IAC-19-E7: Remediation of Space Debris: A Fundamental Legal Challenge?

THE PATH TO ESTABLISHING AN EFFECTIVE FRAMEWORK FOR SPACE DEBRIS REMEDIATION ON THE BASIS OF MITIGATION: LEGAL PROPOSALS RESULTING FROM THE TECHNICAL RESULTS OF THE REDSHIFT PROJECT

Main author:
Ms. Rada Popova (University of Cologne, Germany)[a*]

Co-authors:
Dr. Alessandro Rossi (IFAC-CNR, Italy)
Mr. Youngkyu Kim (University of Cologne, Germany)
Dr. Camilla Colombo (Politecnico di Milano, Italy)
Dr. Elisa Maria Alessi (IFAC-CNR, Italy)
Dr. Ioannis Gkolias (Politecnico di Milano, Italy)
Dr. Volker Schaus (Technical University, Braunschweig)
Prof. Dr. Kleomenis Tsiganis (University of Thessaloniki, Greece)
Dr. James Beck (Belstead Research Ltd., United Kingdom)

[a] Institute of Air Law, Space Law and Cyber Law, University of Cologne, Albertus Magnus Platz 50923 Cologne, Germany, rada.popova@uni-koeln.de
* Corresponding Author

Abstract

The ReDSHIFT (Revolutionary Design of Spacecraft through Holistic Integration of Future Technologies) project focused during three years on various means to reduce the impact of space debris. The project investigated the synergy between theoretical and experimental results (long-term simulations, astrodynamics, passive de-orbiting devices, 3D printing, design for demise, hypervelocity, impact testing), assessed mitigation technologies, measured the long-term effect of existing guidelines and explored the relevance of these technical findings for the implementation of legal measures for space debris. The status quo of the relevant legal framework is well-known: the international treaties along with general international and telecommunications law incorporate the *corpus iuris* for activities in outer space, supported by a number of non-binding guidelines and recommendations that address space debris more specifically. The practical application and the effectiveness of the legal framework are challenged on a few levels. The complexity of space debris concerning the usability of outer space in a long-term perspective does not only require adequate regulation. It demands a holistic approach that provides a pragmatic trade-off between the restrictions needed and their benefits.

ReDSHIFT demonstrates that debris mitigation actions can be measured in a quantitative way. This plays an important role for the legal considerations on implementing preventive and reactive measures, including ADR. While a high level of mitigation compliance is essential, it is nevertheless not sufficient to reach a stabilization of the debris environment. Hence, remediation is needed to complement and amplify mitigation.

A global strategy - both on the technical and on the legal level, from the planning of the mission and spacecraft design, up to end-of-life - is needed. Legal efforts to minimize space debris should not be concentrated only on compliance and enforcement of existing guidelines. These must be adapted, extended and supported by (new) legal and economic measures. In the paper, by premising the legal analysis on technical findings, possibilities to re-formulate the existing regulations are proposed, including:

- a revised interpretation of the 25 year-rule for MEO, aiming at the deorbiting of GNSS satellites at end-of-life;
- an add-on to GEO disposal rules, accounting for the growing exploitation of inclined GEO orbits for natural end-of-life re-entry;
- recommendations to limit the orbital lifetime in LEO and MEO by exploiting orbital resonances;
- the use of augmentation devices for deorbiting also from orbits higher than LEO;
- recommendations for demisable materials and design-for-demise procedures
- economic incentives to promote ADR.

Keywords: space debris mitigation, enforcement of voluntary measures, end-of-lifetime disposal

1. Introduction

The theoretical and experimental results of the ReDSHIFT project include findings based on satellite engineering, long-term dynamical simulations and modelling, satellite technology development, 3D printing, design for demise, hypervelocity, impact testing as well as a thorough assessment of mitigation technologies [1].

In the second half of this 3-years project, the impressive spectrum of technical findings has been the basis for a thorough legal analysis of the binding rules applicable to space debris contained in space law and general international law. In particular, it has resulted in a critical revisit of the voluntary measures for space debris mitigation as adopted by the Inter-Agency Space Debris Coordination Committee (IADC) and The United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS). On the grounds of this analysis, certain conclusions could be drawn on the effectivity of the current set of applicable measures and proposals could be formulated as to how to update and reformulate the mitigation guidelines and to extend them with further compliance, economic incentives and remediation measures.

While the holistic technical and legal analysis in ReDSHIFT was mainly focused on the applicability and scope of mitigation practices and guidelines, it also led to substantial conclusions as the effectiveness of mitigation for overcoming the challenges resulting from the constant increase space debris *vis-à-vis* remediation is concerned and underlines the importance and the need to include remediation in the efforts to sustain orbital usability.

2. Overview on existing space debris mitigation measures

Currently, space debris mitigation measures are the first and foremost action undertaken by the international space community on the legal level in response to the risks posed by of space debris.

The first set of space debris mitigation guidelines was elaborated in the framework of the IADC [2]. Issued in 2002 and revised in 2007, this first international instrument for the mitigation of space debris had been 'agreed to by consensus among the IADC member agencies' [3]. Despite the fact that consensus on the contents of the guidelines was reached among the national space agencies of major space-faring nations participating in IADC, the guidelines are a set of voluntary technical standards for space debris mitigation rather than a (binding) legal instrument. The guidelines have various important normative values that space-faring nations could implement as law, but their legal effect is limited because of their non-legally binding nature. Therefore, the guidelines elaborated under the auspices of the IADC serve as a recommendation and can, but must not be adhered to.

