CHALLENGES IN EUROPEAN AEROSPACE
5TH CEAS AIR & SPACE CONFERENCE

CONTRIBUTING TO ORBITAL SUSTAINABILITY WITH AN INDEPENDENT DECOMMISSIONING DEVICE FOR SATELLITE AND LAUNCHER SPACE IMPLEMENTING SPACE DEBRIS MITIGATION MEASURES

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ABSTRACT

The increasing number of space debris together with the growing rate of satellite launches is jeopardizing the fruitful exploitation of outer space and the sustainability of space activities. Space Debris Mitigation requirements are being implementing by national Governments, Space Agencies and space operators in order to limit the space debris risk as much as possible. An approach based on an independent and rapid decommissioning device able to remove quickly and safely satellites at end-of-mission appears to be the most promising solution for a large number of applications.

1 WHY ORBITAL SUSTAINABILITY

The ESA Space Debris Office estimates that in space there about 750,000 objects larger then 1cm [7, 20] originated by human activities. Of these "space bullets" only 17,000 are traceable and catalogued, and only about 1250 are controllable active satellite: the remaining objects are wondering uncontrolled, at risk of colliding with operational satellites. This represents a critical threat to space exploitation: if the number of objects around our planet is not kept under control and eventually reduced, manned and unmanned missions will be increasingly difficult, requiring expensive protection and lifetime consuming collision avoidance manoeuver, severely impacting research and business space applications.

Eventually, business as usual scenarios [7, 9, 19] show an increasing number of collisions that may generate a collision reaction within the next 200 years, transforming our orbital space into an inoperable environment with major fallout on human activities on Earth.

While 50 years ago it seemed there was enough room for upcoming satellites, with time uncontrolled and abandoned satellites started exploding and crashing into each other. About 50% of all traceable objects [7, 9, 20] are generated by in-orbit explosions or collisions, with the result that, today, about 300 million junk objects [3, 7, 9, 20] fly at very high speed (up to 30'000 km/h) at risk of collision with other satellites; this without taking into account asteroids or other Near Earth Objects. Space debris poses a risk in two major ways [14]. First, it represents a navigation hazard for operational satellites: a collision between a piece of debris and a satellite risks to damage the latter and, in the worst case, to cause its loss (in 2009 an Iridium operational satellite was destroyed by defunct Russian satellite). Today satellite operators sacrifice propellant (thus satellite's life and potential revenues) to perform manoeuvres for avoiding impacts and assuring the satellite removal at end-of-life according to current debris mitigation guidelines. Also, although defunct satellites monitoring activities are now funded publicly, we can expect that this cost will be soon covered by respective satellites owners, especially in the case of commercial entities. The second major risk involves people on Earth: according to NASA[1], only in 2014 about 100 tons of junk fell on Earth. On average, one junk object per day falls on the Earth from Space and it is

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[1] http://tass.ru/en/non-political/778607

particularly difficult – and sometimes impossible – to forecast the exact place of impact on ground with a reasonable accuracy.

2 SPACE DEBRIS IMPACT ON COMMERCIAL USE OF SPACE

The Satellite Industry represents a business of about 200B$ per year[2]. According to Euroconsult, in the next eight years 115 satellites will be launched on average each year worldwide, without taking into account cubesats and the large constellations of small satellites that recently have been announced and introduced into the market that alone could double the number of satellites in orbit in a few years. Space market is considered to be in its early stage, with a consistent margin of growth before reaching its mature phase.

The costs a space operator should consider, although different from one operator to another, are already increasing and potentially could impact and threaten a commercial business model. In particular, direct costs such as propellant consumption for collision avoidance manoeuvres, down time during the latter manoeuvers, insurance costs and decommissioning at the end of mission are paired by costs of other nature: the risk of a failure on the decommissioning phase and thus the cost a constellation may suffer having a dead satellite in the proximity of the operative satellites, the reputational loss and eventually the space slot occupation costs, especially for GEO satellites [3].

