaly (MAN)

Each of these orbits have different levels of debris and therefore, present a different probability of collision.

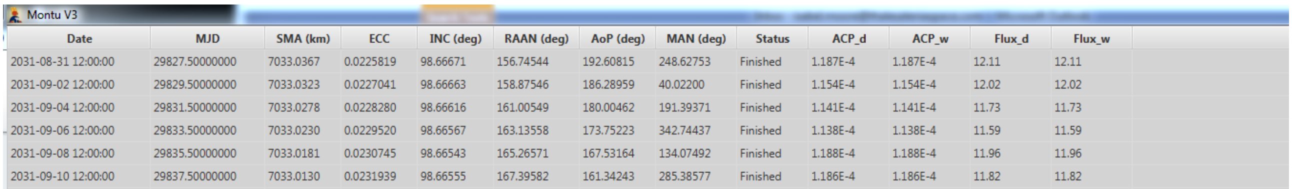
ARES has four functionalities but only one of them was used in this study. Functionality 1 generates two annual collision probabilities for a specific orbit: one for the "detected population of debris" and one considering the "whole population of debris". The fluxes of debris for these two populations are also given for reference. In this study only the Annual Collision Probability (ACP) for the whole population was extracted since collisions can occur with both detected and not detected debris.

Throughout this study the ACP only refers to collisions which are considered catastrophic. A catastrophic collision in this paper is a collision whose energy-to-mass ratio (EMR) exceeds 40 J/g. This is a typically accepted value for the EMR threshold for a catastrophic collision [25]. A collision exceeding this EMR would completely "destroy the satellite and/or lead to a massive fragmentation". It is these destructive collisions which have the potential to render orbits unusable for many years to come and it is for this reason that the study focuses on them.

Considering collision probability during the de-orbiting phase is a more complex task than ARES was designed for. The tool was not designed to deal with an evolving orbit. For instance, with the two day time step OSCAR captures more than 4500 different orbits for the standard 25 year scenario. This data would need to be manually typed into ARES and ran for each scenario. Therefore, in order to generate the results an automation of running ARES was required.

2.2.2 Montu

Montu is a proof of concept Java application to link the OSCAR and ARES tools from the DRAMA toolset. It enables multiple orbits generated by the OSCAR tool to be sequentially analysed by the ARES tool, collating and summarising the results in a simple Graphic User Interface (GUI), see Fig. 2-1. The tool imports an OSCAR output file and then executes ARES for each orbit in turn whilst storing the ARES results and displaying the outcomes. The output from Montu is the ACP for each of the orbits through which the satellite passes during the whole de-orbit phase. At the end of



Montu V3

Date	MJD	SMA (km)	ECC	INC (deg)	RAAN (deg)	AoP (deg)	MAN (deg)	Status	ACP_d	ACP_w	Flux_d	Flux_w
2031-08-31 12:00:00	29827.50000000	7033.0367	0.0225819	98.66671	156.74544	192.60815	248.62753	Finished	1.187E-4	1.187E-4	12.11	12.11
2031-09-02 12:00:00	29829.50000000	7033.0323	0.0227041	98.66663	158.87546	186.28959	40.02200	Finished	1.154E-4	1.154E-4	12.02	12.02
2031-09-04 12:00:00	29831.50000000	7033.0278	0.0228280	98.66616	161.00549	180.00462	191.39371	Finished	1.141E-4	1.141E-4	11.73	11.73
2031-09-06 12:00:00	29833.50000000	7033.0230	0.0229520	98.66567	163.13558	173.75223	342.74437	Finished	1.138E-4	1.138E-4	11.59	11.59
2031-09-08 12:00:00	29835.50000000	7033.0181	0.0230745	98.66543	165.26571	167.53164	134.07492	Finished	1.188E-4	1.188E-4	11.96	11.96
2031-09-10 12:00:00	29837.50000000	7033.0130	0.0231939	98.66555	167.39582	161.34243	285.38577	Finished	1.186E-4	1.186E-4	11.82	11.82

Figure 2-1. Screengrab of MONTU running.

the simulation the results can be saved to a Comma Separated Value (CSV) file which can be opened in Microsoft Excel for further analysis. Various options are provided in Montu to alter the analysis performed in line with the options provided by ARES: Future scenario, spacecraft collision area, EMR and spacecraft mass. Currently the tool does not post-process the results, however, more functionalities can be added.