The IADC guidelines formed the basis for the adoption by the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) of space debris mitigation guidelines. A dedicated Working Group on Space Debris, established within the Scientific and Technical Subcommittee of UN COPUOS, developed a set of recommended guidelines that are based on the technical content and the definitions of the IADC guidelines, in order to promote the existing space debris mitigation measures into a set of high-level qualitative guidelines and make them widely accepted among the global space community. The UN COPUOS guidelines were adopted by consensus in the 50th session of the plenipotentiary UN COPUOS in 2007 and were brought to the UN General Assembly the same year, which endorsed the guidelines in its resolution 62/217 and invited all Member States of the UN to implement those guidelines through relevant national mechanisms [4].

As the IADC guidelines, also the UN COPUOS Space Debris Mitigation Guidelines are 'not legally binding under international law'. They recommend that 'Member States and international organisations should voluntarily take measures, through national mechanisms or through their own applicable mechanisms, to ensure that these guidelines are implemented, to the great extent feasible, through space debris mitigation practices and procedures' [5].

Both sets of guidelines are based on the three common principles that some countries had already adopted in their own space debris mitigation standards and requirements, namely:

- Limiting the objects released during normal operations;
- Preventing on-orbit break-ups;
- Removing post-mission spacecraft from the useful densely populated orbit regions.

2.1. Limiting the objects released during normal operations

The first guidelines are concerned with limiting the objects released during normal operations, the so-called "operational" or "mission-related" objects. They are debris released mostly during the launch and orbital injection phase, when an orbital stage of the launch vehicle is separated from the main stage or when an injected spacecraft deploys its solar panel, antenna and sensors. Examples for such operational debris include:

- Launch vehicle connectors and fasteners: separation bolds, clamp bands, etc.

- Fairings: fairings and adapters for launching multiple payloads, etc.
- Covers: nozzle closures, etc.
- Others: yo-yo masses and lines, etc.[6]

Due to the variety of mission-related debris, the space-faring nations control the total quantity of debris released during mission by size or lifetime limit. Those quantitative criteria vary from State to State. For example, the United States requires an evaluation and justification for each release event of a debris object the diameter of which is larger than 5 mm. In addition to the limitations on size and number, NASA imposes different lifetime limits for the LEO and GEO regions. The ESA regulates the total number of released debris objects without a lifetime limit [7]. While the United States set aside slag particles ejected from solid rocket motor [8], the ESA requires slag and pyrotechnics particles not to be larger than ten micrometres in diameter [9].
The growth of the orbital debris population is aggravated by the problem of intentional destruction. Fragmentary debris caused from deliberate explosions and collisions can be considered as mission-related debris in principle, given that intentional destruction of spacecraft falls under the aims of missions for military or security purposes. This issue of intentional destruction will be discussed separately.

Considering the variety of mission-related debris objects and the difference of the quantitative criteria to regulate them in national requirements, the guidelines aimed at limiting debris released during normal operations, seem, at this stage, not to be suitable for being directly transferred into legal obligations. The national standards seem difficult to be harmonised and permit exemption from the requirements, depending on missions.

2.2. Prevention of on-orbit break-ups

Break-up includes collision, explosion, rupture or any other event that generates fragments. For the purpose of prevention, break-up events can be classified into:

- accidental explosion;
- accidental collision;
- intentional destruction.

The collision between Iridium 33 and Cosmos 2251 in 2009 dramatically altered the debris environment in LEO. Together with the fragments caused by the 2007 anti-satellite (ASAT) test in the Fengyun-1C satellite (see below under section 2.3.), approximately 5500 large fragments were generated. The debris generation during these two events account for more than 60% increase to the debris population in LEO [10]. For accidental explosions, the existing IADC and UN COPUOS guidelines recommend passivation as a preventive measure, which means the removal of all forms of stored energy, including residual propellants and compressed fluids, by idle burn or venting, and discharges of electrical storage devices. These passivation measures are proven to be effective because there have been no recorded explosions of successfully passivated spacecraft and orbital stages [7]. Moreover, fuel depletion of orbital stages can be performed to function as a braking manoeuvre and to leave the stage in a reduced-lifetime orbit. For the prevention of accidental explosion, passivation measures can, especially in the form of depletion of residual propellants, become legal requirements at least for orbital stages of the launch vehicle, if they remain in orbit after their payload delivery missions. This measure is also difficult to be generalised into a norm of international law but would be better to remain as a technical standard.

As regards accidental collisions, the guidelines recommend estimating and limiting the probability of accidental collision with known objects during the orbital lifetime of spacecraft, and if the collision risk is not considered negligible, the performance of collision avoidance measures.

2.3. Intentional destruction

Intentional destructions of spacecraft have been performed to prevent recovery of certain satellites and to test anti-satellite military weapons. The two recent examples are the Chinese ASAT test in January 2007 when China launched a missile armed with a kinetic-kill vehicle to destroy its Fengyun-1C weather satellite in LEO; and the US ASAT mission in February 2008 to destroy a malfunctioning intelligence satellite USA-193 carrying high toxic substance by SM II missile. The first event generated an unprecedented amount of space debris cloud, while the latter left almost no space debris in orbit within one week after the interception. In 2019, another relevant event happened when in a test, India deployed a kinetic kill weapon to demonstrate its ASAT abilities in LEO [11]. Despite the low altitude of the orbit, the test generated fragments at a high altitude that are still in orbit. Both the IADC and UN guidelines recommend the avoidance of international destruction of spacecraft or other harmful activities that generate long-lived space debris. If such activities are necessary, they should be conducted at sufficiently low altitudes to limit the orbital lifetime of fragments. As a comparison of agency regulations, the ESA prohibits the intentional destruction of systems [9], but the NASA leaves room, as long as it complies with the area-lifetime and object-lifetime limits, defined for mission-related objects [12].

