ISU TEAM PROJECT: AN INTEGRAL VIEW ON SPACE DEBRIS MITIGATION AND REMOVAL

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ABSTRACT

The issue of space debris poses challenges not only in technical, but also legal, political and economic dimensions. A sustainable solution needs to take into account all of them. This paper investigates such a potential solution in a multidisciplinary approach.

To this end, it addresses the effectiveness of the existing debris mitigation guidelines, and identifies technical improvements for mitigation. It continues examining technical concepts for debris removal and performing proper cost-benefit trade-offs. The results of new simulations to assess the damage cost caused by space debris are presented. Based on these findings, an organizational framework and political recommendations are developed which will enable a sustainable use of space starting in 2020. The findings are compiled into a roadmap, which outlines 1) a path to the full adherence to debris mitigation guidelines and 2) the removal of ten large pieces of debris per year by a dedicated international organization, including expected expenditures necessary for its implementation.

1 INTRODUCTION

In 1978, Kessler and Cour-Palais produced a model predicting the ever-increasing growth of space objects due to cascading on-orbit collisions, a phenomenon known as the Kessler Syndrome [1]. Additional long-term simulations of the Low Earth Orbit (LEO) environment have shown that the critical density of objects will reach a point where these collisions will produce more objects than atmospheric drag alone can remove [2], thus requiring human intervention to prevent an uncontrollable increase of orbital debris. Such a critical density has already been reached at an altitude of 800 to 1000 km [2]; the Fengyun-1C anti-satellite test in 2007 created over 3000 observable (i.e. larger than 10 cm) fragments at that altitude, and the collision in 2009 between Kosmos 2251 and Iridium 33 added another approximately 2000 fragments [3].

In the summer of 2012, 32 students from 16 different countries convened at the International Space University's (ISU) Space Studies Program (SSP) to develop a potential solution to the space debris problem during a 9-week summer session at the Florida Institute of Technology. This paper serves to present the results of the interdisciplinary and international research conducted during this program.

2 SPACE DEBRIS: A CALL TO ACTION

The problem of orbital debris has been studied for more than 30 years, and since that time the international space community has progressively adopted space debris mitigation practices. However, despite these measures, there has been no indication that an effective solution for active debris removal (ADR) will be implemented in the near future, and multiple analyses show that the debris population will continue to grow due to collisions with other debris, even in a scenario with no future launches. Since mitigation measures alone cannot prevent the problem of cascading space debris creation, ADR initiatives must take place in the next 20-50 years in order to guarantee a self-sustaining orbital environment and access to space.

An effective solution will require several components including the development of new mitigation and removal technologies, political and legal frameworks, financial and business cases, and strategies of raising awareness in the general public and political forums. Though the technical challenges associated with orbital debris are considerable, the barriers of politics, unenforceable legal treaties, and national priorities in the space arena pose an even more significant challenge. Most space faring nations appear to be adopting a "wait-and-see" approach to the problem, paying only lip-service to the notion that we must all be responsible for

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the objects we put into space. This paper addresses each of these components individually and presents a solution which can be implemented today, ensuring a bright future for our endeavours in space.

3 ORBITAL DEBRIS MITIGATION

Orbital Debris Mitigation (ODM) is a set of cost effective measures to reduce the creation of new orbital debris and to increase the survivability of operational spacecraft, with the ultimate goal of sustaining the space environment. This part of the study first focused on compliance with the existing seven UN Space Debris Mitigation Guidelines (G1-G7), as adopted by UN General Assembly Resolution 62/217 in January 2008 [4]. After measuring and evaluating compliance, recommendations are put forward to improve international efforts in space debris mitigation.

The compliance analysis took into account data collected since 2007, and trend assessments were made from historical records. Where possible, statistical data were used. However, obtaining credible data for all space agencies was not possible. In this instance, conclusions were made qualitatively, based on subjective assessments from specialists in the field of orbital debris.

Each guideline was assessed against two parameters: its relative “impact” on the space environment to cause space debris and the level of “compliance” shown by space users to abide by the guideline. An "overall" impact rating was made through the combined effect of the two assessments. The results are shown in Tab. 1.

