

Special on space debris at IAC21

Samar AbdelFattah

Principium has been increasingly concerned with the problem of space debris. The long term perspectives of interstellar studies inevitably lead i4is to consider the question - *How do we get there from here?* Until we develop an interplanetary culture, commerce and society the only "here" is the surface of our home planet. In P34 we illustrated the problem with our back cover image - a shot from ESA's latest space debris movie [1].

In P35, our November 2021 issue, we considered *Losing Access to Space - Are we building a fence around our planet?* [2].

Here Principium Contributing Editor Samar AbdelFattah summarises a selection of papers at IAC21 addressing this topic. A longer list of authors and papers follows - it is almost certainly incomplete.

Principium welcomes further discussion of this very significant potential barrier to our long term goals - email: John.Davies@i4is.org or Principium@i4is.org.

All figures are credited to the presenters and figure numbers are as in the presented papers.

Large Constellations

IAC-21,A6,5,9,x66275	Rendezvous and proximity operations design of an active debris removal service to a large constellation fleet	Mr Giacomo Borelli	Politecnico di Milano; D-Orbit SpA	Italy
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IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/66275/

Open paper: [www.researchgate.net/publication/355827730 Rendezvous and Proximity Operations Design of an Active Debris Removal Service to a Large Constellation Fleet](https://www.researchgate.net/publication/355827730_Rendezvous_and_Proximity_Operations_Design_of_an_Active_Debris_Removal_Service_to_a_Large_Constellation_Fleet)

Reported by: Samar AbdelFattah

The paper presents Active Debris Removal (ADR) service designed for LEO large constellation deployment which will safely deorbit the failed assets by performing a rigid capture. Since the growth of the region deployment is massively growing without any proof of the sustainability of these constellations in the space domain. The focus of the work here is the proximity and Rendezvous and Proximity Operations (RPOs) required during the ADR service mission to approach, capture, and deorbit the debris object. There were multiple mission architectures that introduced the ADR service. Some examples of these architectures were introduced in the paper as follows: The first mission architecture is the chaser mission, where the servicer is designed to approach each failed satellite in a constellation, capture the satellite and transfer it in a disposal orbit (complying with a five year re-entry time). Another concept is the mothership architecture, where the servicer approaches the failed asset and attaches the deorbiting kit. In this architecture the transfer from and to the disposal orbit is done using delta-v. In addition to these two, the chaser plus station architecture is considered where one servicer is used to capture and deorbit each target with a main station for refuelling.

[1] *Time to Act* www.esa.int/ESA_Multimedia/Videos/2021/04/Time_to_Act

[2] *Losing Access to Space* i4is.org/wp-content/uploads/2021/11/Losing-Access-to-Space-Principium35-print-2111260906-opt-9.pdf

With the Rendezvous as the main Concept of Operations (ConOps), the mission of the services first considered two types of constellation for the ADR design baseline:

1. Small class satellite (light target): OneWeb Arrow Spacecraft of 150 kg mass
2. Large class satellite (heavy target): EliTeBus- 1000 bus (GLOBALSTAR and Iridium-NEXT) of 750 kg mass

Second, the service were designed in the manner that provide the following requirements:

- Req-1: The servicer shall be able to rendezvous and capture the target. No cooperation or collaboration from the target shall be considered.
- Req-2: The servicer shall be equipped with onboard sensors dedicated to the measurement of bearing, range and pose of the target to enable and support the rendezvous operations.
- Req-3: The servicer shall be capable to perform the final operations in proximity regardless of the natural illumination conditions.

The envisioned ConOps is shown in Fig 1 with the following chronological sequence of the operations during one mission:

1. Absolute orbit phasing
2. Far-range rendezvous
3. Mid-range rendezvous
4. Inspection
5. Target preparation for robotic capture
6. Final approach forced motion
7. Robotic operations and capture
8. Stack stabilization and deorbiting