As noticed above, the effectiveness and the practicability of the prevention of on-orbit break-ups depends not only on the technical measures such as passivation or conjunction assessment, but also on the political will of space-faring nations to keep outer space out of destructive weapon tests and armed conflicts. The measures could be strengthened in two different directions:

- through an improvement in the technical standards for launch service providers and satellite operators;
- through achieving international consensus on the prohibition on, at least, destructive weapon tests in orbit.

2.4. Post-mission disposal from the densely populated useful orbits

For the end of life of spacecraft, the IADC and UN COPUOS guidelines propose two disposal measures: either de-orbiting followed by re-entry (within 25 years according the IADC recommendation) or re-orbiting to a 'graveyard' orbit outside the original orbital region, whereby the first re-entry option is preferred.

2.4.1. Post-mission disposal in LEO

The IADC and UN COPUOS guidelines recommend post-mission disposal measures to spacecraft operating in the LEO (defined in the guidelines as the orbital space up to an altitude of 2,000 km) and GEO regions, but do not address missions in MEO, because it is not defined as a protected region.

2.4.2. Post-mission disposal in GEO

The IADC defines the protected GEO region as plus minus 200 km of altitude and plus minus 15 degrees of inclination around the exact altitude of GEO at 35,786 km. One of the major contributions of the IADC towards space debris mitigation is the formulation of a formula which gives a near-circular orbit that remains above the GEO protected region. This re-orbiting formula is adopted by the ITU in its Recommendation on Environmental protection of the geostationary satellite orbit [13].

2.4.3. Post-mission disposal in MEO

While the MEO region is mostly used for navigation and communication satellites, so far there are no international guidelines, which establish a protected zone for MEO or recommend disposal measures in the region. This is mainly due to the facts that (1) retired GEO and HEO objects periodically pass through the not densely MEO region and that (2) satellites which have been re-orbited above the MEO region might revisit the operational orbits in the MEO region again if not properly disposed [7; 14-15].

Among the existing space debris mitigation guidelines, end-of-life disposal measures have more potential to develop into a legal norm than others. They do not impose one technical option, but rather require certain behaviour at the end of mission. Compliance can be monitored and proven through space surveillance networks. Once these measures are adopted as binding international law, spacecraft manufacturers and operators can take into account an appropriate end-of-life disposal measure at the mission design phase. Two difficulties can be observed. Private spacecraft operators may not be motivated to carry out end-of-life disposal, because they have to sacrifice economic interests in proportion to the fuel consumption for de-orbiting or re-orbiting. Additionally, small satellites which are making inroads into every area of space applications and will change the orbital environment as we know it substantially, may not have a propulsion system to perform such manoeuvre.

3. Findings from ReDSHIFT Concerning Space Debris Mitigation

The technical findings of the aforementioned extensive theoretical, experimental and modelling efforts provided a solid basis to measure the effectiveness of mitigation actions based on the existing guidelines in a quantitative way. This allows, on the legal level, to critically assess the potential positive effects of mitigation measures and to establish whether – provided compliance is given – this would suffice to stabilize the orbital environment in the most used orbital regions LEO and GEO.

3.1 Application of the technical findings of the space debris population modelling on space debris mitigation guidelines

The modelling of the space debris environment performed within ReDSHIFT can contribute to improve Guideline IADC 5.4./UN COPUOS 3 (Limit the probability of accidental collisions in orbit). In particular, the guidelines distinguish between "known objects" and "small objects".
"Known objects" are contained in the Two-line Element Data Set of Catalogued Objects, usually larger than 10 cm in LEO and larger than 1 m in GEO, which have already been tracked and identified [16]. Small debris is smaller than these catalogued objects down to the order of 1 mm which cannot be detected and tracked by the current space surveillance network system and should be estimated statistically.
The modelling can thus contribute to an understanding of the distribution of these pieces of small debris.

3.1.1 Regulatory implications from long-term orbital debris modelling

Orbital debris modelling predicts the trend of the space debris population in the LEO, MEO and GEO regions, taking into account all debris-generating and debris-reducing events. In the category of debris-reducing events, the space debris mitigation measures, including the performance of end-of-life disposal manoeuvres, collision avoidance and passivation measures, are considered with a certain success rate. This simulation result can make two contributions to the improvement of the current space debris mitigation guidelines.

First, the long-term simulation is performed under the different scenarios, varying the success rate of end-of-life disposal manoeuvres, collision-avoidance performances and so on [17]. In this way, the simulation can predict how much each mitigation practice can help in reducing the space debris population, and therefore determine the degree of importance. For example, the simulation results show that the in-orbit collision avoidance manoeuvres have a rather small impact on the space debris population, because spacecraft can perform such manoeuvres only during their operational time, normally 10-15 years. Moreover, most of the objects currently in space are inactive. After the end of mission, the spacecraft will remain in orbit for many more years, depending on their residual orbital energy; e.g. for spacecraft on the Sun-synchronous orbit in the LEO region, which is the most crowded orbital region, the residual orbital lifetime can be as high as 100 years. Therefore, it can be concluded that the end-of-life disposal is of paramount importance to avoid future accidental collisions in orbit.