2.2.3 Population Files

In order to calculate the collision probability for an orbit, ARES makes use of the Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) model for natural and man-made space particles. MASTER includes all known debris sources and the expected evolution of their respective orbits. The most recent MASTER population files [26] are those from 2009. They cover a time span from the 1st of May 2001 to the 1st of May 2050. This presented a problem in this study as for some of the cases re-entry did not occur until 2055. The collision probability outputs for these last 5 years are just repetitions of the one from the 1st of May 2050. Therefore, a linear fitting function to those last 5 years was applied. The influence on the results should not be significant as the last years for all cases are the ones with the lowest collision probability.

Predictions are required for all dates after the 1st May 2009. These can be based on three different future scenarios which are built around different levels of adherence to mitigation guidelines, each associated to a different group of population files: Business as Usual, Intermediate Mitigation and Full Mitigation. Table 2-4 shows how the three scenarios are defined.

Table 2-4. Definition with respect to debris mitigation measures of the future scenarios considered in DRAMA.

	Business as Usual (BAU)	Intermediate Mitigation (IM)	Full Mitigation (FM)
Explosion Traffic	BAU	Reduced steadily to 5% by 2020	Reduced steadily to 5% by 2020
Solid Rocket Motor (SRM) Firings	BAU	Reduction from 100% in 2020 to 5% in January 2030	Reduction from 100% in 2020 to 5% in January 2030
Maintenance & Reparation Operations (MRO) prevention	n/a	Total prevention after 1 January 2015	Total prevention after 1 January 2015
Rocket Bodies (RB) Deorbit	n/a	n/a	For perigee < 2000 km, 100% success rate after 1st January 2015
PL Deorbit	n/a	n/a	For perigee < 2000 km, 100% success rate after 1st January 2020
RB & PL Reorbit	n/a	n/a	For GEO objects in accordance with IADC guidelines: 100% success rate after 1 January 2020

All three scenarios were considered in this study. However, the main focus was on that of Full Mitigation. This was considered to be the most truly representative as it is the only future scenario which factors in satellites performing some sort of de-orbit manoeuvre at EoL.

2.3 Data post-processing

The collision probability is calculated in DRAMA using the laws of kinetic gas theory. The mean number of collisions against an object passing through a stationary medium is given by Eq.1.

$$c = vDA_c\Delta t \tag{1}$$

Where Ac is the collision area, v is the velocity of the object, Δt is the time spent travelling through the medium and D is the particle density of the medium. In the context of DRAMA, the particle density represents the debris density (number of pieces of debris). The time considered in ARES is one year in order to provide an annual probability. The collision area of the satellite is the same as the cross-sectional area used for OSCAR.

The probability of no collisions can be expressed using Poisson statistics defined in Eq. 2.

$$P_{i=0} = e^{-c} \qquad (2)$$

Where i is equal to the number of collisions.

And therefore the probability of having any number of collisions is given in Eq.3.

$$P_{i\geq 1} = 1 - e^{-c} \qquad (3)$$

If c is a very small number it is possible to approximate the result of Eq. 3 as c. The probability of having any number of collisions in the given time period is then equal to the mean number of collisions which take place in that same time period.

