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Approaching a New Era in Orbital Debris Mitigation: A Holistic Overview of Economic and Environmental Factors

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Abstract

The number of orbiting bodies has increasingly grown in an unrestricted and unregulated manner over the last decade, and one collision can trigger a cascade effect that may affect the access to space for a long time span. To aid in the mitigation of such problem, the arrival of on-orbit servicing brings hope into the panorama, setting its foundations in the arising of the New Space economy. Recently, several proofs-of-concept have been demonstrated and the economic interest in this sector, along with its implications in asset liability, has risen supported by the maturation of space technology and reduced launch costs. Among the wide range of servicing options is active debris removal by de-orbiting the spacecraft into the atmosphere. However, the effect of spacecraft incineration on Earth´s atmosphere is yet lightly studied, and the long-term impact on the sustainability of the mesosphere remains unknown. This study presents an overview of de-orbiting techniques in maturation, the market size, the implications of systematic and continuous usage of that technique in the atmosphere, and how it will allow for a new approach to end-of-life obligations for spacecraft operators.

Keywords: Active Debris Removal, De-orbiting, Atmospheric Pollution, New Space

Acronyms

ADR	–	Active debris removal
GEO	–	Geostationary Earth orbit
IADC	–	Inter-Agency Space Debris Coordination Committee
LEO	–	Low Earth orbit
OOS	–	On-orbit services
TRL	–	Technology Readiness Level
T&T	–	Tugging and towing services

1. Introduction

With the ever-growing effort for developing space-based technologies since the decade of 1950s, the side effects of such development echoes today on the verge of an imminent collision that may jeopardize the access to Earth's orbit. Decades of large investments and ambitious plans to overcome the so-called *last frontier* have pushed aside the environmental awareness of the consequences of such milestones. As a result, a cascade effect may bring an already unsustainable situation into a complete calamity.

Currently, the mapping of Earth's orbit presents around 60 % of mission-related debris, rocket stage remainings, and defunct spacecraft; and 40 % of debris fragments that were primarily originated by any of the previous forms. This is thoroughly explained in a model that firstly defined the Kessler Syndrome in the late 1970s [1].

In 2020 only, more than 3500 object were added to Earth's orbit, summing up to almost 700 tons; from these, more than 55 % of the objects and 70 % of the mass was put in Low-Earth Orbit (LEO). The balance of the year is clearly negative, as solely 393 objects and 180 tons re-entered the atmosphere – the vast majority originated in LEO [2].

According to empirical data of 2021, there are around 30 000 tracked pieces of large-sized space debris with more than 10 cm in diameter. The majority is currently catalogued and regularly tracked by space surveillance networks that inform about possible incoming collisions – a capacity that had significantly increased over the last years [2].

However, the smaller parts do not. Although one can arguably affirm that space hardware can be protected from pieces of debris smaller than 1.4 cm diameter by shielding them to withstand collisions – such as in the case of the International Space Station [3] –, the untracked range until 10 cm remains uncontrolled. As of 2021, it is statistically estimated that more than 1 million objects between 1 cm and 10 cm diameter orbit the Earth, and so do 330 million objects between 1 mm and 1 cm [4].

As such, it is no longer possible to rely on orbital decay to ensure access to orbit while expecting that no collision occurs. This threat has been identified and attention raised when in 2002 the Inter-Agency Space Debris Coordination Committee (IADC) published the first internationally accepted set of measures to ensure the mitigation of space debris, recommending a 25-year limit for de-orbiting whenever direct re-entry or disposal to a graveyard orbit is not possible [5].

The problem of on-orbit collision was materialized in 2009 at the incident between the Kosmos-2251 and the Iridium-33 satellites. This event triggered the attention of major stakeholders, which led to a preliminary assessment which confirmed «the instability of the current LEO debris population» [6].

In fact, the turning point has already been passed, and although researchers keep on deploying new models to propagate current conditions into future scenarios, it is now clear that even if all activity suddenly stopped, an increase of orbital debris will occur. The scenario based in the current increasing rate of launch depicts a worrying future, as showcase in Fig. 1. The economic impact of a possible cascade effect is worrisome [7].

Nevertheless, the current unprecedent efforts to control the problem are noteworthy. In 2019, international standardization entities such as ISO have released standard mitigation requirements for space systems in an important step for a comparable and fair process of constraining debris generation by new activity in orbit [8]. The IADC guidelines were also recently reviewed, resembling the need to increase the probability of success of deorbiting activities for objects passing by LEO protected regions to 90 %, and mentioning that such probability may have to be higher for large constellations [9].