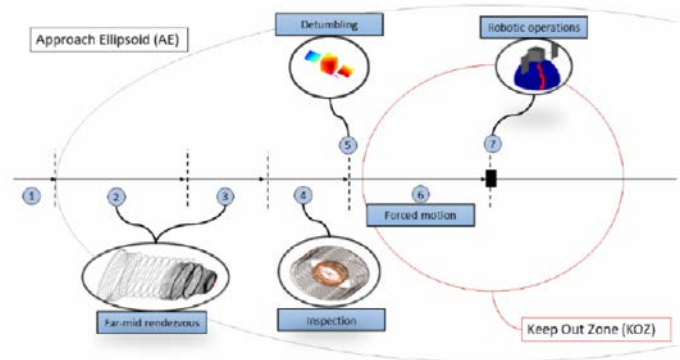


Fig 1 RPOs concept of operation for each service to a failed uncooperative satellite of the constellation fleet

For the ADR service, a suggested sensor payload was presented in the paper for visual object detection during the proximity operations. The payload includes mainly a Narrow Field of View (NFOV)

Visible Camera with an additional Wide Field Of View (WFOV) camera. To enhance robustness to illumination conditions, an Infrared IR sensor is used to provide image measurement of the object in the closer range. At the last, the use of LiDAR sensor was to provide the range measurement of the target from mid-range. The detailed range performance of the payload is illustrated in Fig 2.

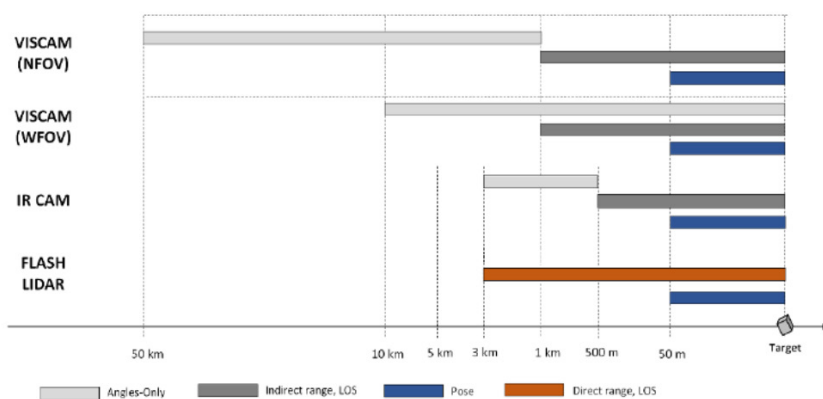


Fig. 2 Operation matrix of the sensor suite in function of the separation distance during the proximity operations

The authors discuss the far and mid range rendezvous design through analysing the Navigation and Guidance Control with the main objective for the servicer at this initial phase is to reduce the distance between the target and services for the rendezvous operations to run autonomously. They start Relative Guidance and Navigation Control (R-GNC) where each subfunction of the R-GNC servicer block is presented and simulated in a high fidelity environment.

After the analysis of the R-GNC, the authors discuss the onboard real-time navigation which is performed using an Extended Kalman Filter (EKF). In this case and during the mid-range operations the filter convergence is supported by the full observability conditions provided by the LiDAR range information. The GNC during the far and mid-range operations is implemented in a shrinking horizon Model Predictive Control (MPC), where at each GNC update, the guidance and control solutions are updated according to the filter estimate.

◀ Fig 3 shows the table presenting the simulated far and mid-range rendezvous phases along with the R-GNC mode used.

Phases	Guidance and Navigation	Separation
Far-range 1	Observability enhanced (w)	From 50 km to 10 km
Far-range 2	Energy optimal	From 10 km to 1 km
Mid-range	Energy optimal	From 1 km to 500 m

Fig. 3 Simulated ranges with R-GNC mode used results

After achieving the objective of reducing the rendezvous distance for a few hundred metres using the R-GNC at the end of the mid-range approach, the authors discuss in detail the inspection phase which will be required to proceed with the close-proximity operations. In this phase, the servicer performs a series of manoeuvres and fly-arounds which allows the onboard observation of the target pose and physical characteristics. This information will be a strict requirement for the ground go-command to proceed with the closer approach forced motion and operations.

Finally, the paper discusses the final stage of rigid capture. There are two possible scenarios during this phase depending on the tumbling status of the target object:

1. The target is not tumbling: the relative motion of the target capture point in the servicer body frame is limited and the rigid capture can be performed using the robotic arm (the capture point for the two targets used in the paper as a design baseline were defined and displayed).
2. The target is tumbling: contactless control of the target tumbling state is used employing the plume impingement effects of the servicer's onboard thrusters to prepare the target for the save rigid capture operations (the control algorithms for the servicer's thruster that will be used for detumbling were presented in the paper).