Second, the simulation can predict whether the compliance with the current space debris mitigation guidelines would be sufficient or not to keep the near-Earth space environment sustainable in the long term. One of the scenarios described in the orbital modelling in Deliverable 2.1. of the ReDSHIFT project [17, 18] assumes a higher degree of compliance of space activities with the proposed mitigation guidelines (namely a 90 % compliance to a 10-year rule). However, the simulation results demonstrate that even if such a high compliance is provided, the space debris population will not cease to increase. Apart from the impact of the Kessler syndrome, these results take into consideration the emerging projects onlarge constellations, sometimes over thousands, of small satellites. This leads to the conclusion that in order to stabilise the space debris population in the long-term, preventive mitigation measures for future missions are urgently needed, but will not be sufficient. Therefore, additional re-active remediation measures (such as Active Debris Removal) for existing missions will be necessary.

3.1.2 Regulatory implications from mapping orbital resonances (associated with solar radiation pressure and luni-solar perturbation for LEO, MEO and GEO orbital regions).

From those maps, impulsive manoeuvres were designed from any orbital region to attain a condition for de-orbiting followed by a natural re-entry, where possible, or to move onto a graveyard orbit (re-orbiting, for example in GEO and MEO), otherwise [19-28]. This dynamical map and manoeuvre design tool can be used by spacecraft operators at the end of mission and during the mission planning phase to facilitate the re-entry of spacecraft into the Earth's atmosphere by increasing the eccentricity of orbit or by identifying a graveyard orbit which is stable on the long-term. This research result can improve the end-of-life disposal measures of the current space debris mitigation guidelines.

3.2. Technical findings related to the current guidelines for mitigation

The so-called '25-year rule' suggests to de-orbit spacecraft after 25 years, or (less preferably), to re-orbit it above the protected LEO region.

The technical findings demonstrate that, first, re-entry can be accelerated through the exploitation of resonances in certain regions in terms of semi-major axis and inclination of orbit. For this, to reach these orbital regions, certain (impulsive) manoeuvres at the end of mission may be needed which require additional fuel consumption and concomitant economic loss [19]. In order to overcome this issue, for future missions it would be advisable to induce the launch towards orbital locations that are near the resonances to be exploited at end-of-life. In this way, the compliance with the 25-year rule can be facilitated. [20]

Second, acceleration of re-entry through the exploitation of resonances could be introduced also for MEO. While the MEO regions are of wide use to navigation and communication satellites, there is no specific international guideline recommending end-of-life disposal from the region. De-orbiting time from the MEO region is generally considered long because of the high altitude; and re-orbiting spacecraft to an orbit above the MEO region is likely to lead to revisiting the MEO region again and might, furthermore, cause potential interference with satellites in GEO. The dynamical map research result demonstrates, however, that re-entry could take less time than previously expected, in case orbital resonances are exploited. For example, starting from a typical Galileo orbit (23,222 km), a satellite can re-entry with two Hohmann-type braking manoeuvres within the time span of 60 to 80 years. This re-entry solution is also expected to satisfy the 25-year rule in the LEO region, because the total time spent in the LEO region for most of objects (98.5%) would be less than one year due to the high eccentricity.

Third, a dynamics study of the GEO region was performed considering initial orbits with a semi-major axis of the Geostationary orbit (i.e. 42165 km) plus or minus 250 km and considering all orbit inclinations, from planar orbits to inclined orbits. In the GEO region the re-entry option can be achieved only for initial orbits with an inclination higher than 60 degrees. This can be attained with a manoeuvre that can go from 1 up to 200 m/s. The corresponding re-entry time could vary from a few decades (15-20 years) to almost a century or more. It is noticeable that solutions with a lifetime of less than 25-years can be found [21–29]. In the region between 40 and 60-degree inclination, solution exists for re-entry or graveyard. These solutions can be characterised by the re-entry time versus Δv budget. For planar orbits with an initial inclination less than 40 degrees, the manoeuvre to reach a re-entry condition would require a thrust much above 200 m/s, therefore it was considered to be unfeasible for current spacecraft (the value of 200 m/s was chosen as maximum Δv budget). In this case, only graveyard solutions can be found as already proposed within the IADC. However, it must be stressed that the perigee height of the graveyard orbit varies depending on the spacecraft orientation with respect to the Sun-Earth line.

The IADC and UN COPUOS space debris mitigation guidelines only propose re-orbiting of spacecraft 200 kilometres above the operational GEO orbit with 35 km of tolerance for the effects of gravitational perturbations (this rule was made for the GEO). As said, dynamical map research on the GEO region suggests that there exist natural re-entry solutions for spacecraft in the inclined GEO region, taking advantage of orbital resonances. There are increasing trends of the use of inclined GEO orbit (for example, through Chinese Beidou satellites). The solutions depend on the orientation of the spacecraft's orbital plane with respect to the Sun and the Moon. It should be noted that during the de-orbiting procedure, the time passing through the LEO region is estimated to only a few days, undoubtedly satisfying the 25-year rule.