As such, to ensure that there is at least an alternative plan, services are or will soon be deployed in orbit so as to validate core technologies that could potentially mitigate the space debris problem. In tandem, policy-makers may now start enforcing more restrictive measures, while a whole new range of services erupts in this new aerospace subsector of the economy.

2. Background

The servicing market of this new subsector in aerospace has seen a broad set of definitions, and consensus is hard to reach concerning an uniform nomenclature of concepts that are often used as interchangeable.

A worth noting effort was made by ESPI in its most recent report about in-orbit services [10], where clarity is provided. Therefore, that nomenclature is adopted throughout this paper, in accordance to Fig. 2.

On-Orbit Servicing (OOS) as a category that encompasses the larger set of services that can be offered on orbit is considered a subset of the general category of On-Orbit Operations, which would equally include On-Orbit Manufacturing and Assembly at the same level.

Within OOS, one can then distinguish between 3 categories, namely Maintenance, Inspection, and Tugging & Towing (T&T). Concerning the former, the services of repairing, reconfiguring, refuelling, recharging, and upgrading a spacecraft are included, while the Inspection category is self-explicative. Concerning T&T, one can include services of orbit keeping, orbit correction, component relocation within the same space system, recycling of raw materials or components, and active debris removal (ADR). This latter will then include both de-orbiting by forcing the re-entry of the object, and parking relocation to a graveyard orbit.

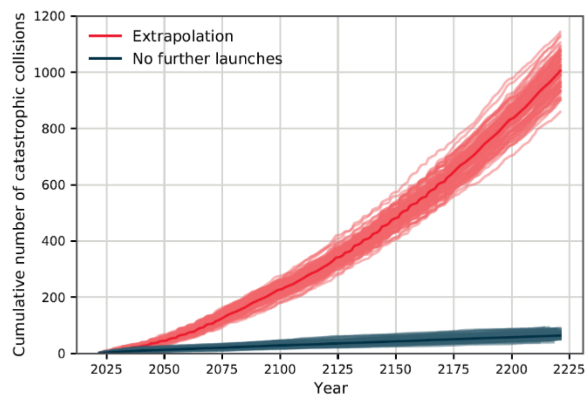

Fig. 1. Number of cumulative collisions in LEO in the simulated scenarios of long-term evolution of the environment (image credits to ESA [2])

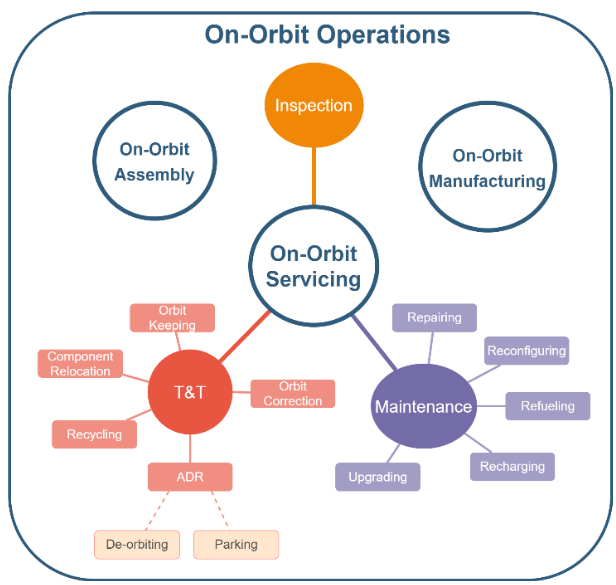

Fig. 2. On-Orbit Operations categorization (adapted from ESPI Report 76 [10])

As such, one can conclude that OOS comprises services that depict very handy capabilities to expand the lifetime of a spacecraft by simply refuelling it or refurbishing damaged parts, or to safely decommission inoperative spacecraft. In fact, performing regular *in situ* inspections to space hardware and ensuring the application of a proper maintenance program is the way forward to keep a sustainable access to space by preparing today's designs to receive such complementary services while in orbit, in the future.

However, according to the statistical estimations depicted in Fig. 1, the problem is already critical today. T&T services are the response to provide in the present, and although component relocation and material recycling may still seem some years off as to core technology development, orbit keeping and correction services are already possible, having been successfully proven by a Northrop Grumman's subsidiary with the mission MeV-1 in early 2020 and MeV-2 in early 2021.