However, as stated above, each orbit outputted from OSCAR represented a period of two days. In order to scale the ACP down to two days the time period considered had to be modified. In Eq.1 the value was multiplied by 365 days as this is the Δt considered. To obtain the 2 day collision probability (2DCP):

$$2DCP = \frac{ACP}{365} * 2 \qquad (4)$$

This gives a value for the satellite collision probability during each two day period. Therefore the probability of the satellite never having a collision during the entire de-orbit phase is the multiplication of the inverse of all of these assumed independent events.

$$P_{NC} = (1\text{-}2DCP_1)*(1\text{-}2DCP_2)*\ldots*(1\text{-}2DCP_n) \qquad (5)$$

This allowed an overall de-orbit phase collision probability to be obtained using Eq.6.

$$P_C = 1\text{-}P_{NC} \qquad (6)$$

This enabled a direct comparison between overall collision probability for the entire de-orbit phase for different de-orbit times and strategies. Within the context of this study only different de-orbit times were considered. A range of de-orbit times were studied: 25, 20, 15, 10 and 5 years and for each one, the three different future scenarios were considered: FM, IM, BAU. Longer de-orbit times were not considered as 25 years is the current worst case for a compliant spacecraft. The next step was to investigate the impact of shorter de-orbit times on the satellite. It was outside the scope of this study to consider passive de-orbit devices. Therefore, to reduce the de-orbit time the EoL perigee must be lowered which requires an extra amount of fuel. These values were also obtained using OSCAR. The mission baseline tank was then considered along with 2 larger tanks. By comparing the leftover tank capacity for the EoL manoeuvre with the propellant required for the different de-orbit times it is possible to select a tank for each de-orbit time. This allows a direct comparison of the system impact between the five de-orbit times considered.

3 Results

3.1 De-orbit collision probability

As discussed in the previous section, ARES outputs 4 main results: collision probability and flux for both the detected and the whole population of space debris. Regardless of whether the debris can be detected or not, it can still potentially catastrophically collide with the de-orbiting satellite. Consequently, it is the value for the collision probability given for the whole population that is the useful parameter for this study. Besides, both values were the same for the detected population and the whole population for the orbits considered. This is because the orbits through which the satellite passes are less than 800 km altitude, which is a relatively low altitude, and because objects which can cause a catastrophic collision need to have high kinetic energy. Larger debris are more likely to have higher kinetic energies, and if in addition to that they are in low altitudes they are more easily detectable. According to DRAMA's radar calculations all the debris with catastrophic collision potential are detectable for this mission.