ReDSHIFT also considered the use of drag and solar sail for EOL deorbiting. Maps were produced to show the requirements in terms of required area of the sail (given the mass of the satellite) to deorbit in a desired time from a specific orbital region. Some combinations of initial semi-major axis, eccentricity and inclination allow to deorbit with a very low sail area as the resonances due to solar radiation pressure and the Earth’s oblateness are exploited [31–36]. If the initial conditions of the operative satellite are far from the resonances, then an impulsive manoeuvre can be implemented to reach those deorbiting pathways. As an alternative solution, a more complex sail attitude control strategies can be implemented to achieve a continuum increase in the eccentricity vector. This control strategy requires the sail to turn its attitude perpendicular and then parallel to the sunlight every 6 month approximately [37]. At the expenses of a more advanced attitude system such a "modulating" sail can allow deorbiting from a larger range of orbital inclinations, semi-major axes and eccentricities. In this sense, an output was the computation of maps of such a ``modulating'' sail that define the area of the sail (given the mass of the satellite) required to deorbit with a modulating control attitude in a desired time from a specific orbital region.

3.3. Regulatory implications from 3D printing and defining passive de-orbiting solutions through solar sail.

The current space debris mitigation guidelines recommend the end-of-life disposal, especially the re-entry into the Earth's atmosphere for spacecraft in the LEO region, but are silent on the phase of demise. Because the controlled re-entry in which spacecraft is disposed of into the ocean can be more costly, complex and risky, un-controlled re-entry is an attractive option especially for LEO missions and allowed within a certain ground casualty risk. If inactive spacecraft survives the atmospheric re-entry, however, it could bring about casualties or damage to properties and the environment on Earth. If there are guidelines for design and material of spacecraft, and for angles of atmospheric re-entry, they would contribute to decreasing the casualty risk on Earth.

The first suggestion is to use demisable materials, components and structures when manufacturing spacecraft. Here, the term demisable signifies being susceptible to melting, vaporising, and/or disintegrating during re-entry of spacecraft into Earth's atmosphere so as not to pose a hazard to personal life, property and the environment on Earth. Several components of spacecraft have received attention from the perspective of demisability, for example propellant tanks due to their materials and the very high area-to-mass ratio that make them decelerate during re-entry and make some elements survive the re-entry. Reaction-wheel assemblies also contain parts made of metals that melt at high temperatures and have structures of generally closed character that shield some parts against re-entry heating. Choosing the demisable materials and structures for such components is essential to facilitate the option of uncontrolled re-entry as an end-of-life disposal.

Some specific recommendations can be made on the demisability of materials, components and structures. Materials which are difficult to melt or burn up in Earth's atmosphere include titanium and stainless steel. The use of titanium should be limited to very small objects with no more than 30g per object. As titanium is not recommended for propellant tanks, the current generation of aluminium- lithium alloys which have been developed for aerospace applications may be a suitable replacement. Composite tanks overwrapped by the Carbon Fibre Reinforced Polymer (CFRP) may not be an acceptable solution unless it can be demonstrated in tests that the overwrapped layer will be removed under relatively low heat flux. The use of stainless steel or titanium flywheel for reaction wheel Assembly is not recommended. Copper-based alloy or other alternative materials should be further researched. Spoked reaction wheel flywheel designs (rather than a solid disk) are seen as advantageous from a demise perspective, because they disintegrate more rapidly. Threaded steel support structures for electronics cards are not recommended.

The dedicated D4D tests proved that the 3D printed and the standard materials are equally demisable. Improved demise is observed whenever an early release of components from the structure is happening. Therefore, the technologies and the design of the joints between the spacecraft structures and the components are critical from a casualty risk perspective. Passive technologies are recommended for joints, with activation of the joint failure at temperatures of 200-2500 °C. Sandwich structures are expected to be demisable. These recommendations may be included as technical standards or in a supporting document to the space debris mitigation guidelines.

The second issue addresses the criterion of re-entry angle and apogees for safe demise. In case of controlled re-entry, spacecraft uses propellant to re-enter Earth's atmosphere at a steeper flight path angle so that its debris can be scattered over an uninhabited region, usually in the ocean. In case of uncontrolled re-entry, in certain cases it would be advisable to maximise the circularisation of orbit, in other words to apply a shallow flight path angle, so that spacecraft has longer exposure to Earth's atmosphere and generates more thermal and mechanical loads, helping in demise of spacecraft. On the other side, the steeper the re-entry is, the smaller the footprint (which is the extent of the domain within which all the parts land) but the less the spacecraft demise. At the same time, the casualty area (where the area of each fragment and a human cross-section is taken and summed over all landed parts) is larger. On the opposite, re-entry circularising is preferred for augmenting the time that the spacecraft spends in the dense stages of the atmosphere so the demise could be higher (less remaining mass), this, however, resulting in a larger footprint.

Therefore, there is no single unique solution as regards orbit circularisation. A "trade-off" must be made depending on which aspect is considered more recommendable in the specific situation. Hence, a choice can be made between a small footprint (as footprint is reduced in an elliptic re-entry) and high demisability (achieved if the spacecraft spends more time within the thicker layer of the atmosphere). As far as large constellations are concerned, the preferred option currently is an elliptical and not a circular re-entry.

3.4. Implications from the use of the ReDSHIFT software tool

Considering the very complex spectrum of naturally given factors and mission design aspects that must be taken into account in planning a space mission, also software can be used to help operators and satellite manufacturers to apply optimal EOL solutions and thus maximize compliance with the space debris mitigation guidelines.

