Astrium perspective on space debris mitigation & remediation

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Abstract
The density of space debris has been increasing for decades. The situation is critical especially in LEO. Astrium is aware of the space debris problem and proposes a four-pillar debris mitigation approach containing **prevention** of debris generation by new launches, **avoidance** of debris by active spacecraft, **removal** of debris (large and small) and the **survival** of in-orbit objects. There is a long-term experience in all these four pillars of mitigation as well as on system and architecture level. The paper will describe the overall mitigation strategy and the different approaches in the four pillars to avoid further debris.

1. Introduction

The density of space debris has been increasing for decades, with the rising number of satellites, rocket bodies and mission-related debris, and with the fragmentation events. The situation is critical especially in LEO. The destruction of one object yields an additional set of debris, and hence a significant increase of the collision probability for many other objects finally resulting in a chain reaction. Experts predict one large collision every 5 years in 2050 and an acceleration of the chain reaction. This would have a severe impact to the LEO domain as useful regime for satellite operations. Already today space debris is a serious problem which is visible through the regular avoidance manoeuvers of the ISS, the threat for sun-synchronous orbits due to the potential destruction of de-functional large Earth observation satellites but also the risk on the safety of ground population due to uncontrolled re-entries (Rosat). Astrium is aware of the space debris problem and proposes a four-pillar debris mitigation approach as drafted in Fig. 1 containing prevention of debris generation by new launches (mainly covered by internal analyses), avoidance of debris by active spacecraft (S/C) (mainly covered by [1]), removal of debris (large and small, mainly covered by internal studies and [2]) and the survival of in-orbit objects (mainly covered by [3]). There is a long-term experience in all these four pillars of mitigation as well as on system and architecture level.

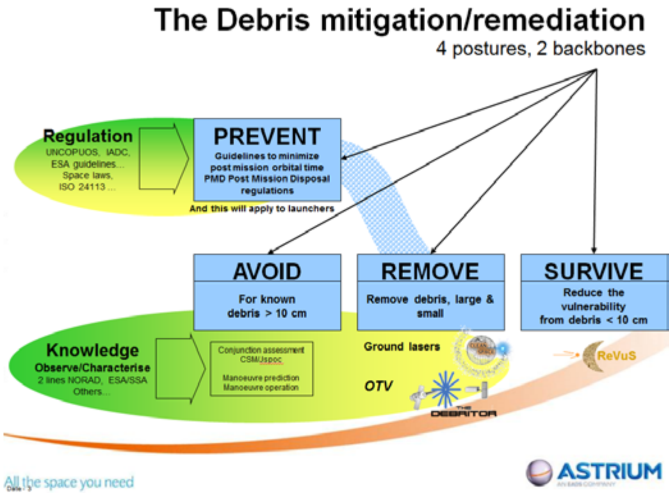

Figure 1: The Astrium four-pillar debris mitigation approach

2. Prevention

The generation of additional debris shall be prevented by Post Mission Disposals (PMD) of satellites and launchers to reduce the maximum lifetime in operational orbits to 25 years after the end of operations, by transferring them into graveyard orbits according to the IADC guidelines or by directly re-entering into the Earth atmosphere. The PMD shall be ensured by on-board capabilities. This has an impact on the system itself. It may also be provided by a special de-orbit kit attached into the satellite by an external removal service. In all cases the cost of the solutions is a strong driver. So it has to be required by regulation and license issues.

In general the PMD requirements are similar, beginning with the fundamental IADC regulations, followed by the code of conducts, guidelines, recommendations, standards (Europe, ESA, NASA, UNCOPUOS, ITU, ISO) and the laws at national levels.

Besides all their communalities there are a few subtle differences in the PMD requirements as listed in Table 1. This has to be considered already at the design stage, sometimes before knowing from where the satellite is going to be launched. Especially the casualty risk is a driver for the design because for larger objects it may be above 10^{-4} [4] making a controlled re-entry mandatory.

Table 1: Requirements for the removal of objects

	Direct controlled re-entry	**Uncontrolled re-entry**	**Success**	**Residual debris & casualties**	**Retrieval (Active debris removal)**
IADC chapter 5.3	preferred	<EOL+25yrs	No	None	Accepted
French Space act Article 40, 44	Strongly recommended	<EOL+25yrs	90% over the PMD duration, computed after launch	DCR : 2.10-5 + 99,999% drop zone, UCR : 10-4	?
European Code of conduct, chapter 5.2	mentioned	<EOL+25yrs	90% at EoM	10-4, except when FR is launching state	?
US NASA STD8719 chapter 4.6	mentioned	<EOL+25yrs or <Launch+30yrs	90% at EoM	DCR : <15J drop zone + 10-4, UCR: 10-4	Accepted, <EOL+10yrs

The success rate of PMD is very often taken at 90% as required by the regulations. This is far away from the real world: for example only 76% (13 out of 17) GEO satellites have succeeded their PMD in 2011 [5] in LEO the success rate is even lower. But even for a PMD success rate of 90% the number of objects will increase as shown by the red graph in Fig. 2. To stabilize the future environment current analyses show that 5 large objects have to be removed per year additionally, beginning in 2020 [6].

The effort for a typical LEO PMD is equivalent to a significant part of the orbit control budget. So with this amount of fuel the mission time could be extended. Thus deciding to stop the operational life of a satellite, and start the passivation and manoeuvers is not an easy decision when the satellite is still providing the operator with significant income.