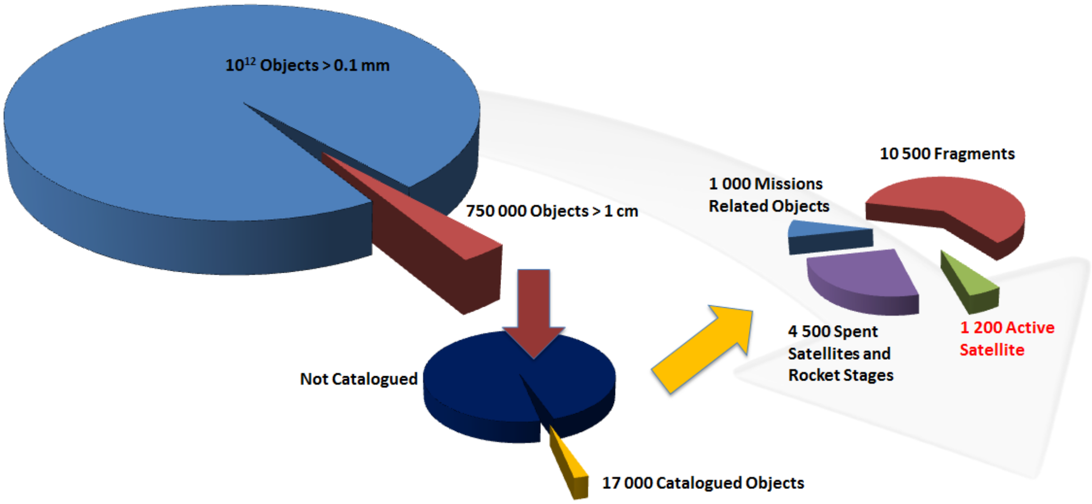

Figure 1: Breakdown of the distribution of orbital debris [source: ESA Space Debris Office]

3 INTERNATIONAL SPACE DEBRIS MITIGATION EFFORT

There is nowadays a general consensus among both the industrial and scientific space communities that effective Space Debris Mitigation (or SDM) measures are necessary in order to maintain future space activities below an acceptable level of risk. Outer space, and especially low Earth orbits, is getting dramatically crowded and the future sustainability and expansion of space industry strongly depends on how the issue of space debris is effectively managed. However, the implementation of dedicated SDM technologies is still seen by many operators and officials as a burden for space industry's

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[2] Source: Euroconsult.

competitiveness. The space scientific community has highlighted in several occasions the long-term criticality and costs of orbital debris for the fruitful exploitation of outer space. Schaub et al. [3] has analysed the way the proliferation of space debris implies direct costs (e.g. debris avoidance manoeuvres, higher insurance costs, etc.), indirect costs (e.g. tracking costs, manoeuvre verification, conjunction analysis, etc.) as well as political costs (e.g. countries' legal liability, active debris removal political implication, terrestrial damages liability, etc.).

Indeed, with the increasing congestion of the most useful orbits, and the coming of the new phenomenon of large constellations of small- and nano-satellites, adopting scrupulous Space Debris Mitigation requirements will not only be a matter of compliance with regulations, but also an efficient way for space operators to reduce the risk of their activities and to preserve in their operational orbit clean of debris in the long term. An example comes from the success rate of the compliance with SDM guidelines in LEO and in GEO. In GEO, where there is a commercial interest in removing the satellites from its operational slots, in order to replace them with the new and more performing satellite, the satellite removal success rate is about 75% [7], whilst in LEO, where the removal manoeuvre is often more complicated than in GEO and the commercial exploitation of the orbits has just begun, the removal success rate is about 50% [7, 9, 10, 11]. The market of satellites adopting technologies responding to SDM requirement is therefore bounded to be driven by international and national regulations and guidelines as well as by the demand of the satellite system integrators that will see those technologies as a competitive advantage for their platforms.

In Europe, the Clean Space Initiative, and in particular the CleanSat programme are setting a clear programmatic roadmap towards the development of building blocks enabling the compliance of SDM requirements on future satellite platforms, which will make Europe the world leading space actor for the sustainability of space activities and will enable European space industry to be leader of a new, large and highly technological market such as the one that the Space Debris Mitigation measures will create.

SDM requirements may mainly come from two sources: SDM regulations and/or directly by satellite integrators and operators.

Several SDM regulations, guidelines or national laws are already in place and apply to European entities. The most important are:

- The Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines, issue 2002, revised in 2007.
- Space Debris Mitigation Guidelines of the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS).
- ISO Standard 24113 "Space Systems – Space Debris Mitigation Requirements", issued May 2011.
- The European Code of Conduct for Space Debris Mitigation, signed in 2004 by ASI, BNSC, CNES, DLR and ESA.
- National laws, of which the most remarkable are: the French Space Operation Act and the German Telecommunications Act (TKG).

At ESA two main documents set up the SDM requirements for Agency's project:

- The ESA/ADMIN/IPOL(2014)2 – Space Debris Mitigation for Agency Projects, issued in March 2014.
- The ECSS-U-AS-10C – Adoption Notice of ISO 24113, issued in February 2014.

In addition to these, the ESSB-HB-U-002 – *ESA Space Debris Mitigation Compliance Verification Guidelines* [18] has been issued in February 2015 in order to provide guidelines on the verification of the ESA SDM requirements.

Although nowadays Europe is certainly leading the international effort about SDM regulation, on the other side of the Ocean NASA was the first organisation to develop orbital debris mitigation policy and guidelines already back into the 90s with the NASA Management Instruction (NMI) 1700.8 "Policy for Limiting Orbital Debris Generation", established in 1993, and the NASA Safety Standard (NSS) 1740.14 "*Guidelines and Assessment Procedures for Limiting Orbital Debris*", issued in 1995. These standards have been upgraded and integrated by the following:

- "NASA Procedural Requirements for Limiting Orbital Debris" – NPR 8715.6A, issued in 2007.
- "NASA Process for Limiting Orbital Debris" – NPR 8719.14A, last issued in 2012.