The disposal module of the ReDSHIFT software tool which is freely available at the project website (http://redshift-h2020.eu/), gets as an input the mass of the satellites, together with its initial orbit and available Δv budget onboard. Depending on the orbital region, the different strategies implemented are exploited to find the optimal re-entry path or the more stable graveyard orbit in the neighbourhood of the initial condition. The module outputs the new trajectory, the re-entry time (for re-entry orbit) or a measure of the orbit stability for the graveyard solutions, the required impulsive manoeuvre and the conditions at 120 km for the computation of the demisability and casualty risk on ground. In case a solar or drag sail can be put onboard, the sail module suggests the required sail area (given the spacecraft mass and the desired deorbiting time), the sail attitude control strategy, and it computes if this is within the technological limit of current sails.

4. Means to strengthen the effectiveness of measures to stabilise the orbital population

As space debris is inevitably created during any planned launch of space objects, and is an inherent part of space activities, its creation as such is not legally prohibited. Both the technical and legal space debris mitigation measures do not aim at totally preventing space debris from being created, but at limiting its creation for future space missions.

Thereby, mitigation measures do not have the aim of reducing the already existing population of space debris, but to add less space debris to it. And, not less importantly, space debris mitigation measures as they are currently formulated, do not limit the generation of space debris in the near-Earth outer space environment as a whole, but address only the more densely crowded orbital regions, which are the Low Earth Orbit (LEO) and the Geostationary Orbit (GEO). Therefore, additional means are needed.

As has been shown above in section 3.1.1, the simulation results demonstrate that even if very high compliance of 90% with a stricter, 10-year instead of 25-year rule for LEO is provided, the space debris population will not cease to increase. and that in order to ensure long-term orbital stabilisation of the space debris population, mitigation measures must be extended through remediation measures.

Also, the assumption of a 90% compliance with the 25-year rule, taken that no new launches occur, leads to the same conclusion. What is more, according to an IADC study on stability of the future LEO environment, even if no future explosions occurs, the simulated debris population will be increased by 30% in the next 200 years [38, 39].

5. Emerging legal basis for space debris remediation

While the exiting legal framework does not directly address space debris mitigation and space debris remediation, the awareness on the risks associated with the overpopulation of certain orbital regions have been recognized by the relevant international fora. In UN COPUOS, since 2010, efforts have been addressed at formulating guidelines for the long-term sustainability of outer space [40-43]. Significant success has been reached in 2019 when, during the 62nd session of the UN COPUOS, a set of 21 guidelines in the categories “Policy and regulatory framework for space activities”, “Safety of space operations”, “International cooperation, capacity-building and awareness” and “Scientific and technical research and development” have been adopted by UN COPUOS and will be endorsed by the UN General Assembly in December 2019 [39]. The aim of this guidelines is to ensure that outer space will remain an operationally stable and safe environment that is available and suitable for exploration and use both by current and future generations [40].

These guidelines are of voluntary nature, but recognize explicitly that the long-term sustainability of space activities may be affected by “The proliferation of space debris, the increasing complexity of space operations, the emergence of large constellations and the increased risks of collision and interference with the operation of space objects” [46].

While the guidelines, due to their voluntary nature [47], do not impose any legal obligations upon States in the use and exploration of outer space, they can be implemented on the national level and thus become binding through their implementation in national safety frameworks [48].

There are a number of considerable legal obstacles to impose a duty for remediation, including, among others [38 at p. 10]:

- The issue of criteria to define which objects and under which specific circumstances constitute space debris;
- The lack of an obligation of States to remove their objects at the end-of lifetime;
- The difficulty in defining criteria on deciding which objects should be removed or manoeuvred in case they pose a risk for other space objects;
- The challenges for establishing a space traffic management system;
- The issue of attributing non-active objects to a certain State in light of the principle of

jurisdiction and control according to Art. VIII of the OST;
- Issues related to acquire consent from the State having jurisdiction (and control) over the space object to be removed;
- Issues of establishing the State of Registry in cases where registration has not taken place or the status of the object cannot be identified;
- Challenges posed by the transfer of ownership over space objects that is not foreseen in the treaties on space law;

The existing non-binding instruments do not fully lack relevance as they can serve as a model for the development of national space laws so as to impose concrete obligations for implementing mitigation measures on private space actors.

The ongoing discussion on these instruments is a clear expression of the willingness of the international community to formulate, even if only on a voluntary basis, certain technical standards for space activities in order to prevent the creation of space debris.

6. Conculsions

While there is no doubt that the road towards legally regulating on remediation measures for outer space is a long and winding one, it is clear that space debris mitigation should not remain the only method at trying to ensure that the near-Earth orbital space remains usable and sustainable on the long-term.

Even before the 2007 ASAT test and the following ones in 2008 and 2019, space debris modelling had already indicated that the LEO debris population of objects larger than 10 cm had reached a point where the population would continue to increase even with zero future launches, due to collisions among existing objects and the induced Kessler effect [10]. While launch numbers will increase with new space activities and unexpected breakup events as well as accidental collisions will continue to occur, mitigation measures will not be able to stop the collision-driven population growth.

A holistic technical input, as demonstrated in ReDSHIFT, is a vital condition for the formulation of any legal rule in this regard and an important quantitative and prognostic factor to calculate and understand how pressing and complex the risks associated with space debris are. They demonstrate that compliance is needed, but not enough; that the existing technical measures as formulated by the IADC, adopted by UN COPUOS and endorsed by the UN General Assembly must become a part of the legal framework, but that further efforts are needed to extend the prevention of the creation of space debris with measures to react accordingly against the risks posed by existing debris through remediation.