Notwithstanding, the aforementioned solutions are poorly applicable to hardware that is not prepared – by means of standardized interfaces – to receive such services: the MeV spacecraft attaches to the target's body and perform orbital corrections – therefore it is a T&T service. Should it be able to attach through a standardized interface and refuel the spacecraft, it would be a Maintenance service.

In fact, this poses a solution to spacecraft that in spite of having passed its nominal lifetime, still present good conditions to pursue the phase of extended operations should more fuel be available. However, for defunct spacecraft, the solution shall be ADR.

As such, while inspection and maintenance may be the forthcoming reality concerning space asset management and operations, and other T&T services may shed light onto the reusability or extended operations of hardware in orbit, the outdated spacecraft still need to be safely decommissioned so as to avoid collisions that may trigger the troublesome cascade effect.

Thus, ADR, consisting in the act of altering the orbit of a purposeless body in space with the sole intention of disposing it, can make use of different methodologies to accomplish such task: either performing an orbit transfer towards a graveyard orbit or even reaching escape velocity, or pushing an orbiting body into the atmosphere.

Considering the definition of LEO and Geostationary Earth orbit (GEO) protected orbits depicted in the IADC guidelines [9], one can affirm that Parking services are more suitable for GEO considering that the remaining options would demand for a larger fuel burn. In fact, it is already a reality in that orbit, mostly due to the high demand for orbital slots in such region, which reflects the need to decommission a spacecraft once the nominal operational phase is over.

As to LEO, the Parking option is energetically less valuable than the de-orbiting one, mostly due to atmospheric drag which contributes to gradually decrease the orbital altitude. This effect becomes dominant with decreasing altitude, so the lower the orbit the more suitable this method is. Ideally, to fulfil the original IADC guidelines [5], one could in principle prove that the spacecraft will re-enter the Earth's atmosphere within 25 years, which should be doable for most spacecraft shapes in a circular orbit up to 600 km altitude.

However, it is currently clear that leaving a spacecraft unattended, inoperative, and uncontrollable for that period is a serious risk to other spacecraft. Should it encounter a functioning spacecraft with a timely warning, the latter would eventually be able to incur into collision avoidance manoeuvres. But should the incoming threat be an equally defunct space body, no active manoeuvring is possible.

Therefore, de-orbiting services are needed and seen as a solution to amend this problem. Demanding for cutting-edge technology concerning proximity operations and rendezvous capabilities, the first functional ADR missions targeting space object de-orbiting are currently in the making.

As such services become available, a predictable market is foreseen to grow and flourish based on a regulatory framework that may enforce the spacecraft decommissioning after the operations phase. Although in GEO that may seem usual, that is certainly not the case in LEO, and implications to the small satellite and constellation markets are expected to be significant.

In addition, assuming that de-orbiting is the most cost-saving ADR option for LEO does not mean that it is environmentally sustainable. The effect of spacecraft incineration on Earth´s atmosphere is lightly studied, and the long-term impact on the sustainability of the mesosphere remains unknown.

3. Analysis

As de-orbiting is foreseen as the most suitable solution to target the problem of space debris in LEO, several factors should be analyzed to better understand the forthcoming path of this ADR solution. The evaluation is multi-fold, as distinct variables are interconnected and will affect each other's development. Nonetheless, an effort is made to perform a comprehensive analysis of such factors.

It is perceived that the technology maturity is still on the verge of the highest Technology Readiness Level (TRL) despite having clearly received a boost with the recent MeV missions and other prototypes. This is heavily related with the incoming need for a concise legal framework regulating assets in LEO. These factors will then eventually create a market demand, although the environmental costs of deorbiting are still unknown.

3.1 Technology Maturity

MeV missions have shown the way forward and proven key core technologies for T&T services. They were meant for GEO and mostly targeted Orbit Keeping and Correction services. By showcasing core competencies such as automated proximity operations and rendezvous, it allowed to raise the global awareness level and increase the TRL of key technologies. De-orbiting techniques may now use such building blocks to tackle the complexity of capturing a non-cooperative target.

Although many concepts for ADR have been theorized and prototyped over the last decade [11] [12], few are the confirmed attempts of on-orbit demonstration of such capacities. Currently, there are two noteworthy efforts to clean LEO by means of deorbiting techniques. The missions mentioned below aim at proving core technologies that would allow demonstrating the feasibility of such concepts, and comprise both confirmed and funded intentions or demonstrators currently in orbit.