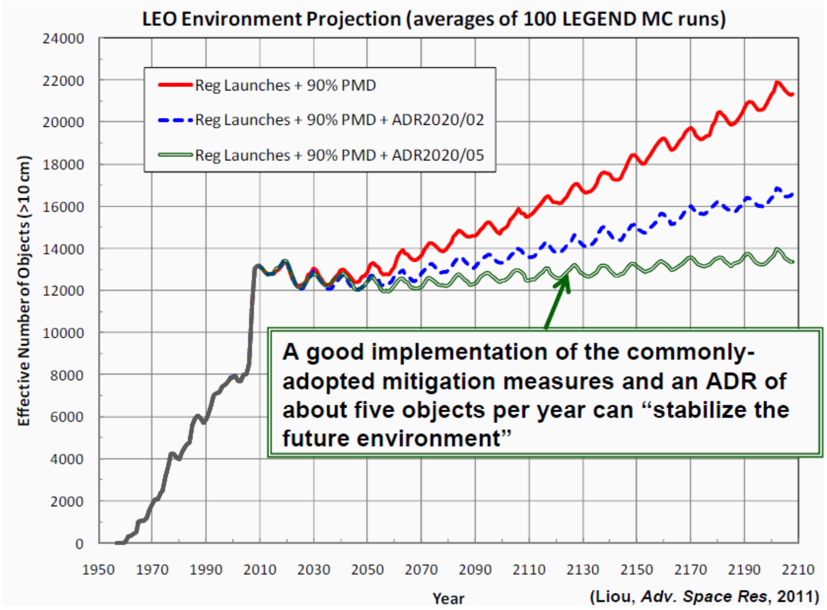

Figure 2: Development of space debris population depending on different PMD and removal strategies [6]

The reasons for a satellite operator to consider the PMD as drafted in Fig. 3 are

- Risk/liability in case its S/C could cause damage
- Regulation
- Scarcity (e.g. slots in GEO)
- Penalty.

For LEO the main reasons are regulation and license issues. Scarcity is an additional important factor for GEO. Penalty, risk and liability are less strong reasons to perform a PMD.

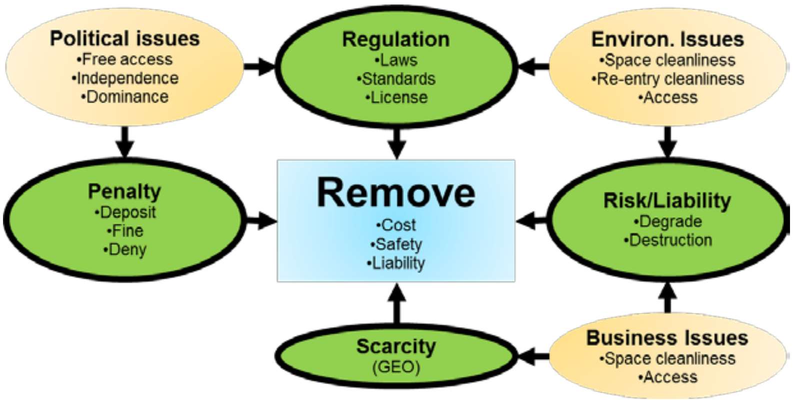

Figure 3: Motivations for removal

So depending on the additional value of the mission extension an external PMD service through a piggy back might be beneficial. This shall be an autonomous device, fully qualified, that would enable a full compliance with the law with zero impact on the client design. Several packs would be available, depending on the orbit and size of the client, e.g.:

- Small satellite LEO 600-800; drag augmentation balloon 20m²
- Large satellite LEO 600-800; drag augmentation sail 100m²
- Large satellite LEO 800-1200; Electrodynamic tether
- Large satellite LEO >1200; solar sails

A de-orbit pack to be embarked as a piggy back is also a building block of an active debris removal (ADR) mission.

3. Avoidance

To avoid objects the debris situation must be known. Currently LEO-objects larger than ca. 10 cm are tracked by the US SSN so that avoidance manoeuvers can be carried out by operational satellites. Also national means (German TIRA or French GRAVES) exist for surveillance and tracking, however additional sensors are needed with improved capabilities in order to tackle the debris problem. In the future, debris location could be known better through a Space Situation Awareness system(s). Astrium has been and is involved in several system studies in this regard, e.g. the current "CO-II SSA Architectural Design" ESA study [1] and the "Assessment Study for Space Based Space Surveillance Demonstration Mission".

From a system point of view the necessary capabilities should be derived from a chain of requirements, beginning from high level mission or customer requirements and flown down to system level. Examples are the high level requirements “reduction of lethal collision risk” and “reduction of catastrophic collision risk”. For both requirements, the to be defined SSA system should reduce collision risk by a tbd amount.

One example for this chain of requirements down to the system capabilities are the current high level ESA SST requirements. Simulations show [1], that in order to reduce the probability of lethal collision by the required 90% compared with the probability without a system, LEO objects of the size of about 5.7 mm must be catalogued. Feasibility of mass cataloguing of the lethal debris is clearly questioned by the tremendous sensing sensitivity required and the subsequent amount of detections to be processed and further correlated. The second example is the reduction of catastrophic collision risk. A catastrophic collision is defined as a collision with Energy to Mass Ratio (EMR) greater than 40 J/g. In LEO, these are objects with a size of a few centimetres which significantly reduces the technical effort compared to the detection of mm-sized objects.