Table 1. Summary of mitigation effects

	Impact	Compliance	Overall
G1	Low	95 %	Low
G2	Low	95 %	Low
G3	High	N/A	High
G4	High	99.7 %	Med
G5	High	94 %	Med
G6	Med	38 % / 58 %	Med
G7	Low	70 %	Low

Guidelines 1, 2 and 7 are assessed as having an overall "Low” impact on the space debris problem. Guideline 1 requires limiting debris creation during normal operations. Guideline 2 requires minimizing the potential for breakups during operational phases. Guideline 7 calls for the limitation of the long-term interference of spacecraft and launch vehicle orbital stages with the Geosynchronous Earth Orbit (GEO) region after the end of mission. Guidelines 3 through 6 are assessed as having an overall impact on the space debris problem as "Med” or "High”. In the report, most attention was given to these four guidelines.

<u>Guideline 3 – Limit the Probability of Accidental Collision in Orbit</u>

This guideline supports the requirement for enhanced detection and tracking capabilities (Space Situational Awareness), allowing collision avoidance conjunctions and manoeuvres to be conducted. In line with this requirement is the need for greater sharing of surveillance data, and ultimately a Space Traffic Management system. Currently, conjunction warnings are readily available for any operator that requests them. However, conjunction accuracy is low and early warning is difficult due to the quality of current detection and tracking systems. It is recommended that computational systems are improved to increase the precision of orbital determination and decrease the loss of resolution over time. International sharing of orbital debris and spacecraft data is a critical factor for improving conjunction analyses.

<u>Guideline 4 – Avoid Intentional Destruction and Other Harmful Activities</u>

Intentional destructions are conducted for the purpose of engineering tests, experiments, or military capability demonstration. The intentional destruction of satellites, if not done at appropriately low altitudes, will result in long-term debris. As a matter of principle, this practice should not be conducted unless absolutely necessary for the protection of human life or the Earth environment, e.g. through the destruction by fragmentation of re-entering debris below 200 km altitude.

<u>Guideline 5 – Minimize Potential for Post-mission Breakups Resulting from Stored Energy</u>

The explosion of upper rocket stages on-orbit is one of the main sources of breakups. Spent upper stages and spacecraft usually contain residual propellants and pressurants that may overheat with exposure to solar radiation. A solution would be to employ passivation techniques which eliminate stored energy on a spacecraft, thus reducing the chance of a breakup. Typical passivation measures include propellant passivation, depressurization, electrical, and momentum system passivation as well as the prevention of rocket self-destruction during orbital flight. These technically and economically modest mitigation measures are efficient ways to help slow the growth rate of orbital debris. They have been increasingly adopted by satellite and launch operators over recent years. Their continued use should be encouraged or even mandated.

<u>Guideline 6 – Limit the Long-term Presence of Spacecraft and Launch Vehicle Orbital Stages in the LEO Region after the End of their Mission</u>

The impact of orbital debris on the space environment is the greatest within LEO. IADC adopted the “25-year rule” which states that a spacecraft should re-enter the Earth’s atmosphere within 25 years of the end of its mission. For most of the extra-large debris in LEO, the approximate period of 25 years is sufficient time, given the altitudes and area to mass ratios of the debris. If the remaining orbital life is greater than 25 years, spacecraft can be de-orbited through different de-orbit measures, which are in greater detail described in section 4.

However, a poor compliance figure of 38 % for satellites and 58 % for rocket bodies requires immediate attention. This guideline has the greatest impact to the orbital debris problem in LEO. The guideline is well publicized amongst the space community. The non-compliance stems from the satellite operator preferring to meet operational requirements. This attitude and resulting practice amongst space users will not change unless mandated. We recommend that the 25-year rule for LEO be mandated by national law in each space-faring nation.

Conclusions

Compliance with the UN Space Debris Mitigation Guidelines is a significant aspect to solving the orbital debris problem. They are however voluntary by nature. Compliance is thus proportional to the cost and ease of implementation, and whether the guideline is in the best interests of the launching state and/or operator. All space faring nations should take up responsibility to implement the Guidelines at the national level and strive towards a greater level of compliance.

4 ACTIVE DEBRIS REMOVAL

Many proposals for ADR technologies were developed within the last decades, each with a unique set of strengths and weaknesses depending on the intended orbit, debris size, and operating principles. To determine the most viable solution for remediation in LEO, we identified the state of the art of ADR technologies. We compare them using a set of key parameters to measure their effectiveness. Finally, ADR solutions are recommended targeting small (diameter $d < 1$ cm) medium (1 cm $< d < 10$ cm), large (10 cm $< d$ and casualty area $A < 8$ m^2), and extra-large size ($A > 8$ m^2).