Authors: Giacomo Borelli - Gabriella Vittoria Maria Gaias - Camilla Colombo - Lorenzo Vallini

CubeSat in Debris Detection

IAC-21,A6,1,2,x66530	STRATHcube: The Design of a CubeSat for Space Debris Detection Using In-Orbit Passive Bistatic Radar	Lewis Creed, Julie Graham, Sebastian Diaz Riofrio, Ciaran Jenkins, Andrew Ross Wilson, Massimiliano Vasile	University of Strathclyde	UK
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IAF cited paper: [dl.iafastro.directory/event/IAC-2021/paper/66530/](https://www.dl.iafastro.directory/event/IAC-2021/paper/66530/)

Open paper: www.researchgate.net/publication/355808576_STRATHcube_The_Design_of_a_CubeSat_for_Space_Debris_Detection_Using_In-Orbit_Passive_Bistatic_Radar

Reported by: Samar Abdelfattah

This paper discusses a cubesat low altitude mission aimed as a Proof of Concept (POC) for the use of Passive Bistatic Radar (PBR) technology for space debris detection in LEO as an in-orbit operation instead of the ground-based tracking. The STRATHcube mission concept involves a radar receiver, an on-board antenna on the cubesat while orbiting at low altitudes. The idea is to detect the variations in radio signals transmitted by

operational satellites orbiting at higher altitudes and known as illuminators of opportunities. In the normal case the bistatic angle is measured as 180 degrees and in case of interruption (variations in the radar signal) the signal processing algorithms can be used to detect the size and the shape of the object passing between the illuminator of opportunity and the cubesat, Fig 1.

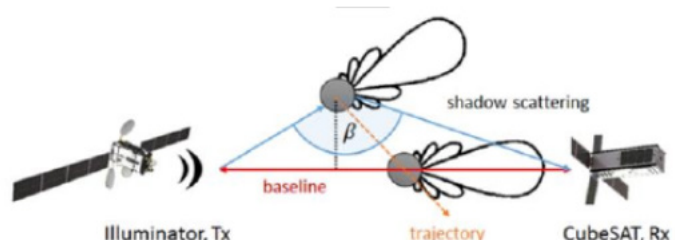


Fig 1 PBR cubesat concept

◀ The team uses the effect of forward scattering to determine Radar Cross Section (RCS) of a target using the equation: $\sigma_{FS} = 4\pi U/\lambda^2$ (U =silhouette area of the target, λ is the wavelength [1])

Thus, the higher the frequency of the selected illuminator of opportunity (small wavelength) and belonging to a larger constellation, the better the chances of link availability and potential detection of smaller debris objects. Also, this will be essential in designing the cubesat payload so that the antenna is able to receive at the operational frequency of the illuminator.

The authors highlighted their preferences when it comes to selecting the illuminator of opportunity for their STRATHcube. Starlink was discussed as their most preferred for a constellation group, however, the frequency limitations eliminated a lot of interesting options. Since Starlink, OneWeb and TeleSat networks operate at high frequencies (Ku- and Ka-bands), the PBR experiment will not have suitable "Commercial off-the-Shelf" (COTS) batch antennas that can operate at these frequencies. Thus, older communication constellations like Iridium and Globalstar were more suitable for the mission frequency requirements. With 24 operational satellites only available with the Globalstar option, the selection was made for Iridium with its 75 operational satellites which were enough for the experimentation of the PBR technology. Although the authors discussed later on the availability for a custom designed patch antenna through Endurosat; However, this option was eliminated due to the limited budget for the student-led project nature of STRATHcube. As the main payload of the cubesat, the tradeoff of the antenna options considered two options, a 3D phased array antenna which is designed by a researcher in the university specifically for STRATHcube, and a commercial off-the-shelf patch antenna. Despite the fact that the custom phase array antenna was an optimum scenario to customize the operation frequencies, the design requirements for mass and power made it an unfeasible option compared to the commercial options. Table 1 shows the design requirements for the 3D antenna. Eventually, the team decided to use the PulseLARSEN Ceramic commercial antenna, Fig 2. In case of failing the radiation or vibration tests, the alternative would be a more conservative yet more expensive option which is the GNSS Active Patch Antenna by ISIS.