Given the high number of objects to be detected and tracked, an effective surveillance system within the SST segment is expected to:

- Detect new objects in space,
- Set-up a data base containing the orbit of all known objects,
- Re-detect already seen objects, and
- Maintain the objects orbital data base while meeting the accuracy envelope requirement.

3.1 General characteristics of Space Situation Awareness sensor network architecture elements

A possible sensor network is comprised of both ground- and space-based assets. The proposed ground sensors include a surveillance radar, an optical surveillance system and a tracking network (radar and optical). A space-based telescope system may provide significant performance and robustness for the surveillance and tracking of beyond-LEO target objects. In addition to the sensors on-ground infrastructure is required, e.g. data centres for the data processing. All these components have to be linked to support the whole chain from the detection of an object with the sensors, the downlink and processing of the data on ground and the command for a collision avoidance manoeuvre [1].

Ground-based radar

In order to perform the surveillance of objects in LEO orbits (up to 2000 km), the most suitable option is to use ground-based radar. Radar assets are insensitive to weather outage effects and can be operated continuously on a 7d/24h basis. However, the required transmitting power limits the range for reasonably sized surveillance radar to the LEO region. A joint surveillance and tracking phased array radar seems beneficial. Fig. 4 shows the operation principle of this fence based surveillance & tracking radar: An object is detected when it crosses the radar fence. Then, it is immediately tracked in order to support initial orbit determination respectively the orbital parameters' refinement process.

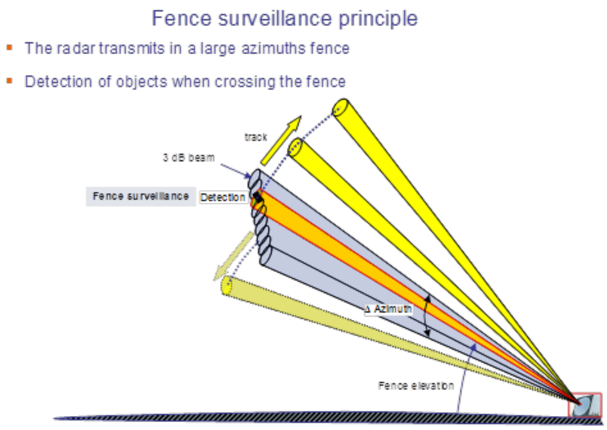

Figure 4: LEO surveillance radar operation principle [1]

Ground-based telescopes

Ground based telescopes are especially suited for the detection of objects beyond LEO. For surveillance the telescopes are moved in a step-and-stare fashion to cover a stripe in a particular direction (see Fig. 5). This approach is particularly suited for the observation of GEO and to less extent MEO orbits, as the field-of-view crossing times are long, which allows observing the same object several times with the same telescope. For such orbits, the coverage of a fence in declination ensures even the coverage of objects with large inclinations.

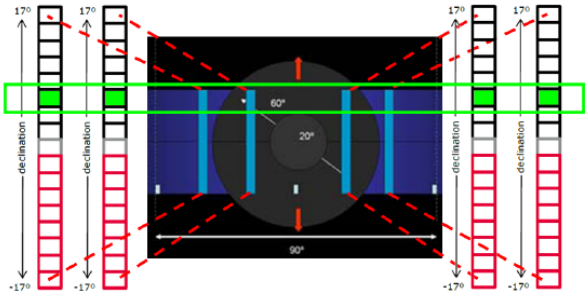

Figure 5: Observation strategy retained for the surveillance of high altitude orbits (MEO/GEO) [1]

However the above approach may have some gaps in the observability of specific orbits. Depending on timeliness and revisit requirements, additional telescopes could be required for the surveillance of non-GEO orbits (e.g. MEO). Additional tracking telescopes may also be required to improve the catalogue accuracy of such orbits. An optical surveillance system (4 sites distributed at different longitudes near the equator) to cover beyond-LEO orbits is recommended.

Space-based Telescopes

Space-based telescopes seem especially suitable for the surveillance and tracking of beyond-LEO objects. Especially for GEO, an SBSS (Space-Based Space Surveillance) satellite can play out its advantages just as radar does for the LEO population:

- An SBSS makes the optical SST system robust, as it is insensitive to weather, atmospheric conditions and the day/night cycle.
- Full longitudinal GEO belt coverage and high availability are obtained along with
- Favourable properties w.r.t. catalogue generation and maintenance due to very good observation timeliness and re-visit times.
- And: no geographical and geopolitical restrictions as for multiple ground-based optical sites have to be considered.

These advantages have been already demonstrated, e.g. by SBV, US SBSS and Sapphire. Analyses [1] point strongly towards a telescope in sun-synchronous LEO for comprehensive GEO surveillance and significant collateral detections and cataloguing of objects in other orbital regimes such as MEO as drafted in Fig. 6. Similar to the ground-based fence concept, the complete GEO belt can be covered with frequent follow-ups. The orbital dynamics of the GEO population carries the objects through SBSS' observation fence within 24 hours, just as the Earth carries the surveillance radar fence through the LEO population once per day. This is at the same time the reason why only one sensor can achieve comprehensive GEO coverage, with enhanced follow-up performance and thus orbit determination accuracy via an optional second S/C. As an alternative, only one S/C could be used for performing both observation and follow-up, resulting in a somewhat reduced total coverage but higher accuracy.