The additional distinction between large and extra-large debris is based on whether re-entry requires to be controlled or can be uncontrolled. To define this boundary, the debris' casualty area can be calculated as a function of debris speed, cross-sectional shape, de-orbit altitude, and human cross-sectional area on the ground (a factor of how exposed people are on the ground) [5]. This number is determined using specialized software for large and extra-large debris and as a general rule, if the impact area lies below 8 m^2 the risk of casualty to people on the ground is below 10^{-4} which is typically the accepted maximum risk [6].

In LEO the critical debris size ranges are between 5 mm and 1 cm, as these pose immediate threats to operational spacecraft, and debris larger than 2 m as their fragmentation, due to breakups or collisions, is the root cause of the long-term population growth [3].

Liou prioritised addressing long-term population growth over immediate threats to operational spacecraft and suggested selecting extra-large objects as the primary targets for ADR based on their collision probabilities and their potential for generating the greatest amount of fragments [3]. His work, in line with other researchers, clearly shows that the majority of the most critical objects is located in high inclination orbits below 1100 km altitude [8].

ADR Technology Comparison

In this study the ADR technologies were grouped according to their operating principle:

- Capture devices: nets, robotic systems, sweepers.
- Contact de-orbiting devices: electrodynamic tethers, momentum exchange tethers, balloons, solar sails, and chemical propulsion de-orbiting systems.
- Contactless de-orbiting technologies: ion beam shepherd, ground-based lasers.

For each group a comparison was made using the parameters *Technology Readiness Level (TRL)*, *Feasibility, Risk, Total Cost, Reusability, Time to de-orbit* and *adaptability for GEO* (in this order of priority).

In the trade-off for the capturing devices, nets and robotic systems robotic systems achieved the highest scores due to their superior combination of technology readiness levels and reusability. Nets were found to be similarly effective but are not as readily reusable for multiple debris capture as robotic systems. Sweepers, devices attached to a spacecraft that absorb incoming debris, were found to have only the potential to remove a negligible amount of debris.

For contact de-orbiting devices, the chemical propulsion systems, with the shortest de-orbit time, highest TRL levels and smallest effective exposure area relative to balloons and solar sails, were found to be the best-equipped technology for de-orbiting extra-large debris. They also provide the opportunity of controlled de-orbit, which will be essential for safe removal of debris of this size. For the large category, the balloons were found most feasible when compared to solar sails as they have a history of being launched since the 1960s.

For the comparison between contactless technologies, ground-based lasers were found to be the optimal solution for medium sized debris as compared to Ion Beam Shepherds due to their superior reusability, TRL and time to de-orbit characteristics. They also represent a smaller financial and mission risk.

Proposed Solutions for Removal

Laser Orbital Debris Removal (LODR) is proposed as the solution to remove medium sized debris (on the order of 10 cm size) in LEO, with the real potential of extending its range to tackle orbital debris up to 50 cm.

This is a cost-effective technology that presents several benefits. There is no need to rendezvous with debris, and no new satellites would need to be placed into orbit for the removal operations. The LODR system is also suited to actively prevent collisions between larger objects and to support a more precise re-entry for selected large pieces of orbital debris for the avoidance of populated areas or air traffic corridors [9]. However, LODR faces many technological challenges and the feasibility still needs to be demonstrated.