The above sets of requirements are completed by the following regulations issued by U.S. federal bodies:

- U.S. Government Orbital Debris Mitigation Standard Practices, approved in 2001.
- The U.S. National Space Policy, issue in 2006 and updated in 2010, addressed to agencies and departments to implement the U.S. Government Orbital Debris Mitigation Standard Practices.
- DoD Directive 3100.10 "Space Policy" issued in 1999.
- FAA 14 CFR 417.139 "Safety at end of launch".
- FCC 47 USC Sec. 301.
- NOAA 15 CFR Section 960.11 "Spacecraft Disposal and Orbital Debris Mitigation Plan".

3.1 Space Debris Mitigation Effort in Europe

In Europe, the technological support to the SDM effort is led by the European Space Agency. The ESA Clean Space Initiative represents the first example worldwide of programmatic institutional attempt to support industry in the development of technologies enabling the effective implementation of space debris mitigation and remediation requirements, as well as satellites eco-design and sustainability of space activities in general. Clean Space aims at guaranteeing the future of space activities by protecting the environment and by minimising the impacts on Earth and space.

In particular, the European Space Agency has started a technology programme coordinated by the Clean Space Office called CleanSat which is ESA's programmatic response to support European industry comply with the worldwide market demand for SDM-compliant solutions. The CleanSat programme is focused on LEO spacecraft.

Table 1 below provides an overview of the applicability of the European SDM requirements for the LEO Region against three key areas identified among the European regulations SDM requirements: Passivation, EOL Disposal Manoeuvre and Casualty Risk.

These three key areas can be defined as follows:

- **Passivation** = depletion of all forms of residual propulsive and electrical energy of the spacecraft, in order to avoid potential explosion risks (e.g. electrical passivation implies disconnecting the batteries, propulsion passivation implies emptying tanks to avoid potential explosion in case of a collision).
- **EOL disposal manoeuvres** = the operation to be performed at the EOM of a spacecraft of launcher stage in order to reduce its chance of collision and clear up permanently its orbital position.
- **Casualty risk** = probability that a person on ground is killed or seriously injured because of an event originated by a re-entering debris.

Regulation	Passivation	EOL Disposal	Casualty Risk
IADC	Passivation measures for the spacecraft or orbital stage should be planned and conducted. Propulsion systems should be designed for passivation.	Limit the presence in LEO Region of space systems after EOL to 25 years. If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere.	Debris that survives to reach the surface of the Earth should not pose an undue risk to people or property.
UN COPUOS	All on-board sources of stored energy on spacecraft and launch vehicle orbital stages should be depleted or made safe when they are no longer required for mission operations or post-mission disposal.	Spacecraft and launch vehicle orbital stages that have terminated their orbital phases should be removed from orbit in a controlled fashion. If this is not possible, they should be disposed of in orbits that avoid their long-term presence in the LEO Region.	Due consideration should be given to ensuring that debris that survives to reach the surface of the Earth does not pose an undue risk to people or property, including through environment pollution caused by hazardous substances.
ISO 24113	During the disposal phase, a spacecraft or launch vehicle orbital stage shall permanently deplete or make safe all remaining on-board sources of stored energy in a controlled sequence.	A spacecraft or launch vehicle orbital stage operating in the LEO protected region, with either a permanent or periodic presence, shall limit its post-mission presence in the LEO protected region to a maximum of 25 years from the end of mission.	For the re-entry of a spacecraft or launch vehicle orbital stage (or any part thereof), the maximum acceptable casualty risk shall be set in accordance with norms issued by approving agents.
European Code of Conduct	Any space system should be passivated at the end of its disposal phase and should remain passivated. Passivation measures should be taken into account in the design phase of the space system. The passivation process should be completed within 1 year after the end of the disposal phase, and its probability of success should be higher than 0.9.	The operator of a space system should perform disposal manoeuvres at the end of the operational phase to limit the permanent or periodic presence of its space system in the protected regions to a maximum of 25 years. This can be achieved, in decreasing order of preference: 1) by performing a direct re-entry of the space system; or 2) by limiting the orbital lifetime of the space	A space project should limit the risk from re-entering space debris to a safe level. The end of life operations should take into account the applicable on ground safety rules, which depend on the launching state. The casualty risk on ground should not exceed 10-4 per re-entry except when France is the launching state where the criteria presented in the CNES "Doctrine de Sauvegarde" are