The Elsa-d mission by Astroscale – a trans-national company backed by private and public funding – is currently demonstrating its concept of operations and core technologies in a trailblazing mission. Launched in early-2021, the mission comprises a *servicer* and a *customer* satellites, weighing 180 kg and 20 kg respectively. It aims at proving proximity operations, rendezvous, and capture with and without relative motion between the formation elements. In August 2021, Astroscale confirmed the successful completion of the magnetic capture of the *customer* after being purposedly released [13].

On the other hand, the ClearSpace-1 mission led by the Swiss company ClearSpace is the most recent effort backed by the European Space Agency (ESA) project ADRIOS, which follows on the footsteps of the previous ESA e.Deorbit mission [14]. Set to remove debris from orbit in 2025, the consortium is developing a spacecraft that can capture a VESPA upper stage of approximately 100 kg. This leftover from a Vega launcher will then be collected by a claw mechanism and prompted back to re-enter in Earth's atmosphere.

As these and other de-orbiting demonstration missions keep flourishing, it is expectable that by the last half of the decade the core technologies have reached TRL 9. However, technology availability does not create the need for such kind of service *per se*. A stronger and more concrete legal framework shall also be present.

3.2 Legal Framework

During the decade of 1960, it became evident that a regulative environment would have to be created to reflect the progress made concerning access and usage of Earth's orbit and beyond.

The *Outer Space Treaty* [15] established the liability principles in use today. Each state or company registered in a given state is liable for their actions in space, including any interference with third party assets in orbit. As a corollary, a state is liable for each object procured or launched from its country, including obsolete, decommissioned, and faulted spacecraft in orbit. Therefore, the legal responsibility over a piece of debris may be attributed to a state.

Although the definition of *fault* may be ambiguous as argued in the ESPI report [16], it is clear that a collision in orbit would generate a legal dispute targeting each one's obligation to perform collision avoidance maneuvers – should both spacecraft be operational –, and the reasons for such a *fault* to occur.

Furthermore, it is also worth mentioning that the *Outer Space Treaty* mandates that no interference shall occur between different nation's objects without prior consent. Applying it to the case of de-orbiting means that either there is a national entity capable of performing such service to an orbiting object of that state, or alternative means of liability transfer should be used.

The current framework poses clear limits to debris mitigation strategies and OOS in general, making geopolitical restrictions in servicing different state-owned objects a reality. Nonetheless, that may enable the potential creation of competing services and technology applications in national markets.

The IADC guidelines recommend a direct re-entry maneuver for objects in LEO protected regions with a success probability of at least 90 % or, if appropriate, a 25-year residual orbital lifetime should be ensured [9]. In spite of the non-mandatory character of these guidelines, even if the residual lifetime is ensured, the hypothetical collision between two bodies in end-of-life conditions brings up the liability question once again.

As such, with the verge of large constellations of small spacecraft, ensuring the 25-year residual orbital lifetime may fall short concerning the stability and control of debris proliferation in LEO. Although new hardware may be prepared to perform direct re-entry in the future, current and forthcoming obsolete spacecraft do not have that capability, and so ADR services are needed.

Nonetheless, it seems clear that de-orbiting services will not be procured if not mandated. Studies and intentions to establish a governing body to enforce the aforementioned measures are not new [17] [18]. The unsuccess of the diplomatic effort in raising awareness about the space debris problem echoes a resonant silence, with several authors comparing it to the climate change negotiation difficulties, emphasizing the benefit of addressing these two urgent issues simultaneously [19].

In the meantime, the technology will pursue its maturation, and once legally obliged, the market of ADR will officially boom.

3.3 Market Demand and Economics

Although market size estimations are difficult to perform for such a broad term as the colloquial *space-based technology* term is concerned, the revenue of satellite services such as television, broadband, mobile, remote sensing, and other fixed services is estimated to range from 120 to 140 billion USD as of 2019 [19].

As to OOS, a Norther Sky Research forecast predicts a cumulative revenue of 6.2 billion USD by 2030. As mission-extension services became flight-proven in the past years, most of the forecasting figures are driven by services offered in GEO, with 72 % of total revenues expected from servicing that region [20].

The said study also addresses for the first time a market forecast for custom de-orbiting services in LEO[†]. It is estimated that cumulative revenues go beyond 64 million USD in a cumulative addressable market of 179 satellites by 2030. However, by that time, only 16 % of those satellites would have been serviced.