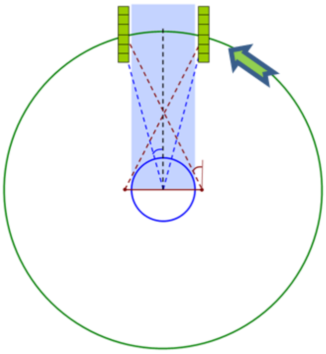

Figure 6: GEO surveillance fence strategy via step-and-stare pattern [1]

Two fences are shown, which could be covered either by a constellation of two S/C or by one S/C only with reduced declination coverage. Besides the nominal surveillance mode, the tasked tracking of specific objects is possible. The operational flexibility of the SBSS will also allow a significant contribution w.r.t. other mission goals such as the detection of manoeuvres and break-up events, object characterisation, special mission support (e.g. for LEOP), timely reaction w.r.t. collision risk assessment and will also potentially contribute to the characterisation of the sub-catalogue small debris population. In addition, an SBSS could host further secondary payloads, e.g. Space Weather sensors.

Especially for GEO one SBSS satellite covers already many objects of the GEO population with full coverage if two satellites are available. All required basic technologies exist already and are proven. Many advantages have been already demonstrated.

3.2 Phased approach

A phased approach is proposed for the implementation of an independent European space debris knowledge and collision prediction, e.g. consisting of short-term, mid-term and long-term measures. For the **short-term**

- existing capabilities like Graves and TIRA are used and
- a European Space Situation Awareness centre can be implemented.

Early performance based on existing assets will show large gaps. The chain from the detection of an object, the data processing until the command of a collision avoidance manoeuvre can be implemented and tested.

For the **mid-term**

- existing capabilities are updated to increase the performance,
- new elements with higher performance for additional improvement are developed and implemented, e.g.
    - o high sensitivity radar for ground based radar (for LEO objects) and
    - o a space based space surveillance demonstrator
    - o a ground-based optical telescopes close to the equator (initial deployment).

For the **long-term** the system shall be completed for a total coverage with a high accuracy. That includes

- further improved ground based radar for LEO objects and
- a fully operational optical space based surveillance component for GEO (and MEO) objects
- ground-based optical telescopes (full deployment).

Astrium expects a high potential in the development of observation strategies and the combination of different sensor data. Astrium can significantly support the collision avoidance, beginning with the modelling and simulations of the debris population, the development of observation strategies up to the design and construction of a ground- and space based SST infrastructure.

4. Survival

The vulnerability of satellites for untracked debris between 1 mm and 10 cm shall be reduced to survive an impact. Larger objects can be detected and avoided, smaller objects can be absorbed by the structure materials. Different solutions are considered to reduce the vulnerability of satellites in LEO, both at system and satellite architecture levels. In particular, new concepts of shielding are proposed to protect critical equipment against particles of up to 4 mm size. Indeed, it appears that the particles of 2 to 4 mm size are the most significant group contributing to damage of satellites as shown in the EC FP7 study ReVuS (Reducing the Vulnerability of Space Systems to small debris) currently led by Astrium Satellites (see [3]). This section is mainly based on the results of this study.

The following three steps approach was the basis of the analyses:

- Vulnerability analysis to evaluate the effects of a collision of a satellite in LEO with small size debris, the potential damage and the critical parts of the satellite, the risk of mission degradation
- the identification and analysis of potential solutions at system level, and at satellite architecture level, with a focus on the shielding concepts and shielding materials
- the resiliency analysis, aiming at evaluating the resiliency of the selected solutions with respect to debris impact and at proposing design rules and standards.

The vulnerability analysis evaluates the effects of a collision of a satellite in LEO with small debris, the potential damages and the critical parts of the satellite as drafted in Fig. 7, supported by the tools MASTER 2009 (ESA Meteoroid and Space Debris Terrestrial Environment Reference Model) for the simulation of the debris environment and SHIELD3

- to evaluate the probabilities of penetration of small debris particles for the satellite and in the equipment
- to determine the failure probability for all equipment parts considered.

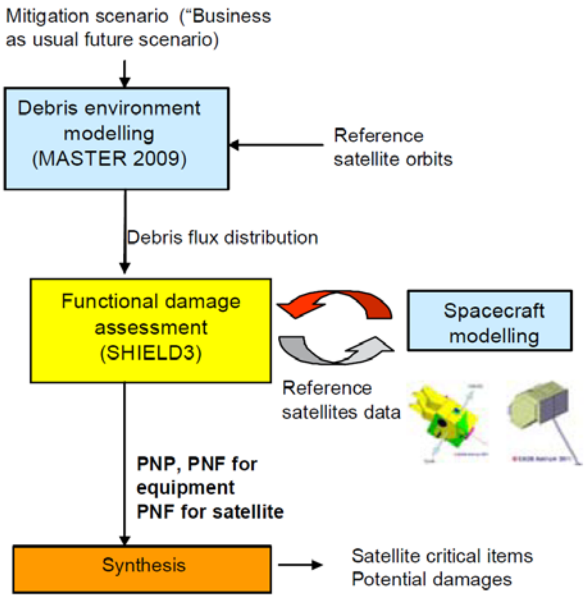

Figure 7: Approach of the vulnerability analysis in ReVuS [3]

