Refining active debris removal strategies

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ABSTRACT

Active debris removal (ADR) is a pragmatic, effective means to remediate the debris-generating potential in low Earth orbit (LEO). The debris-generating potential of resident space objects is a straightforward combination of the distribution and characteristics of massive derelict objects. However, the strategy to reduce this debris-generating potential is not so straightforward. Previous rankings of the statistically-most-concerning objects provide a good foundation of individual objects whose contribution to the likelihood of future catastrophic collisions make them prime candidates for removal. However, the general load of debris-generating potential coupled with atmospheric drag effects for a given altitude and the individual characteristics of these objects as ADR candidates (i.e., mass, tumble rate, inclination, and energetic sources on board) must all be considered when creating cost-effective ADR strategies. Analytic and empirical observations of the resident space population by LeoLabs are combined with the engineering conops of ClearSpace ADR solutions to generate an optimal ADR strategy for derelict objects deployed by the US Government as an exemplar. This same approach can be applied more widely to create optimal ADR strategies to address the global population of derelict objects in LEO.

1. INTRODUCTION

The population of space debris in low Earth orbit (LEO) is a growing concern for the safety and sustainability of space activities. The European Space Agency (ESA) estimates that while there are about 8,400 functioning spacecraft in Earth orbit, there are approximately 36,500 debris objects greater than ten centimeters in size, about a million pieces of debris between one and ten centimeters, and around 130 million debris between one centimeter and one millimeter[1]. Most of these objects are the products of fragmentation events such as internally triggered explosions and collisions between objects. While trackable debris can generally be avoided by active satellites with propulsion capabilities, at orbital speeds—on the order of kilometers per second—even a small piece of debris can be hazardous to the functioning of a satellite, and a larger, but still nontrackable object might strike with enough energy to cause a fragmentation event.

While there would be significant value in removing nontrackable debris, the challenge of detecting such objects, not to mention capturing and removing them to mitigate their danger to other users is currently beyond reach, both technically and economically. Rather, our focus here is on preventing new debris creation by removing massive derelict objects before they are involved in a collision or explosion and contributing to the further growth of the debris environment.

Prior lists of the most dangerous objects are reconsidered in light of newly available data from LeoLabs. This new study evaluates risk as the combination of collision likelihood, based on actual conjunction events, with collision consequence, as represented by the total mass involved. The concept of pressure is then introduced to evaluate the benefit of removal, and an example scenario is presented.

We then explore some key obstacles to implementing an ADR program, review the sources of the most dangerous objects, especially in recent decades, and filter potential ADR client object lists based on a selection of criteria.. Strategies to minimize the cost of conducting an ADR campaign are presented, and an approach is proposed for crafting a program that optimizes the overall cost-benefit proposition of an ADR campaign.

2. DANGEROUS OBJECTS IN DANGEROUS ORBITS

As a means to foster and prioritize debris remediation efforts, a number of lists of most-concerning objects have been established [1] [2]. In the last few years, two lists of the 50 most-concerning objects—McKnight+2021 [3] and McKnight+2022 [4]—have been published. The McKnight+2021 list was the result of the aggregation of 11 different approaches into one consolidated list. The first 20 objects on this list were SL-16 rocket bodies (nine-ton upper stages from Zenit-2 launch vehicles) that were launched between 1985 and 2007. These objects headed the list largely because they are some of the most massive objects in LEO and are at a very cluttered altitude. Hence, the list highlighted objects with a high debris-generating capacity that also have a relatively high probability of colliding with other massive derelicts.

The follow-on study, McKnight+2022, presented a list based on empirical observations from a year's worth of conjunctions monitored by LeoLabs. This updated top-50 list still included all the SL-16 rocket bodies, but they were no longer at the top of the list. Many of the highest-ranked objects were elevated in the list by a few, very close conjunctions that had an outsized influence on their collision probabilities.

LeoLabs now provides a further update to this assessment. For each object in the LEO catalogue, the number of conjunctions is plotted against its debris-generating risk, which is calculated as the summation of the probability of collision (PC) times mass involved for all conjunctions involving the object over a 19-month period, from January 1, 2022, through July 31, 2023. Fig. 1 depicts the results of this assessment for all cataloged objects above 600 km altitude.