Fig 2 PulseLARSEN Ceramic Patch Antenna

Authors: Lewis Creed - Julie Graham - Sebastian Diaz Riofrio - Ciaran Jenkins - Andrew Ross Wilson - Massimiliano Vasile

Space-based Laser

IAC-21,A6,4,4,x66251	A Strategy for the Mitigation of Debris Shells in LEO using Space-Based Lasers	Lewis Walker, Massimiliano Vasile	University of Strathclyde	UK
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IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/66251/

Open paper: strathprints.strath.ac.uk/79596/1/Walker_Vasile_IAC_2021_Mitigation_of_debris_in_LEO_using_space_based_lasers.pdf

Reported by: Samar AbdelFattah

The paper challenges the current solutions for space debris mitigation or elimination which rely on rendezvous, capture and deorbiting. Thus, these solutions are suitable for the removal of defunct satellites or large fragments. The presented solution uses a space-based laser in an approach to solve the challenges of ground based laser solutions which require a lot of power and lack the accuracy of object detection since it assumes the perfect alignment of the laser beam with the targeted fragment. Similar to the L'ADROIT mission concept [2], the paper proposes a satellite constellation inserted into a shell around the Earth such that the constellation has access to all longitudes instead of the one large satellite placement in the polar orbit. In addition, the authors attempt to investigate L'ADROIT altitude, laser incidence alignment, and assumption on beam waist plane longitudinal alignment with the fragment. ▶

[1] This STRATHcube paper (see the Open paper link above) cites *SISAR Imaging for Space Debris based on Nanosatellites*, Theodorou et al 2015 (pure.strath.ac.uk/ws/portalfiles/portal/101404429/Theodorou_et_al_RSN_2020_SISAR_imaging_for_space_debris_based_on_nanosatellites.pdf) for this equation.

[2] Claude R Phipps. *L'ADROIT—A spaceborne ultraviolet laser system for space debris clearing*. Acta Astronautica 104.1 (2014), pp 243–255 www.researchgate.net/profile/Claude-Phipps/publication/265338032_LADROIT_-_A_spaceborne_ultraviolet_laser_system_for_space_debris_clearing/links/60fc2f481e95fe241a87c5f0/LADROIT-A-spaceborne-ultraviolet-laser-system-for-space-debris-clearing.pdf

- ◀ The solution is designed with two main payloads. A camera for fragment acquisition and tracking through continuous space scanning and a high-power Continuous-Wave (CW) laser to eliminate fragments and impart momentum. The payload is powered by an onboard battery pack which receives its charging supply from the solar panels incorporated in the satellite, which also powers electric thrusters used for orbit maintenance or adjustments.

“Beyond the power system, no detailed attempt to estimate the size and mass of the individual spacecraft is made, however the author expects these would be of the small-sat class, and between 100 and 300 kilograms each. To launch a constellation of one hundred 300 kg satellites, two Falcon 9 launches would be required, costing \$100 million with reused boosters. This assumes onboard thrusters are used to transfer from the delivery orbit to the operational orbit.”

The authors attempt to analyse the propagation of orbits semi-analytically using a tool called CALYPSO which was developed at the University of Strathclyde. However, for the sake of computational efficiency, propagations in this paper are performed with drag as the only perturbation.

Modelling Scenario

The modelled debris shell population of fragments is generated to simulate satellite breakup in a 1,200 km circular orbit at 45 degrees inclination. The selected model (2 cm Aluminium hex nut) which approximately coincides with the peak distribution of Iridium-Cosmos collision debris.

Due to computational demand, a representative population of 632 fragments is propagated over a 10-year mission span, as well as the orbit of a single satellite. The separation between the spacecraft and the fragments oscillates, generating many local minima, which represents candidates for the operation.

However, the filtration criteria is conditioned by:

1. Visibility condition: fragment must be seen by camera at all times; such that the SNR is achievable before the object image moves by one pixel width in the sensor plane.
2. Reachability: fragment must be within 30 degrees of spacecraft negative velocity direction.

Optical Acquisition

At each encounter, a binary number will be given by comparing the minimum required exposure for SNR and the relative angular velocity, the binary number one indicates that the two conditions are achieved, Fig 1. In their analysis, the authors were able to extract information on the rate of these interactions. On average, an encounter of 0.483 per day was concluded for the fragment representing a population of 632 fragments. For a more realistic population of 5,000 fragments, expected encounters are approximately 4 per day.