Although the current and forthcoming market still represents a fraction of the overall OOS compendium and demand is led by government and military entities, it is estimated that revenues will be driven by commercial entities requesting for de-orbiting services, with a 66 % share over institutional entities [20].

However, the foreseeable increasing demand of de-orbiting services in LEO is oblivious of the potential effects of incinerating an increasing number of spacecraft in the atmosphere. Such subject is poorly studied and unmentioned in the current legal framework.

3.4 Environmental Factors

The IADC guidelines currently address the environmental impact de-orbiting spacecraft would have on the ground, mentioning that «ground environmental pollution, caused by radioactive substances, toxic substances or any other environmental pollutants resulting from on-board articles, should be prevented or minimized in order to be accepted as permissible» [9]. NASA's good practices [21] and ESA's debris mitigation guidelines [22] also address this concern.

Although recommendations to handle spacecraft re-entry are already in place concerning the estimation of human casualties and risks for property damage, one can argue that solely the larger spacecraft would make it to the ground. With the massification of de-orbiting services, it is expected that more large satellites will be decommissioned, although such services will start becoming available for lower payload masses, thus targeting smaller satellites first. Furthermore, the advent of small satellite constellations would also increase the figure of re-entering bodies that would completely incinerate during re-entry, never making it to the ground.

As such, one can arguably affirm that although de-orbiting may increase the amount of spacecraft reaching the surface, the procedures for tackling that challenge will not change as they are already defined according to IADC recommendations. Nonetheless, either large and small spacecraft will past through the re-entering phase where a significant portion of its mass will be incinerated in the mesosphere. In fact, it is estimated that 60 to 90 % of the re-entering mass burns in the atmosphere, with the remaining reaching the ground [23].

As these figures increase, the impact on the composition of the mesosphere and lower atmospheric layers should be monitored and evaluated, as the long-term consequences are yet unknown. It is reported that high-altitude aluminium deposition is expected to dramatically increase in the atmosphere as large constellations de-orbit when compared to normal levels due to meteoroid ablation. That may increase the rate of ozone depletion and damage the ozone layer once particles sink into the stratosphere [24].

Furthermore, the same study also emphasizes the scattering properties of the said substance at certain wavelengths, which may eventually change the Earth's albedo. Studies and simulations on the by-product generation of ablating metallic alloys are already in place [25], although *in situ* measurements are still incipient.

4. Discussion

As previously assessed, the aforementioned variables are interconnected and each one act as an enabler to the other. It is possible to conclude that successfully mastering one would not necessarily mean the sustainable creation of a controllable and profitable solution.

Technically, key technologies for de-orbiting services and OOS in general are on the right path for fully-fledged deployment by the end of this decade. With only one de-orbit demonstrating mission to date – currently ongoing –, a few others funded, and several intentions revealed, it is difficult to estimate when it would precisely happen.

The demand driver depends on the orbital plane considered. Satellites in GEO would inherently benefit from ADR services such as Parking or other T&T services, and would allow for longer satellite lifetimes and fewer launches. On the contrary, in LEO, the most impacting service would be de-orbiting, as mission-extension services would not be needed as the miniaturization of spacecraft and technology

[†] The Northern Sky Research forecast officially mentions this study as an assessment of the *ADR* market [20]. Interpreting the definition of *ADR* in such study allows for the conclusion that it exclusively refers to *de-orbiting* services as depicted in Fig. 2.

development would make it cheaper to just replace the spacecraft by a new one.

As such, demand in LEO is – and will be in the near future – driven by institutional players in an attempt to foment a potentially profitable market. Notwithstanding, the technical maturity will not create demand *per se* if servicing is not mandated.

Considering the technology replacement rate in LEO, the 25-year recommendation will likely fall short of significance for small satellites and large constellations in general. This concern would be raised when a significative portion of the population on orbit is compliant with such recommendation but inoperative, meaning that it would not be possible to avoid collisions.

According to ESA's report on space environment [2], approximately only half of the satellites in LEO protected regions are decommissioned as per the IADC guidelines. A residual percentage of these is through direct de-orbiting, being the most used option to ensure the 25-year requirement compliance, depicted in Fig. 3.