		system to less than 25 years after its operational phase; or 3) by transferring the space system to a disposal orbit.	applicable.
French LOS	At EOL, all reserves of energy shall be permanently depleted or shall be incapable of generating debris. All means of energy production shall be permanently deactivated.	Baseline: controlled re-entry. If controlled re-entry not possible (duly justified) uncontrolled re-entry in 25 years. If casualty risk $>10^{-4}$ controlled re-entry compulsory.	$<2{:}10^{-5}$ for controlled re-entry; $<10^{-4}$ for uncontrolled re-entry.
ESA IPOL	During the disposal phase, a spacecraft or launch vehicle orbital stage shall permanently deplete or make safe all remaining on-board sources of stored energy in a controlled sequence. Space systems performing disposal by controlled reentry at EOM are not required to have passivation capabilities. In this case risk aspects are covered by the requirements on disposal reliability and re-entry safety.	Uncontrolled re-entry within 25 years from EOL. If casualty risk $>10^{-4}$ controlled re-entry compulsory.	The casualty risk shall not exceed 1 in 10,000 for any re-entry event (controlled or uncontrolled). If the predicted casualty risk for an uncontrolled re-entry exceeds this value, an uncontrolled re-entry is not allowed and a targeted controlled re-entry shall be performed in order not to exceed a risk level of 1 in 10,000.

Table 1: overview of the applicability of the European SDM requirements for the LEO Region against three key areas identified among the European regulations SDM requirements.

3.2 Space Debris Mitigation Effort in U.S.

Figure 2 below summarises the regulations on SDM requirements in place in the United States. The U.S. National Space Policy supervises the other relevant department involved in the regulatory effort. While the institutional portion of the space market is regulated by NASA and the Department of Defence, the commercial market is managed by the Federal Aviation Administration (FAA) as it regards the launch phase, the Federal Communication Commission (FCC) as it regards the radiofrequency licensing of satellite communications, and the National Oceanic and Atmospheric Administration (NOAA) for Earth observation missions.

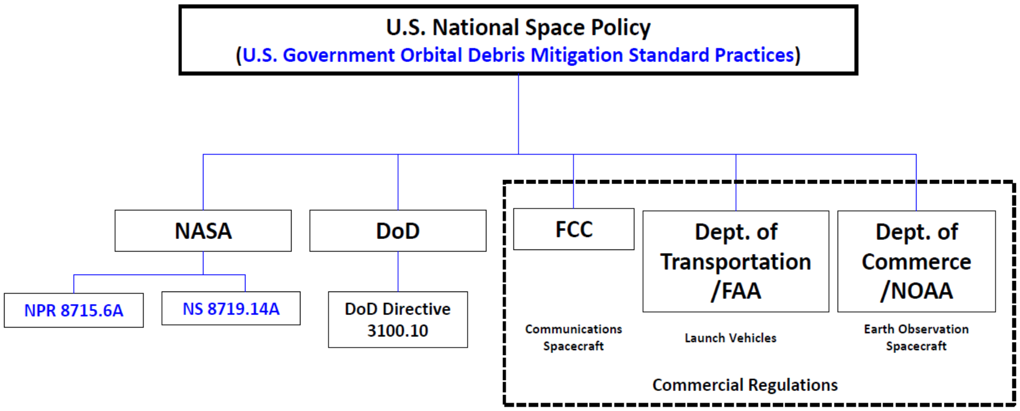

Figure 2: regulations on SDM requirements in place in the United States (Source: [2])

Regulation	Passivation	EOL Disposal	Casualty Risk
NPR 8715.6A / NS 8719.14A	Design of all spacecraft and launch vehicle orbital stages shall include the ability and a plan to deplete all on-board sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or post-mission disposal.	All debris released during the deployment, operation, and disposal phases shall be limited to a maximum orbital lifetime of 25 years from date of release.	The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules. For uncontrolled re-entry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000).
US Gov. Standard Practice / DoD Directive 3100.10	All on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when they are no longer required for mission operations or post-mission disposal.	Eliminate of minimise mission-related debris. Limit the orbital lifetime in LEO of such debris to 25 years.	Limit the human casualty re-entry risk to 1 in 10,000.
FCC	Energy shall be removed at the spacecraft's end of life, by depleting residual fuel and leaving all fuel line valves open, venting any pressurized system, leaving all batteries in a permanent discharge state, and removing any remaining source of stored energy, or through other equivalent	Post-mission disposal plan shall be detailed and declared in compliance with applicable laws and regulations.	Casualty risk on ground shall be assessed and stated if planned post-mission disposal involves atmospheric re-entry.

	procedures specifically disclosed in the application		
NOAA	In-orbit accidental break-ups/explosions shall be minimized, and break-ups/explosions risk shall be assessed and stated.	Compulsory post-mission disposal by one of: i) atmospheric re-entry; ii) manoeuvring to a storage orbit; iii) direct retrieval. Post mission disposal shall comply with applicable federal regulations.	Limit the human casualty re-entry risk to 1 in 10,000.