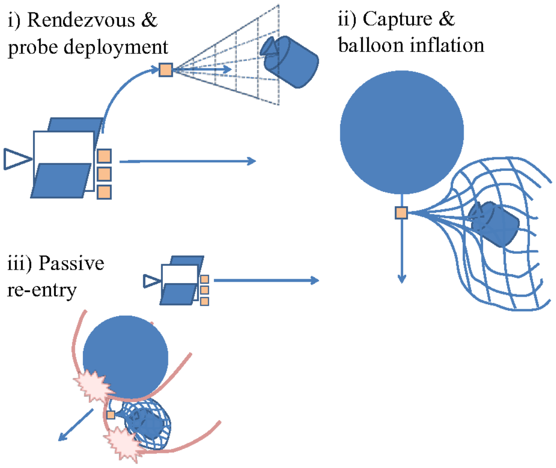

Figure 1. SpiderSat ADR scenario

SpiderSat is a proposal for removal of debris larger than 10 cm. A single mission can de-orbit many pieces during its lifetime. The concept is based on a hub satellite with a complete communication and attitude control system capable to shoot smaller removal probes towards orbital debris. Each removal probe uses a net to capture the debris and a balloon to passively de-orbit it as depicted in Fig. 1. The lightweight balloon significantly increases the area subjected to atmospheric drag and solar radiation pressure, leading to passive de-orbit. The deployed balloon can be rigidized after deployment to minimize the risk of collapse due to puncture caused by possible space debris impact [10,11]. For rigidization the concept of UV and glass temperature curing are the most promising for this application. In both cases, the resin of the composite in the balloons surface becomes rigid due to the UV light of the sun or the temperature decrease from the storage box to the environmental condition. Following the ejection of the first removal probe, the SpiderSat hub satellite executes rendezvous with the next orbital debris object of interest to restart the process.

The key technologies for SpiderSat are available today: balloon deployment mechanisms have a high technology readiness level, though the net requires more development work before being used for debris capturing. The simplicity of the passive de-orbiting system (mainly based on atmospheric drag) makes it a reliable concept, which can be launched in the near future.

The removal of extra-large debris requires a dedicated solution that includes controlled de-orbit manoeuvres because atmospheric friction is not sufficient to completely burn the object during the re-entry.

During the capture phase, it is important to consider debris attitude stability or "tumble", because debris with stable attitude can be captured performing simpler manoeuvres. Extra-large debris are found to eventually stabilize over years due to interaction with the Earth's magnetic field as confirmed by observations from ground [12]. By giving priority to rocket bodies launched more than 10 years ago, the design of the capture phase gains significant simplifications.

Regarding the de-orbiting phase, a number of studies have been analysed [13-16]. Among them, a technique employing a mechanical interface specifically designed to dock with Ariane IV upper stages and chemical propulsion to perform controlled re-entry resulted to be the most effective for rocket bodies.

Fig. 2 presents a pictorial view of the active removal phases, where the chaser first rendezvous with the extra-large debris using electrical propulsion, then docks with and stabilizes it in the desired attitude to perform the de-orbit. The chaser connected with the debris decreases its orbit altitude using electrical propulsion (Fig. 2 iii) and finally starts the re-entry into atmosphere using chemical propulsion.

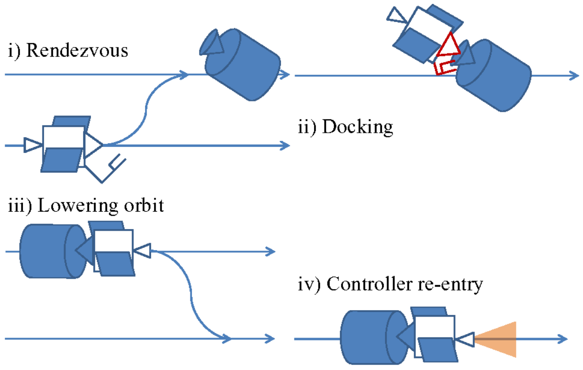

Figure 2. Chaser ADR scenario

The mission profile is based on the assumptions that each chaser de-orbits only single extra-large debris and that the docking interface is specific for the type of debris (e.g., Ariane IV upper stages).

To minimize the launch costs multiple chasers should be packed in a single launch. Alternatively, a small group of chasers could be put on-orbit together with another suitable Earth Observation (EO) mission.

Conclusions

Following a survey and a comparison of current ADR technologies we defined a set of solutions addressing the debris removal in LEO. We propose laser technology for medium sized debris removal. We present a novel concept of SpiderSat, which involves both net capture and inflatable balloon for large debris removal. For ADR of extra-large debris, we propose the Chaser equipped with robotic arm(s) and chemical propulsion; the former is used to capture the debris, and the latter for propulsive re-entry. Though the cost is high for the extra-large debris solution, it is also the most effective to safely remove the primary debris targets [3].

5 POLICY AND LAW

Any feasible approach to resolving the problem must be founded on solid political viability. The diverging interests on the international stage make orbital debris a true conundrum [17]. It distinguishes itself from other current international issues due to a unique set of contradicting interests (shown in Fig. 3) complicating the solution process.