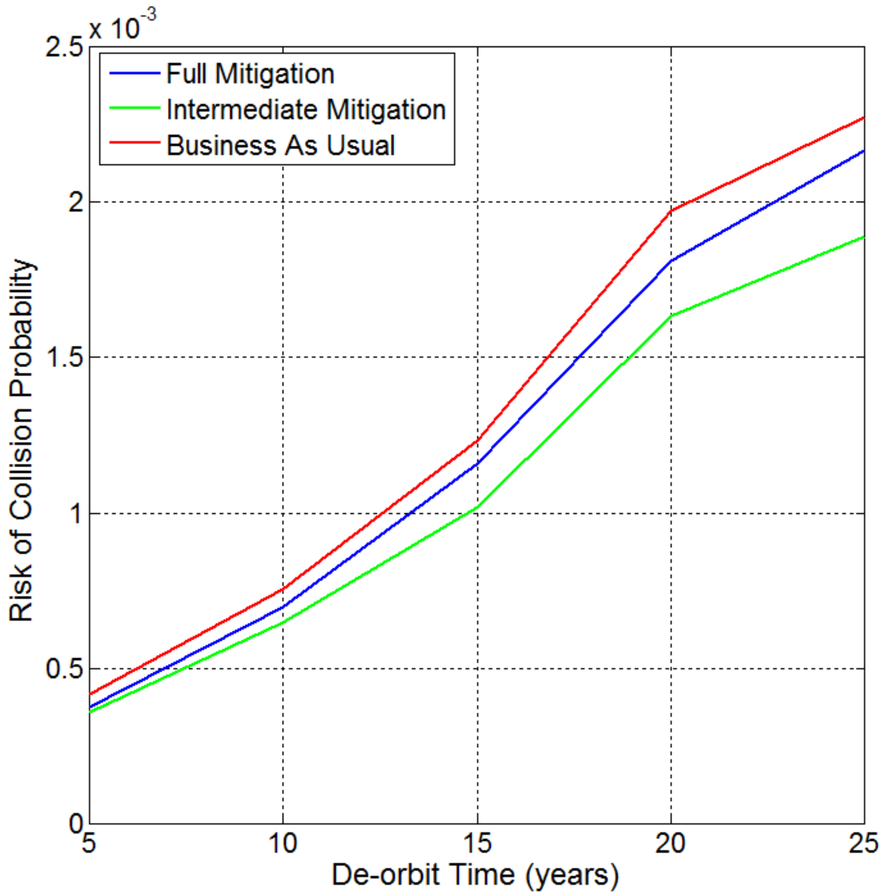


Figure 3-1. Graph showing collision risk against de-orbit time considering the three DRAMA future scenarios.

Figure 3-1 shows the probability of having at least one catastrophic collision for each de-orbit time for each future scenario. The first thing to note is that the BAU scenario is the worst of the three, and surprisingly, intermediate mitigation is the best one with the lowest collision probabilities. There is a logical explanation for this in how the three future scenarios have been defined. As explained earlier, full mitigation is the only scenario where full compliance with the 25 year de-orbit limit is applied. This is the only difference between Full and Intermediate Mitigation. With no other satellites purposefully performing de-orbit within 25 years, the congestion of lower orbits is decreased, especially for the 25 year de-orbit case. As it can be seen in Figure 3-1, the trend is similar for the three scenarios, although the Intermediate Mitigation scenario increasingly diverges from the others as de-orbit time increases. However, the current mitigation guidelines rely on 25 years being the ideal de-orbit time and are targeting 100% compliance. Therefore, Full Mitigation is the most representative scenario to further analyse and discuss the results.

The collision probability appears to have an approximately linear relationship with de-orbit time when comparing between 5 and 20 years. As expected, the longer the de-orbit time, the higher the likelihood of collision. The probability for 25 years is more than 6 times higher than the probability for 5 years, more than 3 times higher than the probability for 10 years and twice as high as the probability for 15 years, see Table 3-1.

Table 3-1. Collision Probability for each de-orbit time and comparison against 25 year standard.

De-orbit time (years)	De-orbit Collision Probability		Ratio with 25 year baseline
25	2.3E-03	1/442	n/a
20	1.8E-03	1/552	1.25
15	1.2E-03	1/861	1.95
10	7.0E-04	1/1436	3.25
5	3.7E-04	1/2683	6.07

Table 3-2 shows the orbits where the maximum collision probability was observed. There is a certain level of consistency in the perigee and more prominently in the apogee altitude. Both the RAAN and the AoP are considerably different for each orbit. There is some consistency between the dates which have the highest collision probability. They all occur towards October or very beginning of November, including Intermediate Mitigation and Business As Usual scenarios. More simulations would need to be ran to understand if there is any meaning behind this result.

Table 3-2. Orbital parameters for identified obit with highest collision probability for each de-orbit time considered with the Full Mitigation future scenario.

	FM25	FM20	FM15	FM10	FM5
Apogee	743	731	749	757	753
Perigee	488	481	439	439	388
RAAN	26	37	340	280	258
AoP	9	348	92	246	276
Inclination	98.7	98.7	98.7	98.7	98.7
Max. Collision Probability	1.27E-06	1.15E-06	8.60E-07	7.18E-07	9.26E-07
Date	31-Oct-36	31-Oct-36	01-Nov-34	05-Oct-33	10-Oct-32

Figure 3-2 shows how the collision probability varies throughout the 20 year de-orbit case considering the full mitigation scenario. The apogee and perigee altitudes are also shown. The overall trend of the data is that collision probability reduces as the apogee becomes lower, potentially due to the fact the satellite is crossing less orbits. When the apogee drops to about 650 km the collision probability experiences a rapid decrease up until the date of atmospheric re-entry. This trend is the same one found for the 25 year case and is consistent across the three future scenarios. For lower de-orbit times the trend is also similar but the decrease in collision probability is more rapid from the beginning.