The analyses show that debris below 1mm has a high density impact probability of impacts, but only a few penetrate the satellite. Effects on equipment are very low. There is a very high ratio (>= 100) between the density of debris in the range (1-10 mm) and in the range (10-50mm). The risk of being impacted or penetrated by small debris is much higher at 800 km than at 500 km. The radar satellite TerraSAR-X satellite evaluated presents a very low vulnerability to impacts small debris, with a high probability of non-failure (PNF), due to its cylindrical shape along the velocity axis, the rigid body mounted solar arrays and its low altitude (515 km) outside the main density of debris particles. There are three kinds of potential damages identified:

- First the most critical case is the loss of mission which could result from penetration of debris in the tanks and non-externally redundant equipment. In case of internally redundant equipment the level of failure depends on the internal architecture.
- Second the performance of the satellite could be degraded due to the loss or degradation of the energy supply (solar cells, batteries), the radiators, payload equipment, etc.
- Third the satellite reliability could be reduced due to the loss of redundant equipment.

Based on the results of the vulnerability analysis, two main categories of solutions have been defined:

- solutions at system level
- solutions at satellite architecture level, which include the shielding solutions.

The system level solutions aim at mitigating the risk at system level. Such solutions can take into account the full range of debris size. An example is the fractionated satellite concept, which consists in sharing some functions of a satellite (communications with ground, computing capability, payloads, etc.) on modules forming a cluster, based on wireless communications and interconnecting network. With an adequate distance between the modules, a collision with debris could lead to the loss of a module, but not the complete mission. Another example is the distributed system concept, which will adapt the principles of existing terrestrial wireless to distributed space system architectures. Possible concepts of operations are also part of the system level solutions.

At spacecraft architecture level, several axes of solutions can be considered, such as:

- Adequate equipment location and physical segregation of the redundancies
- Review of architecture of subsystems, such as solar arrays electrical architecture, propulsion configuration, harness configuration, etc.
- Shielding of the spacecraft: different strategies of shielding can be considered. However, their impact on the spacecraft is different in terms of accommodation and satellite performance (mass, thermal behavior, electrical properties, RF properties), and is a criterion of evaluation of the shielding strategies.

These solutions will be evaluated with respect to their accommodation on the spacecraft and the impacts on the spacecraft configuration in terms of mass, launcher interface, propellant budget, thermal behavior, etc.

The shielding solution will have a significant impact on the mass and on the layout of the satellite. Thus, the shielding solution will be rather used at equipment level, for those items experiencing the highest risk. The analysis of the reference satellites, and more generally of the current and future LEO satellites, show that various basic configurations of equipment can be defined according to their location in the satellite for equipment having a risk of failure due to debris. Tens of configurations have been identified, e.g. to mount equipment behind a radiator or MLI. A review of the occurrence of such configurations on various current LEO satellites to identify and select the most frequently used has been done in the scope of ReVuS. Still specific analyses for each spacecraft may be beneficial due to the very different design.

A typical shielding has a multi-layer configuration as drafted in Fig. 8 with an outer layer (bumper) to fragment the debris into the smallest possible particles, an intermediate layer to increase the fragmentation and absorb most of the energy of and some particles and an equipment wall to absorb remaining particles.

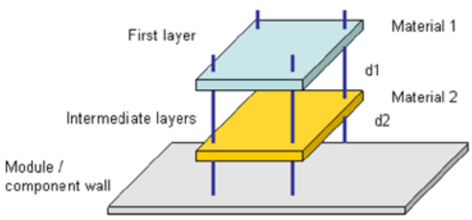

Figure 8: Typical design of a multi-layer configuration [3]

In general a multi-wall is a better protection against debris than thicker walls because the debris is fragmented which decreases the final impact energy for the equipment wall. A combination of different shielding bricks (e.g. reinforced MLI + reinforced panel) means an additional reduction of the vulnerability. That includes also the use of different materials (e.g. aluminum or carbon-fiber-reinforced plastic) and thicknesses. Each shielding concept has an impact on the performance of the satellite, again especially w.r.t. mass and volume and the effort for the design which drives directly the costs.

Several tests of the material and different bricks shall be performed to evaluate and optimize the selected shielding concepts. Finally design rules and new guidelines for debris impact mitigation shall be proposed.

5. Remediation

5.1 General Considerations

The challenge is to remove 5 to 10 large debris per year in order to stabilize the debris situation. To achieve that goal a wide range of different concepts have been analyzed for single- and multi-target missions, based on new technologies such as sensors to detect the target and evaluate the tumbling rate, systems for capture and stabilization of targets and systems for de-orbiting. The aim was to develop a vehicle able to remove several debris objects and thus hosting several capture systems and de-orbit packs (Debritor). Such a vehicle should be made of off-the-shelf subsystems or equipment in order to lower the development cost at maximum and thus the cost of a mission. In addition concepts to remove small debris (e.g. by laser) have been analyzed. The main part of this section focuses on general aspects and the general Debritor concept and is based on the results of [2].