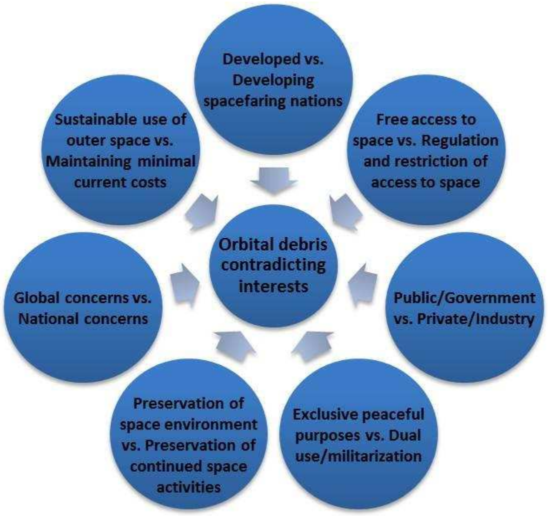

Figure 3. Orbital debris contradicting interests [19]

From a policy and law perspective, a number of recommendations should be made to facilitate the resolution of the space debris problem:

- ICAO should consider developing a dedicated branch, called ICAO-Space, as proposed by Prof. Ram Jakhu *et al.* [18], which would formulate Standards and Recommended Practices (SARP) for global Space Traffic Management.
- An international organization dedicated to orbital debris removal should be created, referred to as the "International Orbital Debris Removal Organization" or IODRO
- ISO should set standards for the certification of "clean" launch vehicles and satellites, being those which do not create debris, and incorporate systems for passive or active de-orbiting.
- The UN Office of Outer Space Affairs mandate should be strengthened to ensure the effective implementation of space debris mitigation and ADR. In addition to the UN Debris Mitigation Guidelines, the UN should adopt by UN General Assembly Resolution a set of Debris Removal Guidelines, to be implemented at the national level.

IODRO's mission would be to finance, coordinate, manage, operate and license international efforts in orbital debris removal. It is assumed that the original Member States of IODRO would be the 12 current members of the IADC, open for other UN Member States to join the organization. IODRO would rely on a consensus-driven decision process involving all member states, to decide issues such as the selection of debris for removal, the technology to develop, and prime contractors for ADR missions. IODRO would have legal personality and the status of a launching state. Therefore, IODRO would be responsible and liable for its space activities in accordance with the existing Outer Space treaties. IODRO will have the ability to license, own, launch and operate space missions, retaining jurisdiction over them, and responsibility for its space objects and activities in space.

Damages arising from IODRO activities would be borne by the organization itself. The Member States would sign cross-waivers, similar to the ISS Agreement(s), for IODRO's in-orbit activities, diminishing potential lawsuits arising from damages caused by IODRO activities, as most space assets belong to IODRO member states. Risk for damage on the Earth's surface, for instance in the case of damage arising from re-entry events, would be fully carried by IODRO. The organization could take measures to insure itself for this kind of potential claims. IODRO member states will fund IODRO at a level commensurate with their share of their contribution to the orbital debris problem. More on the financial model of IODRO is found in the next section.

6 THE ECONOMIC RATIONALE AND FINANCIAL MODEL

The technical and political challenges of orbital debris removal are only one aspect of the overall solution. An economic rationale and a viable financial framework must be formulated to develop and operate the technical solutions, and provide a solid basis that enables the policies to be implemented. We therefore discuss the economic rationale for tackling and ultimately solving the orbital debris problem, and then present a viable financial model for the funding of orbital debris mitigation and removal activities.

The economic rationale for orbital debris mitigation and removal

There is no simple mathematical formula that justifies orbital debris removal as an urgent problem that is currently making activities in space non-viable from an economic standpoint. In other words, the estimated cost of annual damages incurred by the orbital debris does not, currently, exceed the predicted costs of comprehensive orbital debris mitigation and removal missions. It is therefore currently not a net-gain to fund an expensive ADR mission. The situation is furthermore complicated by a discrepancy between the profitable orbital regions and the regions most affected by space debris: most revenue is made by infrastructure in the geostationary region where the majority of commercial communication satellites is stationed, while the space debris problem is most critical in LEO, which is mostly used by government owned EO satellites. These government owned satellites pay relatively little revenue (USD 2.24 billion of USD 110.53 billion in total [20]), and are mostly self-insured.