3.2 Impact on platform

The impact on the platform does not consider a change of the monopropellant hydrazine propulsion system considered for the mission. Table 3-3 shows the three tanks considered in this project. These three tanks were identified in the context of the Phase A study. The ATK 80392-1 tank is the mission baseline tank. It is possible to accommodate the larger tanks within the platform, albeit with some re-shuffling of equipment. The satellite has a launcher interface ring of 937 mm and can therefore accommodate any of the three tanks. There would be no major impact of embarking the larger tanks except with respect to the increase in mass, fuel and therefore, cost.

Figure 3-3 shows which tank is suitable for this satellite for each de-orbit time.

Table 3-4 summarizes the delta-V and fuel required for each de-orbit time as well as the impact on the satellite mass.

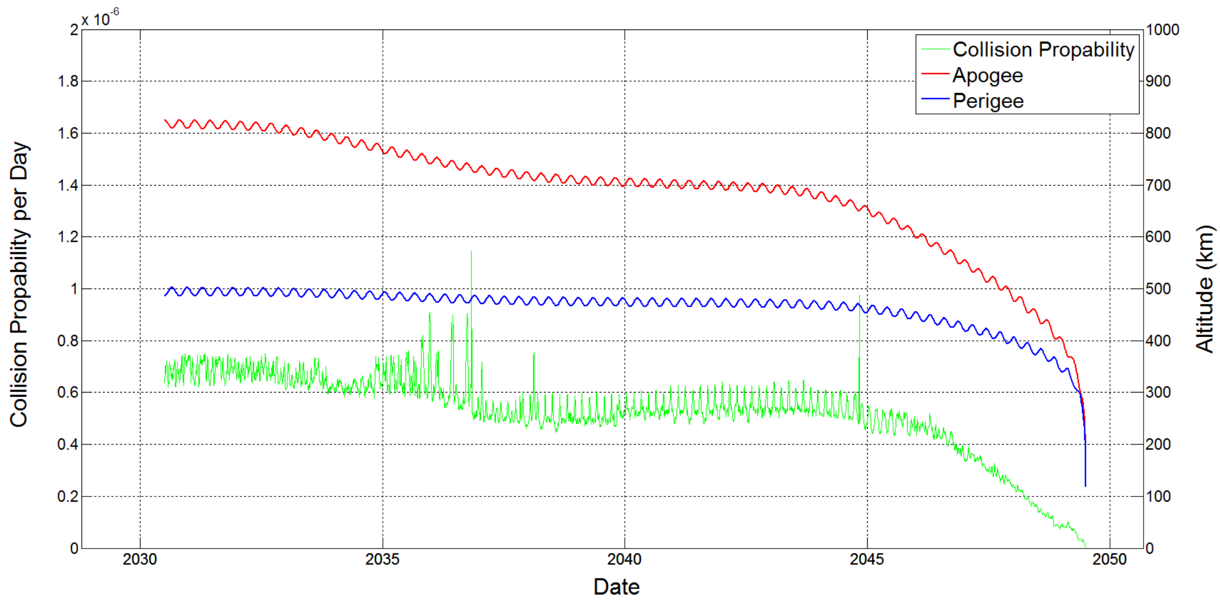


Figure 3-2. Graph showing how collision probability and the apogee and perigee of the orbit vary with time for the 20 year de-orbit case.

Table 3-3. Parameters of the three tanks considered in this paper.

Tank	Mass of Tank (kg)	Height (mm)	Tank Diameter (mm)	Capacity (kg)
ATK 80392-1	5.63	507.7	419	37
Airbus BT01	8.5	474	480	39
ATK 80486-1	6.01	484	484	45