Four main critical points have been identified:

- the feasibility of such mission with a non-cooperative target; many studies have been performed, many innovative concepts have been presented and analysed. A few have been tested on ground such as a capture with a net or a harpoon (Astrium), a few have performed an IOV such as a de-orbitation with a sail (NASA). A lot remains to be done (e.g. DEOS, led by Astrium).
- the selection of the debris to remove; this is about selecting the most dangerous debris first. This means in particular targets with enhanced probability of suffering a catastrophic collision, producing a large number of new potential impactors [7]. It could be done for example by using a combined factor made of the mass of the debris together with the collision probability on this particular orbit and its remaining lifetime.
- legal aspects; as soon as a debris removal spacecraft will approach a debris, legal question will be raised. Obviously the debris owner will have to accept the removal, but this is not as simple. This is about liability, property transfer, risk transfer, insurance, and casualties on ground. This is currently analyzed in detail by Astrium in an ESA funded study about an ADR service.
- the cost of removal ; no doubt that it has to be low, but how low? This is currently analyzed in detail by Astrium in an ESA funded study about an ADR service.

Amongst these four critical points, the cost of removal is possibly the strongest because such missions bring no intrinsic value on ground, no new applications, no new services, no science, not even any law compliance. So reducing the cost is of paramount importance. The cost of removal per debris is dependent of a lot of inputs. Basically, the equation can be simplified along the mission/system/equipment level with major recommendations.

- At mission level; consider a multitarget mission, where several targets will be processed by the same spacecraft. The alternative launcher solutions could be traded off with respect to the different mission size (number of target to be processed).
- At system level; reduce/cancel the cost driving requirements: autonomy, redundancies... limit on board hardware and involve ground as deeply as possibly, use as far as possible the simplification brought by a relaxed timeline since a debris is passive and thus is not sensitive to the duration of the rendezvous and capture.
- At equipment/sub assembly level; reduce the non-recurrent, use off the shelf existing devices.
- At component level; lower the grade of the components down to an acceptable minimum.

Obviously all these levels are linked, and a continuous feedback loop needs to be implemented to define the most efficient and less expensive solution for each function.

The main design drivers of a debris removal system are a strong propulsion capability, relative navigation with and identification of a debris target, capture and de-orbit systems, compatibility with a given launcher. Astrium has a huge expertise in all these segments on programmatic, system and architecture level. W.r.t. space debris Astrium is involved in studies and programs like the ADR service study, DEOS, OTV, a patent for a harpoon to capture objects, internal studies on ion-beam shepherd, passive devices etc.

Propulsion

The system will have to provide a high ΔV, which is due to transfer to successive targets, approach & proximity operations, post capture control and target de-orbiting. The main parameters are shown on Fig 9.

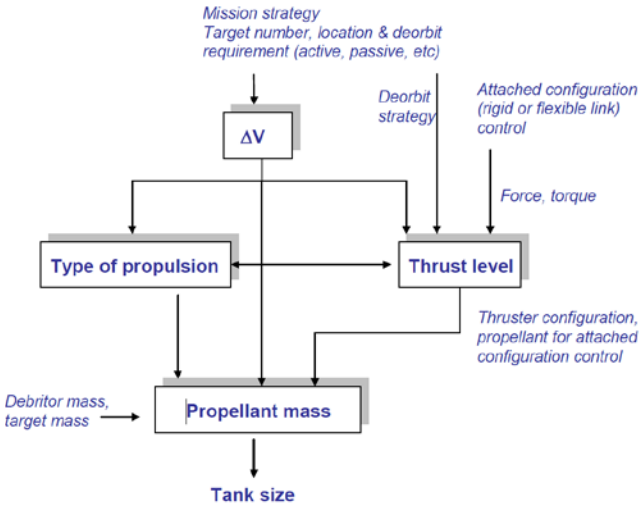

Figure 9: Propulsion main parameters [2]

The thrust level (and subsequently the thrusters size and configuration) is driven by ΔV and time constraints; it is in general constrained by the de-orbitation strategy, in particular if a direct re-entry is carried out in a single boost.
The type of propulsion depends on thrust level requirements and on mass and time constraints. The resulting mass of propellant (and the size of the thrusters) has a direct impact on vehicle mass and configuration.
The main choices are as follows:

- Electrical versus chemical propulsion (to minimise mass)
- Separation of constraints due to transfer & RVD phase and due to de-orbit phase
- Transfer and de-orbit strategy versus level of thrust and effort on target

Rendezvous sensors

Sensors needed for far Rendezvous (RV) including target acquisition and close RV (up to tens of meters) navigation, target identification (& recombination), target tumbling rate and axis evaluation, navigation data elaboration (relative distance, position, attitude). The number of sensors and their requirements in terms of pointing accuracy, stability, and data processing shall be minimized.

Type of capture system

It drives the minimum distance with target, the required pointing accuracy, the alignment manoeuvre with adequate surface/direction, the type of link (rigid, flexible) and control of post capture configuration. It impacts the vehicle configuration and layout due to the implementation of one or several capture systems with constraints of position with respect to the target. Each capture system has to be selected as function of the targeted debris, as a capture system is not necessarily applicable to all debris)

Type of De-orbit system

It could be an active or a passive system. The selection will be driven by targeted debris de-orbiting requirements (such as direct re-entry, or perigee decrease). The size of the de-orbit system depends on the characteristics of the targeted debris, in particular its mass and size. The type of de-orbit system has an impact on the vehicle configuration and layout. The capture and de-orbit systems shall be defined coherently. The main choices for these two systems are:

- A set of capture and de-orbit system per target,
- or a single capture system and one deorbit per target
- or one capture per target and a single deorbit