The direct economic loss due to fatal impacts of space debris on operating spacecraft was approximated using the ESA MASTER debris population model and results of the SHIELD3 impact risk assessment software. Fig. 4 shows the probability of fatal failure for the SPOT5 optical EO satellite that was derived from this data and used as a representative failure model.

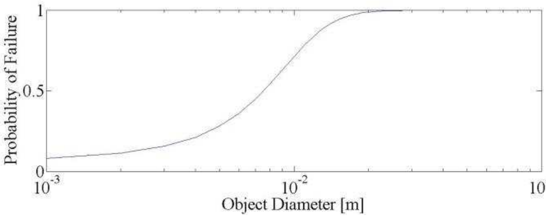

Figure 4. Failure model for the SPOT5 satellite

In conjunction with MASTER data on debris object fluxes at different diameters and an approximated area of 76 SSO satellites, total probabilities of fatal failure of a SSO satellite per year were calculated. Using data from NASA mission cost models, an average cost of satellite production and launch of USD 38 million was assumed, leading to the annual losses presented in Tab. 2 (figures in millions of USD). The results correlate well with those of other studies [21].

Adding up to roughly 4% of the total cost of SSO missions launched in 2012, these figures alone do not constitute a convincing economic rationale for ADR.

Table 2. Economic loss caused by debris impact (in USD million)

Debris Size\Year	2012	2055
>10 cm	0.1	0.2
1 cm to 10cm	1.5	3.8
1 mm to 1 cm	13.0	21.4

However, the hardware cost of spacecraft does not necessarily reflect the inherent “value” of space assets, and the revenue they generate. The value of the “space economy” increased to an estimated USD 290 billion in 2011. EO satellites, operating mostly in LEO, generated USD 2.24 billion in revenue in 2011, spread over 92 operational satellites, and this figure is expected to almost double by 2020. 110 satellites launched in 2011 alone had a manufacturing value of USD 11.9 billion. Using these figures, roughly USD 107 billion worth of satellites by manufacturing value are currently orbiting the Earth [20]. An ADR mission for extra-large debris, estimated to cost USD 100 million to manufacture, launch and operate, represents a very small sum spent to reduce the risks of destruction of very valuable assets.

The cost of ADR missions should be viewed as an insurance against the future potential loss of assets; a “pay now to avoid paying much more later” approach. As indicated by the figures in Tab. 2, the debris that is expected to cause most damage is that of diameter 1mm to 1cm; i.e. the debris that currently cannot be tracked and be shielded against only with considerable effort [22]. Both improved shielding and better resolved tracking will require substantial investments. Removing the debris could be an alternative. An alternative, however, that becomes more expensive over time. Using the number of objects created by the Iridium-Cosmos collision and now tracked by the US Space Surveillance Network (1886 as of 12 June 2012), the cost of removing them can be approximated. Since they are tracked, it is assumed that they are larger than 10cm. With an orbital system to remove these pieces costing about USD 500.000 per piece [23], the cost of removing only these large pieces would add up to more than USD 900 million, far more than the roughly USD 130 million that removing the two intact satellites under IODRO would cost.

An additional source of revenue loss for satellite operators is through time lost while performing collision avoidance manoeuvres. The annual collision-avoidance manoeuvres performed by Canada’s RADARSAT-2 EO satellite equate to one day per year of lost revenue, and this is typical for other LEO satellites as well [24,25]. Calculating the daily revenue this satellite generates [26] and averaging this across all EO satellites, an annual revenue loss of USD 52 million through debris collision avoidance manoeuvres is derived.

The funding of IODRO

As Tab. 3 shows, IODRO would require approximately USD 670 million annually during the operational phase to remove ten large pieces of debris per year. During the preparatory phase, IODRO member states would use their funding to directly cover the costs of research and development activities by their in-house industries. Once in operations, IODRO missions would follow the juste retour principle, where development, manufacturing and operation funds are allocated to member states proportional to the amount of funding they contribute to IODRO.

Table 3. Cost model of IODRO, in millions of USD

Cost\Year	Preparatory Phase (2021-2023)	Operations (2024-2053)
Operations		198
Launches		120
Hardware & others		282
Internal overhead	24	72
TOTAL	**24**	**672**

The funding of IODRO should be based on the principle of common but differentiated responsibility among space faring nations. The bulk of the funding for IODRO, USD 440 million, would therefore come from those nations who own the vast majority of orbital debris objects. Whether calculated by total mass or by number of debris objects, the United States, Russia and China bear the majority of the responsibility. Another USD 180 million would stem from USD 15 million contributions from each of the 12 original IODRO member states.