Many of the legal obstacles for space debris remediation seem to be a significant constraint for formulating and imposing legal rules. However, it can be expected that given the need for a trade-off between the interest in the use of outer space and the need to ensure that such use remains feasible also in the future, certain restraints on the freedom of exploring and using outer space will have to be considered in the light of active debris removal and space traffic management.

Acknowledgements: *This work has been funded through the European Commission Horizon 2020, Framework Programme for Research and Innovation (2014-2020), under the ReDSHIFT project (grant agreement n. 687500).*

References

[1] Rossi A. et al., ReDSHIFT: A Global Approach to Space Debris Mitigation, Aerospace Vol. 5, p. 64, doi:10.3390/aerospace5020064 (2018).

[2] The IADC was formed by the national space agencies of Japan, the Russian Federation and the United States together with the ESA in 1993. It grew rapidly with the addition of the space agencies of China (CNSA) in 1995; France (CNES), India (ISRO), and the United Kingdom (BNSC) in 1996; Germany (DLR) in 1997; Italy (ASI) in 1998: the Ukraine (NSAU) in 2000; Canada (CSA) in 2010; and South Korea (KARI) in 2014.

[3] Inter-Agency Space Debris Coordination Committee, *IADC Space Debris Mitigation Guidelines*: *IADC-02-01*, 2002.

[4] United Nations General Assembly, *International cooperation in the peaceful uses of outer space*: *A/RES/62/217*, 1 February 2008.

[5] United Nations Office for Outer Space Affairs, *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*, United Nations, Vienna, 2010.

[6] Inter-Agency Space Debris Coordination Committee, *Support to the IADC Space Debris Mitigation Guidelines*: *IADC-04-06*, May 2014.

[7] H. Klinkrad, *Space Debris*: *Models and Risk Analysis*, Springer, Berlin, 2006.

[8] National Aeronautics and Space Administration, *Process for Limiting Orbital Debris*: *NASA-STD-8719.14A*, 8 December 2011.

[9] European Space Agency, *European Code of Conduct for Space Debris Mitigation*, 28 June 2004.

[10] Liou, J.-C., An Assessment of the Current LEO Debris Environment and the Need for Active Debris Removal, presentation given at the ISTC Space Debris Mitigation Workshop, 26-27 April Moscow, Russia, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100017146.pdf.

[11] See, for example, Secure World Foundation, India's ASAT Test: A Jolt to Space Stability?, 6 May 2019, https://swfound.org/events/2019/indias-asat-test-a-jolt-to-space-stability.

[12] National Aeronautics and Space Administration, *Process for Limiting Orbital Debris*: *NASA-STD-8719.14A*, 8 December 2011.

[13] International Telecommunication Union, *Environmental protection of the geostationary-satellite orbit*: *Recommendation ITU-R S.1003-2*, December 2010.

[14] Alessi E.M.; Deleflie F.; Rosengren A.J.; Rossi A.; Valsecchi G.B.; Daquin J.; Merz K., A numerical investigation on the eccentricity growth of GNSS disposal orbits, Celestial Mechanics & Dynamical Astronomy, 125, 71-90 (2016)

[15] Rosengren A., Skoulidou D.K., Tsiganis K., and Voyatzis G., Dynamical cartography of Earth satellite orbits, Adv. Spa. Res., 63 (2019).

[16] Inter-Agency Space Debris Coordination Committee, *Support to the IADC Space Debris Mitigation Guidelines*: *IADC-04-06*, May 2014.

[17] A. Rossi, G.B. Valsecchi, E.M. Alessi. The Criticality of Spacecraft Index, ASR, 56 (2015), pp. 449–460.

[18] Schaus V., J. Radtke, E. Stoll, A. Rossi, C. Colombo, S. Tonetti; I. Holbrough, Results of reference long-term simulations focussing on passive means to reduce the impact of space debris, Proceedings of the 7th European Conference on Space Debris, ESOC, Darmstadt (Germany),18-21/04/2017 (2017).

[19] Schettino G. Alessi E.M., Rossi A., Valsecchi G.B., Exploiting dynamical perturbations for the end-of-life disposal of spacecraft in LEO, *Astronomy and Computing*, Vol. 27, April 2019, pp. 1-10.

[20] A. Rossi, E.M. Alessi, V. Schaus, G. Schettino, G.B. Valsecchi, How an aware usage of the long-term dynamics can improve the long-term situation in the LEO region, IAC 2019, paper IAC-19,A6,2,5,x53774

[21] Colombo C., Gkolias I., "Analysis of orbit stability in the geosynchronous region for end-of-

life disposal", to be presented at the 7^{th} *European Conference on Space Debris*, Oral presentation, 18 - 21 Apr. 2017, ESA/ESOC, Darmstadt/Germany.

[22] Gkolias I.,Colombo C., "End-of-life disposal of geosynchronous satellites", *68^{th}International Astronautical Congress 2017*. 25-29 September 2017, Adelaide, paper number IAC-17-A6.4.3.

[23] Gkolias I., Colombo C., "Study of the dynamical structure of the GEO region and implications in end-of-life disposal strategies", International Workshop on Key Topics in orbit propagation Applied to Space Situation Awareness, KePASSA, July 25-27 2017, ESTEC https://indico.esa.int/indico/event/156/.

[24] Gkolias I., Colombo C., "Disposal Design for Geosynchronous Satellites Revisited". *2018 AAS/AIAA Astrodynamics Specialist Conference*, August 19-23, Snowbird, paper number AAS-18-370.