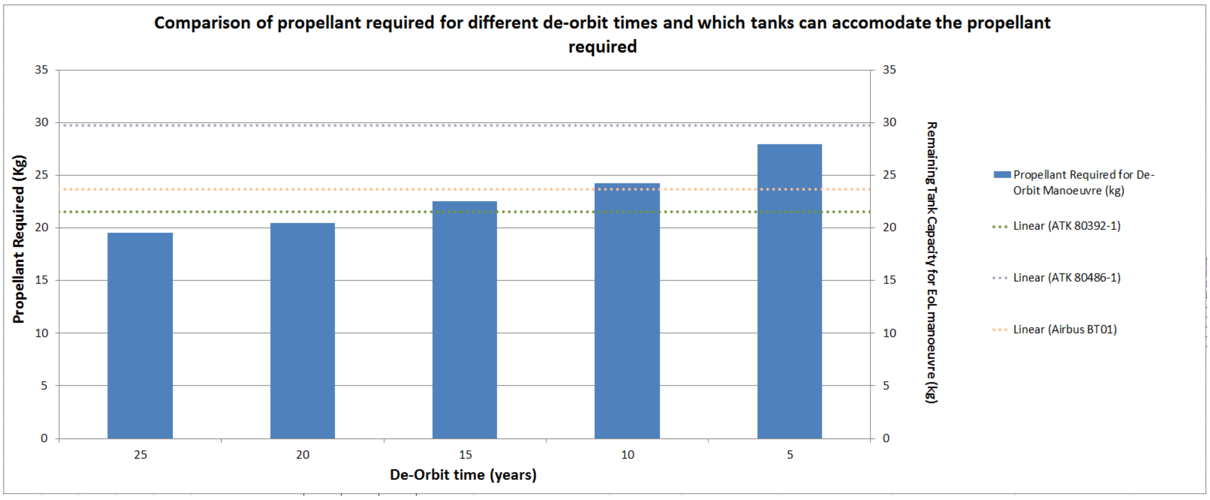


Figure 3-3. Graph to show suitability of each tank to the different de-orbit times.

Table 3-4. Delta-V and propellant required for each de-orbit time and the consequential additional mass required compared to the baseline of 25 years in terms of fuel and tank mass.

De-orbit Time (years)	Delta-V required for EoL manoeuvre (m/s)	Propellant required for EoL manoeuvre (kg)	ΔFuel Mass compared to baseline (25 year solution) (kg)	ΔTank mass compared to baseline (25 year solution) (kg)
25	83.69	19.55	0	0
20	85.94	20.46	0.91	0
15	96.09	22.52	2.97	2.87
10	101.53	24.27	4.72	0.38
5	116.32	27.92	8.37	0.38

The baseline tank is well suited to the 25 year de-orbit case. This is unsurprising as this was the scenario the satellite was designed for. There is still capacity available in the baseline tank for additional fuel, this is usually allocated as extra margin during a Phase A study. However it is interesting to note that this additional volume could instead be used to consider de-orbiting in 20 years as the baseline tank is maintained for this de-orbit time. On the other hand, de-orbiting within 15 years requires 3 kg more of fuel and the use of a larger tank, for instance, the BT01. This tank does not have the best weight to propellant capacity ratio and possibly a better tank could be found. The two shortest de-orbit times require using the largest tank identified here. In practise, a satellite would embark a tank with the closest capacity to the amount of required fuel, hence, a better fit for the two shortest cases could possibly be found. For simplicity, only the tanks identified from the Phase A study work have been considered. The largest tank can carry 46 kg of hydrazine with the mass penalty of the tank itself being less than a kilogram. The total increase in mass (considering delta-tank and fuel mass) for 10 year and 5 year case is 5 kg and 9 kg, respectively. In percentages, the increase in mass with respect to the baseline de-orbit fuel mass and tank mass is 3.6%, 29.9%, 20.2% and 34.7% for 20, 15, 10 and 5 years, respectively. In reality a propulsion engineer would select the most suitable tank in terms of mass and size, avoiding a tank which would require unnecessary fuel to reach capacity, so the system impact could be even less.

4 DISCUSSION

It is clear changing to 20 years does not impact the platform since the same tank can be used. That would reduce the collision probability by 22%. Shorter de-orbit times have a larger impact but are still feasible for this mission. The main impact is the increase in mass, which as previously stated, does not exceed 9 kg for the shortest de-orbit time, which is only 2% of the satellite's dry mass. Nominally, leftover tank capacity is utilised for additional fuel and would be used to extend the mission lifetime. However, the collision risk analysis, which is higher than other accepted risk thresholds, has shown that this fuel could be better spent reducing de-orbit times and consequentially reducing the chance of creating more space debris. Therefore keeping a mission to its intended lifetime could allow future missions to operate with less danger of colliding with debris. However, it is up to the agencies and governments to impose this as operators will want to increase the duration of their mission.