USD 50 million would come from a 5% levy on satellite insurance premiums. In 2011, USD 0.86 billion in insurance premiums were paid, largely by GEO satellite operators [20]. Missions that successfully de-orbit their satellites would have a large portion of the levy returned; those missions that do not or cannot actively de-orbit their satellites are essentially paying into a fund for others to do so. Other researchers like Pelton suggest similar models [27].

7 ROADMAP

To conclude, we made a number of recommendations in a roadmap for future action. Fig. 5 is a summary of these recommendations.

2013 – 2016

- Extended cooperation between space agencies cooperate to develop and provide more explicit information about the costs of debris avoidance, mitigation, surveillance, and response.
- Development of Orbital Debris Removal Guidelines by the IADC.
- UN OOSA mandate is extended to ensure the effective implementation of space debris mitigation and ADR.
- Computational resources devoted to orbital debris trajectory prediction should are increased, improving conjunction-prediction accuracy is. This data is shared globally in a timely fashion.
- Bann of intentional destruction of space objects (satellite and launch vehicles) on-orbit. Only exception: the space object is on a re-entry trajectory with altitude less than 200 km.
- Names and details of those nations and operators who do not adhere to the disposal of GEO satellites are published in visible forums such as FAA publications and at the ITU.
- U.S. makes Orbital Debris Guidelines mandatory under national law. Other nations follow suit by creating similar national legislation based on IADC and UN orbital debris guidelines or other applicable guidelines.

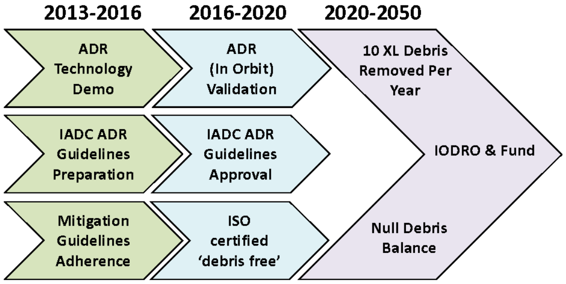

Figure 5. Roadmap for debris mitigation and removal

2016 – 2020

- ICAO develops standards and recommended practices for space traffic management.
- ISO sets standards for the certification of "clean" launch vehicles and satellites. New systems need to be designed in compliance with the ISO standards. ISO standards for spacecraft "body armour" are researched, developed and put into place, to better protect spacecraft against impacts with orbital debris.
- We foresee the adoption by UN General Assembly Resolution of the proposed Orbital Debris Removal Guidelines, to be progressively implemented at the national level by all space faring nations.
- All LEO space objects are mandated to incorporate passive de-orbit technology that can be operated even in the case of total primary satellite loss; this de-orbit technology shall re-enter the space object within the 25-year guideline.
- All LEO space objects without active removal technology are mandatorily placed in an orbit such that they comply with the IADC 25-year guideline though natural decay.

- All launch vehicles and satellites with a risk of explosion due to on-board propellant, pyrotechnic or self-destruct devices, electrical storage devices or other means, must be passivated at end of mission life (once any de-orbit measures are underway), by the external venting of all residual propellant, and the safing of electrical and any pyrotechnic systems.
- Commercial-led ADR missions are promoted to stimulate development of cost-effective ADR technologies, eventually resulting in commercially viable ADR missions.
- Creation of IODRO, dedicated to ADR. IODRO is established as an international organization with legal personality. IODRO manages, finances, develops, licenses, and operates orbital debris removal missions.
- Development and implementation of the "SpiderSat" net-based ADR system for the in-situ capture and de-orbit of medium- and large-sized orbital debris.
- Creation of an international SSA system with an updated and expanded network of sensors to provide a comprehensive and accurate view of all non-classified trackable objects.

2020 – 2053

- Development and implementation of a mission for orbital debris capture that can use chemical propulsion systems to de-orbit extra-large debris on a controlled re-entry trajectory.

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The full text and the executive summary of the ISU SSP12 Report on Space Debris, on which this paper is based, can be found at the ISU on-line library [28].

9 REFERENCES

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