[25] E.M. Alessi, G. Schettino, A. Rossi, G.B. Valsecchi, Natural Highways for End-of-Life Solutions in the LEO Region, Celest. Mec. Dyn. Astron. 130, 34 (2018).

[26] V. Schaus, E.M. Alessi, G. Schettino, A. Rossi, E. Stoll, On the practical exploitation of perturbative effects in low Earth orbit for space debris mitigation, Adv. Space Res. 63, 1979-1991 (2019).

[27] D. K. Skoulidou, A. J. Rosengren, K. Tsiganis, and G. Voyatzis, "Medium Earth Orbit dynamical survey and its use in passive debris removal," Advances in Space Research 63, 3646–3674 (2019).

[28] A. J. Rosengren, D. K. Skoulidou, K. Tsiganis, and G. Voyatzis, "Dynamical cartography of earth satellite orbits," Advances in Space Research 63, 443 – 460 (2019).

[29] Gkolias I., Colombo C., "Towards a sustainable exploitation of the geosynchronous orbital region.", Celestial Mechanics and Dynamical Astronomy, April 2019, https://link.springer.com/article/10.1007/s10569-019-9895-3.

[30] Lücking, C., Colombo, C. and McInnes, C. R., "Solar Radiation Pressure-Augmented Deorbiting: Passive End-of-Life Disposal from High Altitude Orbits," *Journal of Spacecraft and Rockets*, Vol. 50, No. 6, 2013, pp. 1256-1267. doi: 10.2514/1.A32478.

[31] Lücking C., Colombo C., McInnes C. R., Lewis H. G., "Collision probability of satellite re-entry with high area-to-mass ratio", 9th IAA Symposium on Small Satellites, 08 – 12 April, 2013, Berlin, Germany.

[32] G. Schettino, E.~M. Alessi, A. Rossi, G.~B. Valsecchi, Characterization of Low Earth Orbit dynamics by perturbation frequency analysis, 68th International Astronautical Congress, Adelaide, Australia, 25-29 September 2017, paper IAC-17.C1.9.2.

[33] G. Schettino, E.~M. Alessi, A. Rossi, G. B. Valsecchi, A frequency portrait of Low Earth Orbits, Cel. Mec. Dyn. Astron., Celest. Mec. Dyn. Astron. 131:35 (2019).

[34] Alessi E.M., Schettino G., Rossi A., Valsecchi G.B., "Solar radiation pressure resonances in Low Earth Orbits", Monthly Notices of the Royal Astronomical Society, 473, 2407-2414 (2018).

[35] Alessi E.M, Colombo C., Rossi A., Phase space description of the dynamics due to the coupled effect of the planetary oblateness and the solar radiation pressure perturbations, Celest Mech Dyn Astr., 131, 43 (2019).

[36] National Space Society, "Orbital Debris: Overcoming Challenges," National Space Society, May 2016.

[37] Inter-Agency Space Debris Coordination Committee, *Support to the IADC Space Debris Mitigation Guidelines*: *IADC-04-06*, May 2014.

[38] R. Popova, V. Schaus, The Legal Framework for Space Debris Remediation as a Tool for Sustainability in Outer Space, Aersospace (May 2018).

[39] Liou J.-C., Anilkumar, A.K., Bastida Virgili, B., Hanada T., Krag. H., Lewis H., Raj M.X.J., Rao M.M., Rossi A., Sharma R.K., Stability of the Future LEO environment – an IAD Comparison

Study, Proceedings of the 6th European Conference on Space Debris, 22-25 April 2013, Darmstadt, Germany. Edited by L. Ouwehand. ESA SP-723, ISBN 978-92-9221-287-2, 2013, id.2.

[40] UN COPUOS. Report of the Committee on the Peaceful Uses of Outer Space Fifty-Fourth Session, pp. 51–57,

Annex II. Terms of Reference and Methods of Work of the Working Group on Long-Term Sustainability of Outer Space Activities of the Scientific and Technical Subcommittee; U.N. Doc. A/66/20 (2011). Available online: http://www.unoosa.org/pdf/gadocs/A_66_20E.pdf

[41] UN COPUOS. Report of the Committee on the Peaceful Uses of Outer Space Fifty-Seventh Session; U.N. Doc. A/69/20 (2014). Available online: http://www.unoosa.org/pdf/gadocs/A_69_20E.pdf

[42] UN COPUOS. Proposal by the Chair of the Working Group on the Long-Term Sustainability of Outer Space Activities for the Consolidation of the Set of Draft Guidelines on the Long-Term Sustainability of Outer Space Activities; U.N. Doc. A/AC.105/2014/CRP.5. Available online: http://www.unoosa.org/pdf/limited/l/AC105_2014 _ CRP05E.pdf.

[43] UN COPUOS. Report of the Committee on the Peaceful Uses of Outer Space Fifty-Ninth Session (8-17 June 2016), UNGAOR A/71/20 Annex.

[44] UN Doc. A/AC.105/L.318/Add. 4, UN COPUOS Draft Report, Annex II, Guidelines for the Long-term Sustainability of Outer Space Activities of the Committee on the Peaceful Uses of Outer Space, 19 June 2019.

[45] Ibid., 'Background', para. 4 and 'Definitions, objectives and scope of the guidelines', para. 5.

[46] Ibid., 'Background', para. 1 and 'Definitions, objectives and scope of the guidelines', para. 7.

[47] Ibid., 'Definitions, objectives and scope of the guidelines', para. 15.

[48] Ibid., 'Definitions, objectives and scope of the guidelines', para. 9.

.