Table 2: overview of the applicability of the U.S. SDM requirements for the LEO Region against three key areas identified among the European regulations SDM requirements.

It is worth to mention that NASA recently published a Request for Information for the PACE satellite mission [17] asking explicitly for a redundant decommissioning subsystem, able to perform a direct re-entry and dedicated to this function.

4 SPACE DEBRIS MITIGATION EFFORT FOR SPACE OPERATORS

Many space operators now understand the importance of preserving their orbital environment as safe as possible and therefore free from orbital junk. This has a great value especially regarding the recent appearance of large constellations of cubesats and small satellites, whose operational costs and risks could increase considerable without the proper implementation of space debris mitigation measures.

It has to be noted that the SDM regulatory regime is bounded to evolve in order to take into account the progress of the space industry and the new needs of the stakeholders. In particular, the regulation evolution will go in the direction of improving the “25-year rule”, since this was conceived when the launch rate was much lower than it is now, and to extend the protected regions to other orbits, such as MEO. Possible further evolutions may also involve stricter requirements on the passivation of the space systems at EOL and on the restraint of the casualty risk on ground. Although it is difficult to foresee when these changes will occur, the large attention that the space community is paying on the space debris issue could substantially accelerate the process. An example of such an evolution of regulations is the French Space Operation Act: starting from 2021 no waivers will be longer granted and no exceptions will be accepted. This means that every space system launched from French territory (including French Guyana) and/or from French Operators (including, for instance, Arianespace) shall strictly comply with the French law which requires, as an example, the controlled destructive re-entry for all satellites and launcher stages at EOL.

Besides from compliance to applicable regulations, space operators understand that the increasing congestion of the orbits they exploit for their businesses could increase the operational risk over an acceptable level. Operators are liable for any damage their dead satellites may cause to other satellites, therefore the impossibility to perform the disposal EOM manoeuvre because of a major failure that makes the spacecraft out of control is a scenario that, although highly improbable, could cause considerable economic damages.

5 EOM DISPOSAL METHODS

A clear description of compliance needs and casualty risk for different categories of satellites is given in Table 3. The satellite categories identified have been inspired by those selected by ESA in recent Invitations to Tender to European industry.

	PASSIVATION	EOL MANOEUVRE	CASUALTY RISK
Cubesats	Compliance: Power and electrical passivation at EOL.	Compliance: 25-year rule	Compliance: casualty risk $<10^{-4}$
	Methods: Actuators/switch to disconnect SA and/or batteries; charging suppressing software.	Methods: Sails; inflatable balloons/booms; tethers; electric propulsion; solid propulsion.	Methods: Inherently compliant.
Mini satellites < 200kg (no propulsion system)	Compliance: Power and electrical passivation at EOL.	Compliance: 25-year rule.	Compliance: casualty risk $<10^{-4}$
	Methods: Actuators/switch to disconnect SA and/or batteries; charging suppressing software.	Methods: Sails; inflatable balloons/booms; tethers, solid propulsion.	Methods: Inherently compliant.
Small satellites (200 - 500kg)	Compliance: Power and electrical passivation at EOL.	Compliance: 25-year rule if casualty risk $<10^{-4}$. If casualty risk $>10^{-4}$ direct re-entry.	Compliance: casualty risk $<10^{-4}$
	Methods: Actuators/switch to disconnect SA and/or batteries; charging suppressing software; venting valves; tank micro perforator; depletion burns.	Methods: Sails, inflatable balloons/booms; tethers; electric propulsion; liquid propulsion; solid propulsion.	Methods: Demisable critical components (e.g. tanks, reaction wheels, etc.). Direct re-entry.
Small satellites (150 - 500kg) mega constellations	Compliance: Power and electrical passivation at EOL.	Compliance: 25-year rule if casualty risk $<10^{-4}$. If casualty risk $>10^{-4}$ direct re-entry.	Compliance: casualty risk $<10^{-4}$
	Methods: Actuators/switch to disconnect SA and/or batteries; charging suppressing software; venting valves; tank micro perforator; depletion burns.	Methods: Sails, inflatable balloons/booms; tethers; electric propulsion; liquid propulsion; solid propulsion.	Methods: Demisable critical components (e.g. tanks, reaction wheels, etc.). Direct re-entry.
Medium satellites (500 – 2000 kg)	Compliance: passivation not required for direct-re-entry.	Compliance: direct re-entry	Compliance: casualty risk $<10^{-4}$

Direct re-entry	Methods: Inherently compliant.	Methods: liquid propulsion; solid propulsion.	Methods: Inherently compliant.
Medium satellites (500 – 2000 kg) uncontrolled re-entry	Compliance: Power and electrical passivation at EOL.	Compliance: 25-year rule	Compliance: casualty risk $<10^{-4}$
	Methods: Actuators/switch to disconnect SA and/or batteries; charging suppressing software; venting valves; tank micro perforator; depletion burns.	Sails, inflatable balloons/booms; tethers; electric propulsion; liquid propulsion; solid propulsion.	Demisable critical components (e.g. tanks, reaction wheels, etc.).
Large satellites > 2000 kg	Compliance: passivation not required for direct-re-entry.	Compliance: direct re-entry	Compliance: casualty risk $<10^{-4}$
	Methods: Inherently compliant.	Methods: liquid propulsion; solid propulsion.	Methods: Inherently compliant.