Probabilities of 1/1,000 and 1/10,000 are ESA's thresholds for on-orbit break-up (excluding impacts with debris and meteoroids) events and on-orbit manoeuvres to avoid collisions, respectively [27]. Moreover, ESA's Space Debris Mitigation Compliance Verification Guidelines state that "The probability of an accidental break-up due to an impact or collision against an orbiting object is always not negligible" [27]. Even the 5 year de-orbit time represents a probability higher than 1/10,000 and the two worst cases have a collision risk higher than 1/1,000. Moreover, the 25 year case has a probability of collision higher than 1/500. Considering these results, the space community should take into consideration the risk of de-orbiting satellites causing a catastrophic collision. A recommendation from the study is that all satellites not performing a controlled re-entry should adhere to an acceptable de-orbit collision risk set by the agencies. The de-orbit strategy is then specific to each satellite and not a blanket rule. This will help to prevent further creation of debris and high risk orbits becoming even more congested.

The tool can clearly be used to identify better de-orbit strategies that minimize risk. An improvement to the study and future work would be to implement up-to-date population files and consider future population files which incorporate mega-constellations. Identifying alternative de-orbit strategies where de-orbit time is not the only altered parameter will also be possible. For instance, circularising the orbit after lowering the perigee would reduce the number of orbits being crossed and would avoid the high-risk orbits. The purpose of doing so will be to investigate different de-orbiting strategies which would allow satellites to meet new regulations for de-orbit collision risk.

5 CONCLUSION

Recent studies suggest that LEO may have already reached a level of instability [21]. Even with high levels of compliance to the 25 year rule a considerable increase in the LEO region debris population led by catastrophic collisions will likely take place. Currently there is no acceptable risk assigned to the de-orbiting phase for collisions with other satellites or pieces of debris. This is a potential oversight with respect to protecting the space environment from the creation of thousands more debris. The benefits of using a shorter de-orbit time are very clear: the shortest case has a six times lower chance of collision than the longest one. Moreover all of them have a risk higher than 1/10,000 to catastrophically collide with another object and 25, 20 and 15 year cases have a risk higher than 1/1,000. These thresholds are used by ESA for in-orbit break-up risk and in-orbit collisions before EoL, respectively [27]. A collision risk of 1/1000 is considered by the authors to be too high and therefore collision during de-orbit should be considered an important aspect of debris mitigation and mission design. Furthermore, the impact on the satellite for adopting a shorter de-orbit time is limited to an increase in fuel and tank mass; reducing the collision risk by a factor of six requires less than 9 kg (about 2% of the satellite's dry mass). Space agencies should consider introducing a threshold for de-orbit collision risk so that future missions adhere to it. The tool developed for this study, Montu, can be used to find de-orbit strategies that adhere to this threshold. Coupling this tool with up-to-date population files with improved future predictions, currently under consideration within TAS, would make a state-of-the-art addition to DRAMA.

6 REFERENCES

1. ESA Space Debris Office. (2018). *ESA's Annual Space Environment Report,* Issue 2, Darmstadt: ESA.
2. Liou, J.-C. & Krisko, P. (2013). An update on the effectiveness of postmission disposal in LEO. In *64th International Astronautical Congress*, Beijing, China.
3. Rex, D. (1998). Will space run out of space? The orbital debris problem and its mitigation. *Space Policy*, **14**(2), 95-105.
4. Werka, R.O. (1992). *United States Patent No.*