Number of missions versus type of launcher

Two main vehicle options are identified. With a single mission vehicle very large debris (5t to 9t) which requires a direct controlled re-entry might be removed to minimize the casualty risk on ground. The vehicle will have a low amount of propellant and so its size might remain compatible to a single launch medium cost launcher (i.e. Soyuz 5.5t). The main disadvantages of this concept are the high costs because for every removal one vehicle must be launched. So Astrium proposes the Debritor, an "off the shelf" based multi-mission vehicle equipped with several de-orbiting kits to maximize the number of missions (Ref 5). The mass of the kits will depend on mass of debris and type of processing (direct re-entry or decrease of perigee). The number of kits will depend on the vehicle layout capacity. The vehicle will have a maximum amount of propellant but should stay compatible with market available launchers (i.e. 5.5t; 15t, etc…). The selection of the class of launcher will impact the number and selection of targeted debris, the type of propulsion, the number and so the cost of the mission, etc.

5.2 The Debritor concept

Capturing and de-orbiting large debris is a complex mission, with a variety of options as depicted on Fig 10; they depend on the mode and type of capture, the type of de-orbiting, the use of a single or two active bodies, etc.

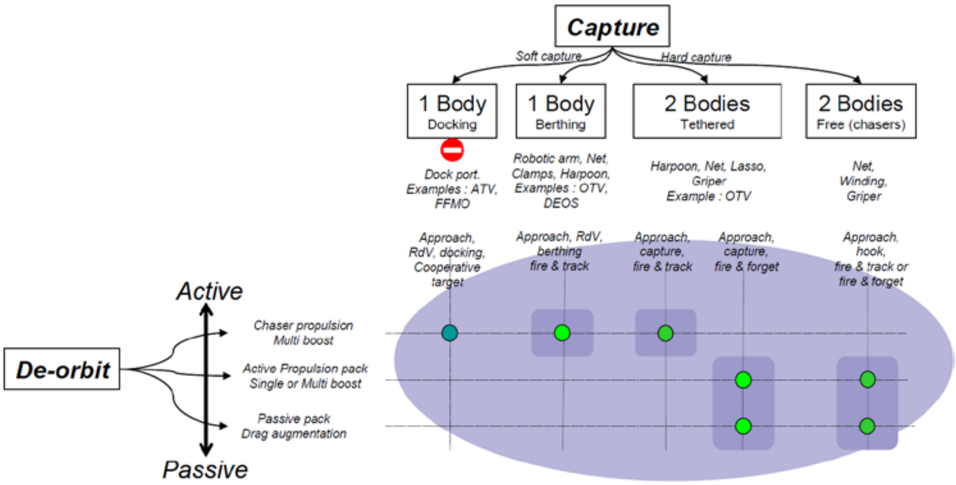

Figure 10: Range of possible debris removal concepts [2]

The approach that has been followed consisted in defining a family of concept, based on a common platform, and on set of capture/deorbit systems (one per target) to take into account diversity of targets. Indeed, the targets mainly located above 70° up to SSO inclination and between 600 and 1000 km as illustrated on Fig 11, could be upper stages or satellites with different configuration (long cylinder versus target with deployed appendages) and different constraints for capture systems. They could have different masses, different requirements in terms of de-orbiting (e.g. some target require a direct re-entry), etc.

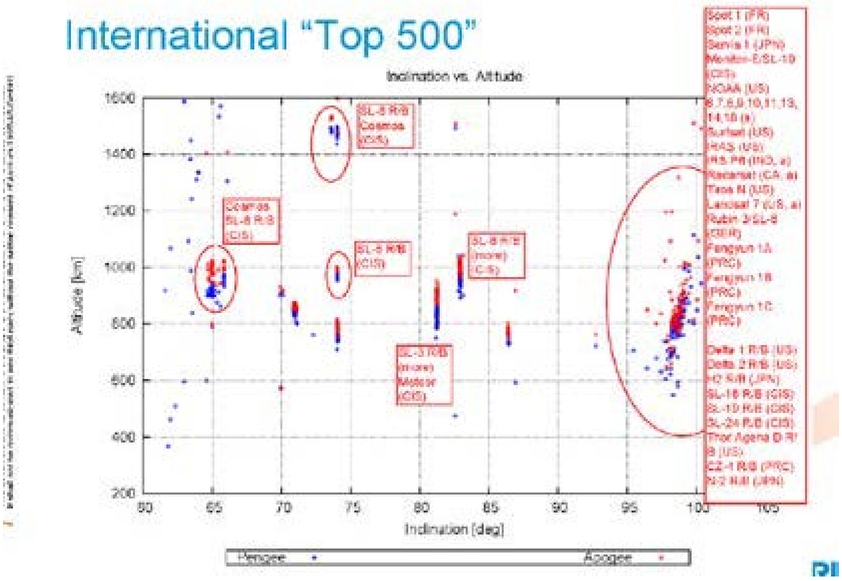

Figure 11: Location of targets in altitude and inclination [7]

The Debritor is a multi-mission vehicle: during its mission, it will be able to de-orbit several targets, in order to reduce the cost of for a target. Its mission defined a priori: all its targets are selected and known before launch. Thus, the mission of one Debritor vehicle could gather similar targets with respect to type or inclination to optimise the vehicle mass at launch, but the mass of these targets can be different, even if they are preferably around the same average value. Another vehicle mission could gather other types of target.