Table 3: compliance needs and casualty risk for different categories of satellites

This table takes into account the most commonly applied SDM requirements by space operators and Space Agencies, and it is focused on low Earth orbits, where the compliance with those requirements looks nowadays most challenging [2, 9, 7, 10, 19, 20], due to the complexity of the post-mission disposal manoeuvres and the long time period involved in accomplish them.

It has to be noted that the critical satellite class is the "500-2000 kg" one. Their compliance with the casualty risk requirement is arguable, and actually depends on the demisability of the spacecraft and on its ability to target a specific footprint on ground during the atmospheric re-entry. While a design for demise would guarantee an acceptable level of risk when re-entering on ground, a direct re-entry approach would drastically contain the time of permanence in orbit after EOM. This has some advantage in relation to the following aspects:

1. Large constellations in LEO;
2. Probability of failure of the satellite before initiating or completing the decommissioning manoeuver;
3. Future cost of the "25 years rule" applied today.

5.1 Mega-constellations in LEO

As recently announced by more than one private entity, LEO may experience new constellations composed by hundreds or thousands satellites. Although these satellites, on paper, are supposed to be small in mass, thus being compliant with SDM applying the 25-year rule, congestion of LEO orbit of all consequent defunct platforms slowly decreasing their orbits for 25 years may create problems of different nature:

- High risk of collision with operative satellites (domino effect on LEO protected region could make orbits out of use);
- Extra-monitoring costs to cover such large fleets for such long time;
- The long-time disposal duration will generate a debris constellation of comparable size of the operating ones crossing LEO orbits;
- Accepting current 90% [1, 18] reliability on passivation and EOM manoeuvre in general may not be enough. Furthermore, space authorities started requiring satellite passivation before the uncontrolled re-entry;
- Reliability of low cost platforms shall anyway be compliant with SDM requirements.

All these risks represent a direct cost operators should take into account in their business model. A faster decommissioning via a dedicated system may offer different advantages in terms of cost saving. However, dedicated mitigation measures for these risks and costs are now under discussion.

5.2 Probability of failure of the satellite before initiating or completing the decommissioning manoeuver

Current mostly accepted SDM guidelines force a minimum success rate for the decommissioning of 90% [1, 18]. In GEO, reducing to 10% the number of defunct satellites improperly or not decommissioned, for example, it is possible to reduce the risk of collision from 1 every 135 years to 1 every 776 years [16]. However, the collision risk is not the only cost driver for commercial operators, as shown by Schaub [3]. A defunct satellite in LEO is a threat for other satellites, but also a threat for the constellation it is from and a cost in terms of monitoring, insurance and image. In MEO a defunct satellite is likely to drift very slowly, basically occupying an orbital slot a decreasing the performance of the constellation if not replaced. Furthermore, considering MEO satellites as mainly operated by governments, the political cost and image cost may be too high. In GEO a defunct satellite drift across the other GEO slots, forcing to collision avoidance manoeuvers. Also, the down time of the replacement satellite while the improperly removed one is drifting, is also worth to be considered.
Using on board systems or integrated decommissioning systems do not seem to address these issues and do not offer mitigation solutions.

5.3 Future cost of the “25 years rule” applied today

Although the “25 years rule”, when established in the 70s, was enough for the current rate of satellites launched, with the new trends of commercial satellites and cubesats may not be up to date enough. Orbit congestion will require more powerful telescopes and radars on ground and in space. Monitoring effort will increase. Collision probability will increase as well forcing to a larger number of collision avoidance manoeuvers, thus sacrificing lifetime of satellites, directly converting into less revenues for commercial operators. Most of these costs are already addressed to the operators and it is likely that also monitoring costs may be transferred to commercial entities choosing to be compliant with the 25 year rule. Faster decommissioning should be able to mitigate these cost impacts.

It is now clear, at this point of the paper, that an independent decommissioning system, dedicated to this function and able to operate also in absence of operability of the host satellite, performing a fast direct re-entry or re-orbiting manoeuver, offer several advantages that will help to preserve the space environment and decrease SDM costs for operators.
These critical aspects have been found by the authors and the D-Orbit R&D Team mitigated and possibly solved by and independent decommissioning device based on solid rocket propulsion.