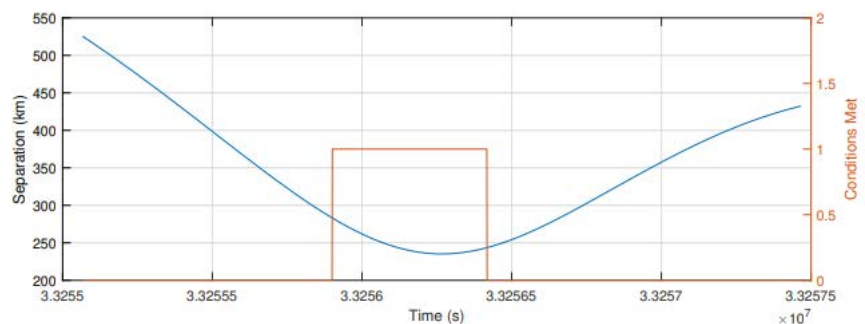


Fig 1 Example of information extracted on the dynamics of a single encounter

Laser Interaction Model

In this section of the paper, the authors attempted to define their Laser-Debris Interaction (LDI) model operations. Started by investigating the element illumination, system photon pressure force, longitudinal laser profile, to finally calculate the required impulse transfer. Using the database of encounter dynamics they obtained (only with the binary condition equal to one), they were able to feed the photon pressure model. And during the visibility window shown in Fig 2, the separation vectors are passed into the Laser-Debris Interaction (LDI) model to integrate the laser pressure force over the course of interaction.

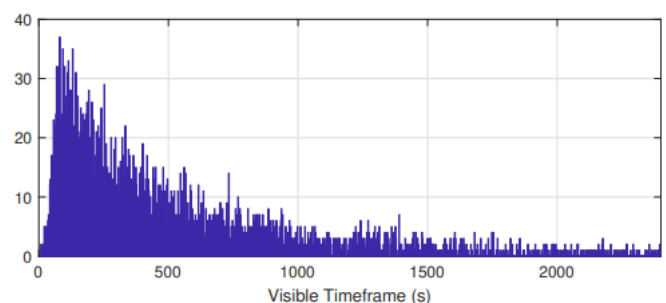


Fig 2 Distribution of visibility window duration

Long Term Mission Impact

The authors were able to scale up the fragments population to 5,000 at the 1,200 km altitude for a 10-years duration's worth of encounters for a single satellite, then modelled the results for a constellation of 100 satellites. In these results, only 417 fragments have been propagated to the end of the 10 years mission to gain an insight into the expected effect of any given fragment in the population. Thus, laser ablation method will be studied in their future work instead of the photon pressure mechanism.

Adaptation for Collision Avoidance

Orbit lowering is a potential use for the satellite constellation that was investigated by the authors at the end of their paper. A random population of 500 fragments were studied after 1 day of collision notice period and then the results were presented after repeating the analysis several times over different notice periods, Fig 3

The concept was subsequently adapted and re-modelled using ablative interaction with pulsed lasers, leading to a far stronger effect on the orbits of fragments in the shell. Using ablation, it is possible to achieve lifetime reduction of decades for fragments in orbits with 1,200 km altitude, which could significantly reduce the risk posed by debris shells left behind after collision events at these altitudes.