The type of the capture system could vary between the missions of two vehicles, and even inside the mission of one vehicle. Likewise, the mass of deorbit system (mainly propellant if active) could vary between two missions (target not the same range of mass) and even from one target to the other in a given mission. Therefore, the vehicle configuration should be flexible to implement different types of capture/de-orbit systems, or even different size of de-orbit system in a same mission. The Debritor concept is made of:

- A platform with large propellant capability (including possibly plasmic propulsion) for the transfer to several targets, the proximity operations, and de-orbiting at end of mission.
- Several set of capture systems and de-orbit packs. At least two types of capture system could be implemented to cover the range of targets. Selected capture systems have a flexible link. Active and passive packs could be implemented.

Family concept allows to size the vehicle for a single mission if needed, or to a given class of launcher by adapting the number of targets. A platform version could be designed for each class of launcher, by implementing different capacity in propellant mass and thus different types of tanks.

To cope with cost issues, the Debritor concept will benefit to the maximum extend from heritage. For propulsion, existing modules are adequate (E3000, Mars Express) and provide an enough propellant capability (up to more than 3.2t). Avionics, power, communications system from existing platform (LEO platform) could be used as needs in terms of data processing, comms, power generation and distribution are similar. However, the use of electrical propulsion system could lead to a much higher required power (possibly in the order of telecommunications satellites power).

In terms of operation, the vehicle has time to fulfill its mission, so that a timeline at minimal cost will be defined. The system will rely as much as possible on the ground control center, in order to reduce the requirements on the on-board autonomy, and thus the costs. To that aim, the use of GEO communications relay (EDRS, or Inmarsat SBSat for instance) during the rendezvous, capture and de-orbiting of a target will allow an adequate ground involvement.
A description of the Debritor configuration and development approach can be found in [2].

6. Conclusion

Astrium is fully aware of the potential threat of space debris to the infrastructure in space and its impact to every-day life. We propose a four pillar approach, considering the prevention of debris generation, the avoidance of debris by active S/C, the removal of debris and the survival of in-orbit objects.

The first aspect is the necessity of Post Mission Disposal which has a huge impact on the design of each satellite. The different requirements w.r.t. the disposal are compared (e.g. maximum acceptable casualty risk) and it is highlighted that the required 90% success rate for a Post Mission Disposal is currently not kept. But even a 90% success rate is not sufficient to stop the generation of debris without the removal of additional debris objects. Next the reasons for the satellite owner to perform the disposal are discussed, with regulation and license issues as the main reasons for LEO objects and the scarcity as additional factor for GEO objects. Finally solutions are suggested to implement an external Post Mission Disposal Service through an autonomous piggy back pack or to use such a pack for an active debris removal.

The second aspect is the avoidance of debris by active S/C. This is only possible if the debris situation is known. Several studies have been and are performed by Astrium to implement a space surveillance and tracking component. Based on the results a first approach for a sensor network is proposed of both ground- and space-based assets, with

- Ground-based radar to detect and track LEO objects
- Ground-based telescopes to detect high altitude objects (especially GEO)
- Space-based telescopes to detect high altitude objects (especially GEO) which significantly support ground-based telescopes.

Astrium proposes a phased approach (e.g. short-term, mid-term and long-term measures) to implement a European Space Situation Awareness system based on existing equipment, its upgrades and the development and implementation of new equipment. For the cataloguing of GEO objects a space-based telescope is recommended because it will already build up a core catalogue with a stand-alone demonstrator.

The third aspect is the survival of in-orbit objects. First the debris population of 2 to 4 mm objects is identified to have the highest probability to cause severe damage. Based on the results of the vulnerability analysis, two main categories of solutions have been defined: solutions at system level, and solutions at satellite architecture level, which include the shielding solutions. An example for the system level solution is the fractionated satellite concept, which consists in sharing some functions of a satellite on modules forming a cluster. With an adequate distance between the modules, a collision with debris could lead to the loss of a module, but not the complete mission. At spacecraft architecture level, several axes of solutions are considered, e.g. different shielding solutions.

The fourth aspect is the remediation of objects. A general analysis about the main critical points highlights the cost of removal as the possibly strongest aspect. The main technical drivers are the strong propulsion capability, relative navigation with and identification of a debris target, capture and de-orbit systems and the compatibility with a given launcher. To reduce the costs we propose a multi-mission vehicle, called the Debritor. Detailed in-house analysis allow the selection of targets based on their value to reduce the overall collision risk and so the generation of new debris. Several of these targets in similar orbits could be de-orbited by a Debritor in one mission. The type of the capture system could vary between the missions of two vehicles, and even inside the mission of one vehicle. Likewise, the mass of deorbit system (mainly propellant if active) could vary between two missions (target not the same range of mass) and even from one target to the other in a given mission. Active and passive packs could be implemented. The platform of the Debritor needs large propellant capability due to the delta-v required for transfer maneuvers between several targets, the proximity operations, and de-orbiting at end of mission. To reduce the cost most components will consist of already existing hardware (e.g. propulsion from E3000, Mars Express and/or available platforms).
In terms of operation, the vehicle has time to fulfill its mission, so that a timeline at minimal cost will be defined. The system will rely as much as possible on the ground control center, in order to reduce the requirements on the on-board autonomy, and thus the costs.

Due to its leading role in many studies and projects related to the space debris topic and its general long-term experience in space business Astrium is able to cover the full spectrum of the space debris challenge as shown in this paper.

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