6 SDM REQUIREMENTS COMPLIANCE BY INDEPENDEDENT DECOMMISSIONING DEVICE

The advantages of an independent, autonomous and rapid decommissioning system based on solid propulsion have already been discussed in literature [4, 5, 6, 13, 14, 15]. In particular, the SPADES study [5], carried out in 2013 in the ESA Concurrent Design Facility, successfully assessed the feasibility of an autonomous de-orbit system based on solid propulsion technologies to be installed on future missions, and this concept is now one of the baselines for the controlled removal of satellites in the ESA Clean Space roadmap. Such a system, will have to installed on satellites and potentially launcher stages before launch, remains dormant for the all duration of the mission, and then is activate at EOM or when the satellite is experiencing a major failure, in order to dispose it or by a direct atmospheric re-entry or in a pre-defined graveyard orbit.

The following table compares for the different classes of satellites the advantages of an independent and rapid decommissioning system.

	Uncontrolled Atmospheric re-entry	**Direct Controlled Re-entry**
EOL Removal Technologies	Drag augmentation systems (sails, balloons, booms); electromagnetic systems (tethers); electric propulsion; low-thrust chemical propulsion.	Upgrade of propulsion system and extra-propellant; independent solid propulsion decommissioning system (SPADES).
Cubesats	Electrical passivation required; long-time EOM monitoring; higher risk of collision during re-entry.	Passivation not required; short time monitoring.
Mini satellites < 200kg **(no propulsion system)**	Electrical passivation required; long-time EOM monitoring; complex EOM manoeuvre; higher risk of collision during re-entry.	Passivation not required; short time EOM manoeuvring and monitoring; compliance with regulations (otherwise impossible without propulsion system for orbits higher than 600km); low risk of impact with other operational satellites.
Small satellites (200 - 500kg)	Electrical and propulsive passivation required; long-time EOM monitoring; complex EOM manoeuvre; higher risk of collision during re-entry.	Passivation not required; short time EOM manoeuvring and monitoring; compliance with regulations (otherwise complex without propulsion for orbits higher than 600km); removal possible even if the satellite is dead; low risk of impact with other operational satellites.
Small satellites (150 - 500kg) mega constellations	Electrical and propulsive passivation required; long-time EOM monitoring; complex EOM manoeuvre; higher risk of collision during re-entry; cloud of re-entry dead satellites for 25 year.	Passivation not required; short time EOM manoeuvring and monitoring; quick removal (1 hour); compliance with regulations; removal possible even if the satellite is dead; low risk of impact with other operational satellites.
Medium satellites (500 – 2000 kg)	Electrical and propulsive passivation required; long-time EOM monitoring; complex EOM manoeuvre; higher risk of collision during re-entry; need demisable	Passivation not required; demisable design not required since direct re-entry on a specific footprint on ground is possible; short time EOM manoeuvring

	design for limiting casualty risk.	and monitoring; quick removal (1 hour); compliance with regulations; removal possible even if the satellite is dead; low risk of impact with other operational satellites.
Large satellites > 2000 kg	This solution is not compliant with current regulations.	Passivation not required; short time EOM manoeuvring and monitoring; quick removal (1 hour); compliance with regulations; removal possible even if the satellite is dead; low risk of impact with other operational satellites.

Table 4: advantages of an independent and rapid decommissioning system providing direct re-entry compared to system providing uncontrolled re-entry.

The advantages listed in Table 4 come at the price of a mass penalty, which in some cases can be considerable. However, the operational advantages can well exceed the additional cost in terms of weight and relative complexity.

7 CONCLUSIONS

Space debris is jeopardizing the future sustainability of space activities and is becoming a serious problem for both the institutional and commercial space stakeholders. The increasing level of space activities (i.e. increasing launching rate, cubesats exponential phenomenon, projects for mega-constellations of hundreds/thousands of satellites) is emphasizing the criticality of the space debris issue, which could soon increase the risk of space activities beyond an acceptable level, both for operators and people on ground.

A remarkable national and international effort is in place for creating a regulatory framework imposing or recommending Space Debris Mitigation requirements to all space operators. Europe and the European Space Agency are leading this effort thanks to the most comprehensive and articulated regulations.

However, space operators themselves are starting showing implementation of SDM requirements independently from the applicable regulations, showing the commercial interest in preserving a sound environment for space systems and infrastructures. This is reflected in an improved success rate in the satellites post-mission disposal manoeuvres, especially in GEO where the orbital slots assigned to each operator represent a strategic and important asset to protect.

A dedicated and independent satellite decommissioning system, allowing the quick and safe disposal of a spacecraft from all possible orbits, is already favourably taken into consideration by many space operators and Space Agencies, since would allow increasing the success rate of the disposal manoeuvre up to the required level, as well as guaranteeing simpler operations, reduced risks and costs, especially for large constellations of satellites.