5,082,211. Los Angeles, California: Teledyne Industries, Inc.
5. Rex, (D). (1997). Space debris mitigation and space systems design. *Acta Astronautica*, **41**(4-10), 311-316.
6. Pardini, C. & Anselmo, L. (1999). Assessing the Risk of Orbital Debris Impact. *Space Debris*, **1**(1), 59-80.
7. Kriskoa, P.H., Johnsonb, N.L. & Opielaa, J.N. (2001). EVOLVE 4.0 orbital debris mitigation studies. *Advances in Space Research*, **28**(9), 1385-1390.
8. U.S. Government. (2000). *U.S Orbital Debris Mitigation Standard Practices*. USA. Available at (http://www.iadc-online.org/References/Docu/USG_OD_Standard_Practices.pdf) (date accessed: 22nd November 2019).
9. Inter-Agency Space Debris Coordination Committee. (2002). *Inter-Agency Space Debris Coordination Committee Space Debris Mitigation Guidelines*. UN Doc. A/AC.105/C.1/L.260.
10. Inter-Agency Space Debris Coordination Committee. (2014). *Support to the IADC Space Debris Mitigation Guidelines*. Steering Group, Working Group 4: Action Item 26.2.
11. Inter-Agency Space Debris Coordination Committee. (2007). *IADC Space Debris Mitigation Guidelines*. Steering Group, Working Group 4: Action Item 22.4.
12. Liou, J.-C. (2011). An active debris removal parametric study for LEO environment remediation. *Advances in Space Research*, **47**(11), 1865-1876.
13. Rossi, A., *et al*. (no date). *Long term evolution of the space debris population.* Pisa: CNUCE Institute & Italian Space Agency.
14. Rossi, A. (1997). Long term Evolution of Earth Orbiting Debris. *International Astronomical Union Colloquium*, **165**, 367-374.
15. Anselmo, L., Rossi, A. & Pardini, C. (1999). Updated results on the long-term evolution of the space debris environment. *Advances in Space Research*, **23**(1), 201-211.
16. Walker, R. (2002). *Update of the ESA Space Debris Mitigation Handbook: Executive Summary*. UK: QinetiQ (ESA Contract 14471/00/D/HK).
17. ESA. (2013). *Which environmental laws and regulations impact most on the space sector?* Available at http://www.esa.int/Our_Activities/Space_Engineering_Technology/Clean_Space/Which_environmental_laws_and_regulations_impact_most_on_the_space_sector (date accessed: 5th January 2019).
18. Alby, F. (no date). *Les Debris Spatiaux*. Presentation, CNES.
19. CNES. (2017). *Débris spatiaux: où en est-on ?* Available at https://cnes.fr/fr/dossier-debris-spatiaux-ou-en-est (date accessed: 25th November 2018)
20. Lioua, J.-C. & Johnsonb, N.L. (2008). Instability of the present LEO satellite populations. *Advances in Space Research*, **41**(7), 1046-1053.
21. Liou, J.-C., *et al*. (2013). Stability of the future LEO environment – an IADC study. In *6th European Conference on Space Debris*, Darmstadt, Germany. DOI: 10.13140/2.1.3595.6487.
22. Kessler, D.J. & Cour-Palais, B.G. (1978). Collision frequency of artificial satellites: The creation of a debris belt, *JGR Space Physics*, **83**(A6), 2638-2646.
23. Stokes, H. (2017). Status of the ISO Space Debris Mitigation Standards. In *7th European Conference on Space Debris*, Darmstadt, Germany.
24. Kelso, T.S. (2009). *Analysis of the IRIDIUM 33 – COSMOS 2251 collision.* Colorado Springs, Center for Space Standards & Innovation.
25. Gelhaus, J., *et al*. (2014). *DRAMA Final Report: Upgrade of ESA's Space Debris Mitigation Analysis Tool Suite,* Revision 1.1. ESA/ESOC Contract No. 4000104977/11/D/SR.
26. Oswald, M. & Stabroth, S. (2010). MASTER *Final Report: Maintenance of the ESA MASTER- Model*, Revision 1. ESA contract 21705/D/HK.
27. ESA. (2015). *ESA Space Debris Mitigation Compliance Verification Guidelines*, Issue 1, Reference: ESSB-HB-U-002.