This way, even when the 25-year recommendation is fulfilled, on-orbit collisions between uncontrolled and decommissioned spacecraft may arguably occur. The strategy that could avoid it would be the direct re-entry, which is currently not heavily implemented. One can conclude from Fig. 3 that the de-orbit re-entry mass share is often larger than the count share, which means that mostly large spacecraft perform direct re-entry. This is to comply with other IADC guidelines concerning risks for people and property on the ground, and the accurate estimation of re-entry time and impact area so that authorities can be notified in due time.

Notwithstanding, the forthcoming need for de-orbiting services will surely increase the number of re-entries in Earth's atmosphere. It is foreseeable that the figure of 180 tons of re-entering spacecraft mass achieved in 2020 [2] – which is almost totally achieved by complying with the 25-year recommendation and not through direct re-entry, as per Fig. 3 – dramatically increases, matching the rising demand for such a service. Rough estimations predict that it may grow to 800 to 3200 tons per year for satellites, and up to 1000 tons for launch vehicles [23], which will raise the levels of metallic alloy deposition above natural levels.

Environmental consequences are still uncertain, as the effect of substances such as aluminium in the mesosphere and stratosphere is not thoroughly studied.

5. Conclusion

An overall evaluation of key governing factors for implementing ADR solutions in LEO was performed, assessing the impact of the technology maturity level, legal framework, market demand and economics, and environmental factors on the development of sustainable and profitable solutions to tackle the problem of space debris.

It is concluded that technology maturation and institutional demand per se would not suffice to create a potential market. The legal context, which currently presents non-binding recommendations, shall be reinforced so that concrete requirements for end-of-life behaviour are internationally accepted and enforced.

Nonetheless, such potential tool for creating a commercial market will also dramatically increase the mass re-entering the atmosphere way above natural levels. As the international community is yet oblivious of the environmental consequences of such activity, it is advised that studies concerning spacecraft re-entry by-product formation and the medium- and long-term chemical impact on the atmosphere composition are performed.

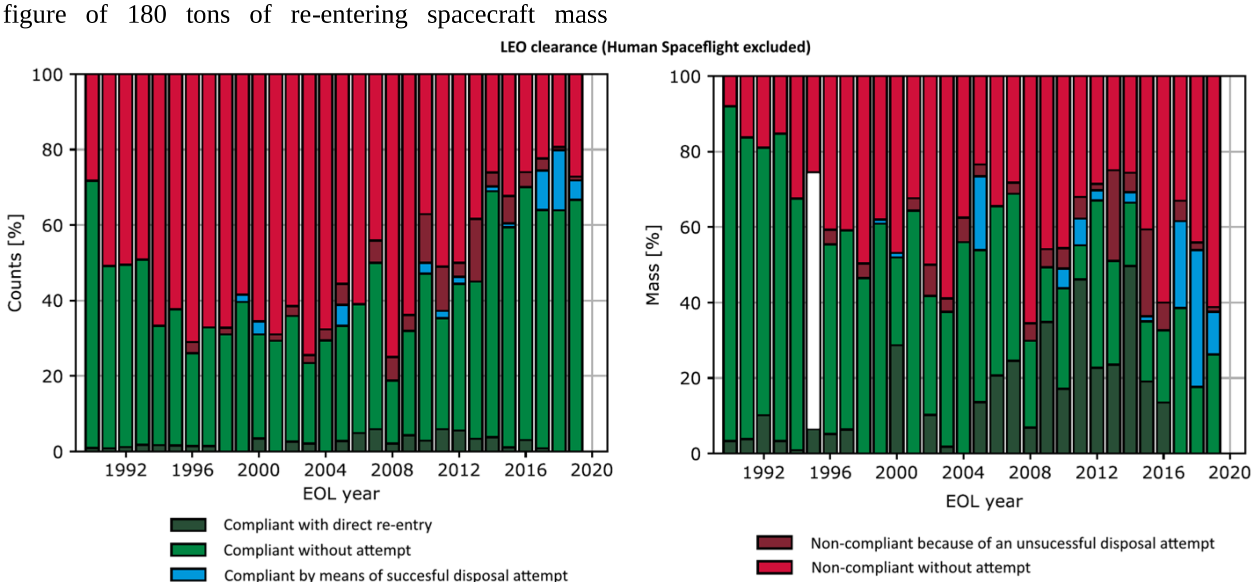

Fig. 3. Relative share of disposal behaviour classes concerning the 25-year recommendation in function of the end-of-life (EOL) year, in terms of count and mass for payloads in LEO (image credits to ESA [2])

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