8 NOMENCLATURE

LEO – Low Earth Orbit;
GEO – Geostationary Earth Orbit;
MEO – Medium Earth Orbit;
GTO – GEO Transfer Orbit;
SDM – Space Debris Mitigation;
IADC – Inter-Agency Debris Committee;
FAA – Federal Aviation Administration;
FCC – Federal Communication Commission;

NOAA – National Oceanic and Atmospheric Administration;
EOM – End-of-Mission;
EOL – End-of-Life
SPADES – Solid Propellant Autonomous Deorbit System

9 REFERENCES

[1] – ESA Policy on Space Debris Mitigation. Rosario Nasca, Independent Safety Office (TEC-Qi). CleanSat Workshop, ESTEC, Noordwijk, 18th March 2015.
[2] – Orbital Debris Mitigation Policy and Unique Challenges for Small Satellites. J.-C. Liou, D. Jarkey, Nasa Orbital Debris Program Office, Jacobs. Small Satellite Conference, Logan, Utah, 10th August 2015.
[3] – Cost and risk assessment for spacecraft operation decisions caused by the space debris environment. Hanspeter Schaub, Lee E.Z. Jasper, Paul V. Anderson, Darren S. McKnight. Acta Astronautica 113 (2015) 66-79.
[4] – ESA Technologies for Space Debris Remediation. K.Wormnes, R. Le Letty, L. Summerer, R. Schonenborg, O. Dubois-Matra, E. Luraschi, A. Cropp, H. Krag, and J. Delaval.
[5] – SPADES, CDF Study Report – Assessment of Solid Propellant Deorbit Module. April 2013.
[6] – End-of-life De-Orbiting Strategies for Satellites. R. Janovsky, M. Kassebom, H. Lubberstedt, O. Romberg, H. Burkhardt, M. Sippel, G. Krulle, B. Fritsche. Deutscher Luft- und Raumfahrtkongress 2002.
[7] – Space Debris – Risk and Mitigation. Holger Krag, Stijn Lemmens, Stefan Frey. ESA/ESOC Space Debris Office (HSO-GR). CleanSat Workshop, ESTEC, Noordwijk, 18th March 2015.
[8] – An Assessment of Cubesat Collission Risk. Hugh G. Lewis, Benjamin S. Schwarz, Simon G. George and Hedley Stokes. 65th International Astronautical Congress, Toronto, Canada.
[9] – Analysis of Mitigation Guidelines Compliance at International Level in Low Earth Orbit. J.C. Dolado-Perez, V. Morand, C. Le Fevre, D.A. Handschuh, T. Philippe. 65th International Astronautical Congress, Toronto, Canada.
[10] – Compliance of the Italian Satellites in LEO with End-of-Life Disposal Guidelines for Space Debris Mitigation. L. Anselmo, C. Pardini. 65th International Astronautical Congress, Toronto, Canada.
[11] – Debris Creation in GTOs: a Review of Launch Practices 2004-2012. S. Fisher, E. David. 65th International Astronautical Congress, Toronto, Canada.
[12] – The Impact of Growing Space Debris on Third-Party-Liability Insurance. A.N. Pecujilic. 65th International Astronautical Congress, Toronto, Canada.
[13] – Proactive Space Debris Removal Techniques. S. Antonetti, L. Rossettini, F. di Tolle. 3rd European Workshop of Space Debris Modeling and Remediation, Paris, 16, 17, 18 June 2014.
[14] – Benefit of Adopting a Spacecraft Decommissioning Device to Implement Orbital Access Sustainability. G. Tussiwand, S. Antonetti, L. Rossettini, F. di Tolle. 7th IAASS Conference, Friedrichshafen. 20-22 October 2014.
[15] – A Satellite Dedicated Decommissioning Device based on Solid Rocket Motor Technology. E. Toson, S. Antonetti, M. Trotti, L. Ferrario, L. Rossettini. EUCASS 2015. 29 June - 3 July, Krakow, Poland.
[16] - Ailor, W.H. and Peterson, G.E., "IAC-04-IAA.5.12.3.01, 55th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law, Vancouver, British Columbia, Oct. 4-8, 2004.
[17] – RFI-NNG15PACERFI – Request for Information NASA PACE mission. 8 May 2015.
[18] – ECSS-U-AS-10C Adoption Notice of ISO 24113: Space Debris Mitigation Requirements.10/02/2012.
[19] – Modeling the Large and Small Orbital Debris Populations for Environmental Remediation. J.-C. Liou, Nasa Orbital Debris Program Office, Johnson Space Centre, Houston, Texas. 3rd European Workshop on Space Debris Modeling and Environment Remediation.
[20] – Orbital Debris: Towards Sustainable Space Activities. C. Bonnal, CNES. Paris Space Week 2015.