Authors: Lewis Walker - Massimiliano Vasile

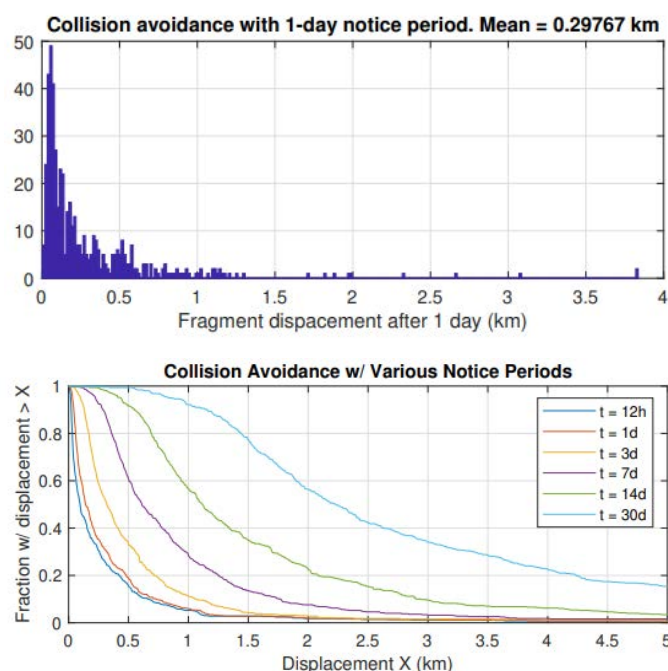


Fig 3 Fragment displacement scenarios

Policy and Legal Feasibility

IAC-21,E9,IP,3,x63533	Active Debris Removal Policy and Legal Feasibility	Josef Koller, Tyler Way, Mark A Skinner	The Aerospace Corporation; Space Policy Institute, George Washington University	USA
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IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/63533/

Open paper: csp.s.aerospace.org/sites/default/files/2021-08/Way_Koller_ADR_20210422.pdf

Reported by: Samar AbdelFattah

According to the European Space Agency (ESA), there are approximately 29,000 pieces of debris larger than 10 centimetres and 670,000 pieces larger than 1 centimetre currently orbiting Earth. In addition, as of February 2021, there are over 6,500 spacecraft and over 2,000 rocket bodies in orbit. The paper addresses, from a regulatory perspective, this growth of space debris risk beside the future risks rising from proliferated low Earth orbit (pLEO) constellations for instance.

In the efforts to establish the obligation of law execution for debris mitigation and/or ADR services, the authors propose a framework based on two principal requirements:

1. Consent between debris owner and ADR service provider
2. Legally binding contract between parties that incorporates domestic law and international obligations

However, in case of multiple states to be involved, the framework adds to the above requirements a

Memorandum of Understanding (MOU) between states, which shall address the following:

- Authorization and licensing responsibilities
- Registration responsibilities
- Technical data exchange
- Liability Issues
- Ownership transfer, if any
- Transparent messaging responsibilities

The framework addresses an additional key political challenge which is the risk of using ADR as an anti-satellite weapon. The mitigation of such risk is achieved by the required consent by the launching state to

◀ the ADR service provider. Thus, a consent-based system draws, therefore, a clear line between prohibited and authorized operations.

Outer Space Treaty Obligations

Although the United States has incorporated OST Article VI provisions throughout its outer space regulatory authorities provided to NOAA, the FAA, and the FCC, none of these authorities yet, dedicated to regulating ADR operations.

Therefore the authors' affirmation on having a well funded entity within the United States government, which would require legislation and congressional approval, to resolve legal and policy problems can only be a longer-term solution. In the meantime, they suggest using their framework to promote ADR activities until processes and procedures become more mainstream and mature into sound policy or law that then can be implemented by the appropriate regulatory agencies.

Registration Convention

An important aspect of registration for ADR is the ownership principle of the treaty. The ADR framework here suggests that the typical responsibilities of the launching state for the ADR service provider would be to register the ADR servicer. And if the ADR service provider is part of a larger international conglomerate, the registration question could be resolved as part of the permission and consent-based contractual agreement, an MOU, or bilateral agreements. Also, in case of any damage/explosions caused by fuel on board, the MOU is used to define the responsible partner.

Liability Convention

Determining the liability of an accident is preceded by determining which launching state is the owner/operator and thus liability holder. Whether the liability should be held by the servicing satellite's launching state or the client's launching state, shall be defined in a contract between the ADR service provider and the launching state of the space debris.

Third Party Liability Regulations and Insurance

Following the insurance requirements in the United States for liability in space activities are covered under the Commercial Space Launch Amendments Act of 1988 which extend to the ADR service. The authors suggest extending the liability beyond launch and re-entry to extend to protection from accidents and mishaps as well.

Ownership Transfer Not Required

An example is given for a commercial launch provider that does not assume ownership of a payload that it places into orbit. In this case, providing a service is not considered a transfer of ownership and the client maintains ownership of its asset as well. Therefore, in the case of ADR, there is no precedent for the requirement of ownership transfers between client owner and ADR service provider, which removes a major obstacle to the legal conduct of international ADR operations.

Framework Analysis with Domestic and International ADR

1. Domestic Entity Removing US Objects

In the US, the current state of art requires a NOAA license for any camera capable of imaging Earth. Despite the fact that NOAA only regulates remote sensing and not the full extent of the space operations and how they are conducted, the remote sensing license and the associated interagency process will have to be sufficient for fulfilling the OST obligation for authorization due to the absence of such on-orbit authority.

2. International Debris Removal

The main challenge here is to answer the question on export control. The issues will depend on the countries involved, the capturing mechanism, and what level of technical data would need to be shared. Thus, agencies controlling the export of technical information will look at the amount of detail shared and decide on thresholds of technical information that would trigger restrictions.

Authors: Josef Koller - Tyler Way - Mark A Skinner

Risk Assessment

IAC-21,E9,IP,2,x64614	Mitigating Space Debris through Risk Assessment Framework	Anne Jing, Olivia Sun, Cindy Chen, Natacha Hughes, Dominik Adamiak	University of Toronto Aerospace Team (UTAT)	Canada
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IAF cited paper: dl.iafastro.directory/event/IAC-2021/paper/64614/

Open paper: www.researchgate.net/publication/356579054_Mitigating_Space_Debris_through_Risk_Assessment_Frameworks

Reported by: Samar Abdelfattah

The authors in this paper are highlighting the growing presence and risk of space debris with 34,000 objects larger than 10 cm, currently orbiting the Earth. Since the first publishing for space debris mitigation guidelines by the Inter-Agency Space Debris Coordination Committee (IADC) in 2002, only 60% of the total payload mass nearing end-of-life in low Earth orbit is compliant with these guidelines. Thus, the paper aims at creating a proposal for a regulatory body centred on a risk assessment framework that will suggest a legal guideline for the Active Debris Removal (ADR) market. While reviewing the state-of-the-art for currently existing ADR and mitigation methods, the paper addresses the technical, legal, political and economic barriers to the creation of a space debris monitoring and removal market. To design and test this framework, the authors start the proposed regulatory system with a discussion on the current existing technical, legal political and economic barriers, explain in details the proposed regulatory system, then discuss the legal clarity provided by the proposed regulatory system. At the end of the paper, a case study on Cosmos-Iridium incident is made with high-level assessment of the two satellites under the proposed risk-rating scheme to apportion liability.

Proposed Regulatory System

A Risk Rating System is suggested to define the 1. monetary contributions (including operation, liability/ insurance, ADR technology development costs), 2. liability conflict resolutions, and 3. A potential target list for ADR target- missions.

The risk rating system is divided into four main factors each having a different weighting out of a total of 20 risk points. The below table summarizes these factors weight and risk points:

Factor	Elements	Points Score
End of life plan considerations	1. ADR retrieval mission 2. Deorbit 3. Graveyard Orbit 4. Passivation	7/20 or 35%
Debris generating potential based on design factors	1. Propulsion system 2. Electrical or power generating systems including TT&C system (telemetry, tracking, communications) 3. Attitude and orbital control system 4. Structural system and thermal systems	5/20 or 25%
Orbital environment analysis		5/20 or 25%
Launch state considerations	1. 1pt - Average risk rating of all the launch states current satellites in orbit 2. 1pt - Estimated mass of debris released in the last 25 years (or since the implementation of the framework, whichever is earlier) 3. 1pt - Data sharing considerations	3/20 or 15%

After the risk rating outline, the authors discuss the monetary contribution. To ensure that the fees accurately reflect each signatory's orbital debris responsibility, in the first year of the organization's operations, the magnitude of each signatory's contribution to the common fund shall be determined via market-share liability. Thus, Market-share liability is suggested to resolve this issue of non-identifiability. The proposed regulatory system ends with an outline for funding the R&D of debris mitigation technologies.

Legal clarity provided by the proposed regulatory system

The authors follow their proposal by addressing current legal and political obstacles, then present a liability scheme supplemented by the risk rating system.

Finally, a display for the complete risk assessment per each of the factors is presented in the Cosmos-Iridium collision case study.

Authors: Anne Jing - Olivia Sun - Cindy Chen - Natacha Hughes - Dominik Adamiak



The effect of a single major collision

Collision between Iridium 33 and Kosmos 2251 -- debris field after 20 and 50 minutes.

Credit: Globe by NASA Worldwind in the public domain. Data based on work of Astronautics Research Group, University of Southampton

(Wikipedia - en.wikipedia.org/wiki/2009_satellite_collision)