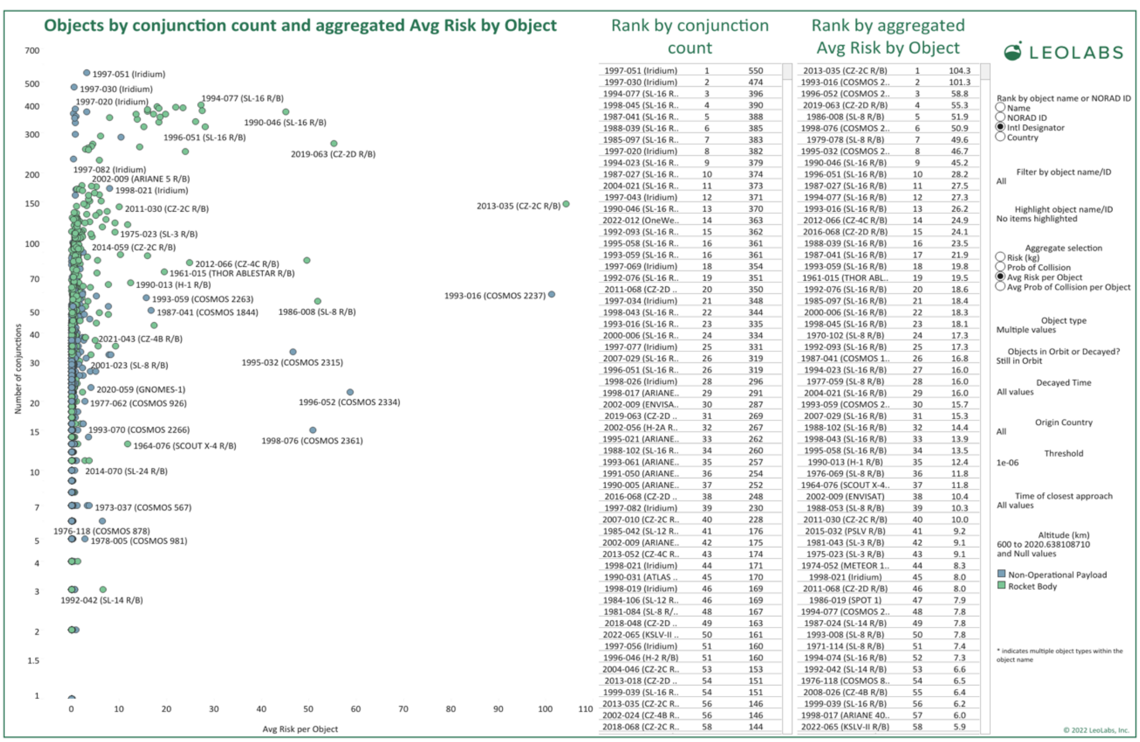

Fig. 1 — Space objects ranked by aggregate average risk

With this approach, the highest ranked SL-16 rocket body is only #9 on the list. This refinement highlights the importance of using large data sets (i.e., over 800,000 conjunctions with a PC > 10^{-6}) and provides a more accurate estimation of debris-generating risk.

While most lists prioritize ADR client selection solely on the object's characteristics, the stochastic nature of collision events suggests that it is just as important to "reduce the debris-generating risk pressure" as it is to remove the "statistically-most-concerning" objects. [5] The range of actual high-PC encounters varies drastically from object to object over time, so the first collision event to occur among the hundreds of massive derelicts may not include the top-ranked candidate for removal.[1] Therefore, we believe that it is important to start reducing the general debris-generating potential for the "bad neighborhoods" (i.e., around 840 km, 975 km, and 1,500 km) with the relative risk ranking of individual objects taken into account as a secondary factor.

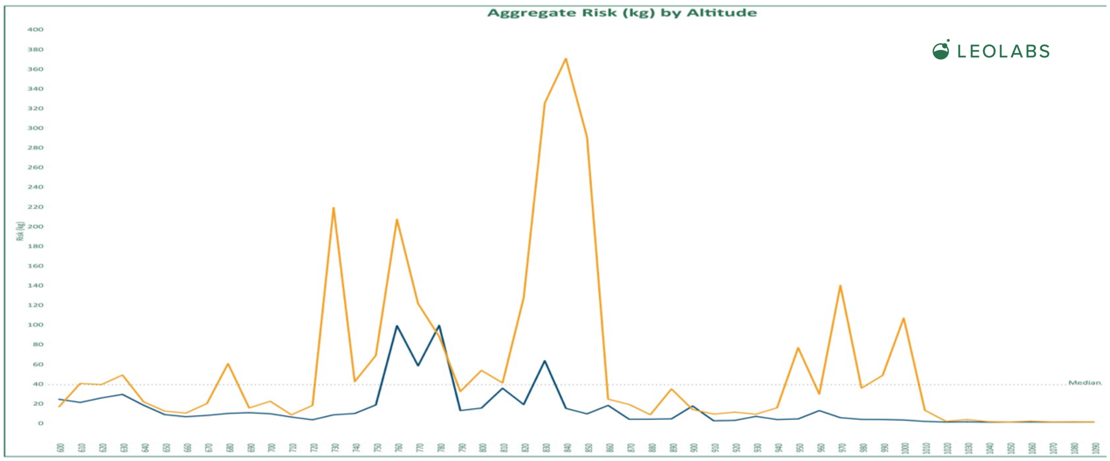

Fig. 2— Aggregate risk or "pressure" by altitude

Fig. 2 shows the baseline pressure for 10-km altitude bands in LEO, zoomed into the 600-1100 km altitude range for the sake of clarity. The gold line shows the risk pressure from debris-on-debris encounters, while the blue line shows the pressure generated by active payloads. The median risk for the range is denoted by the horizontal line. The vertical axis thus provides a gauge of the risk pressure at each altitude.

This pressure metric then provides a tool for evaluating the overall environmental benefits of debris remediation. By removing specific debris objects from the dataset and re-running the conjunction analysis, a new pressure profile can be computed, with its reduction representing the improvement expected from the proposed ADR campaign.

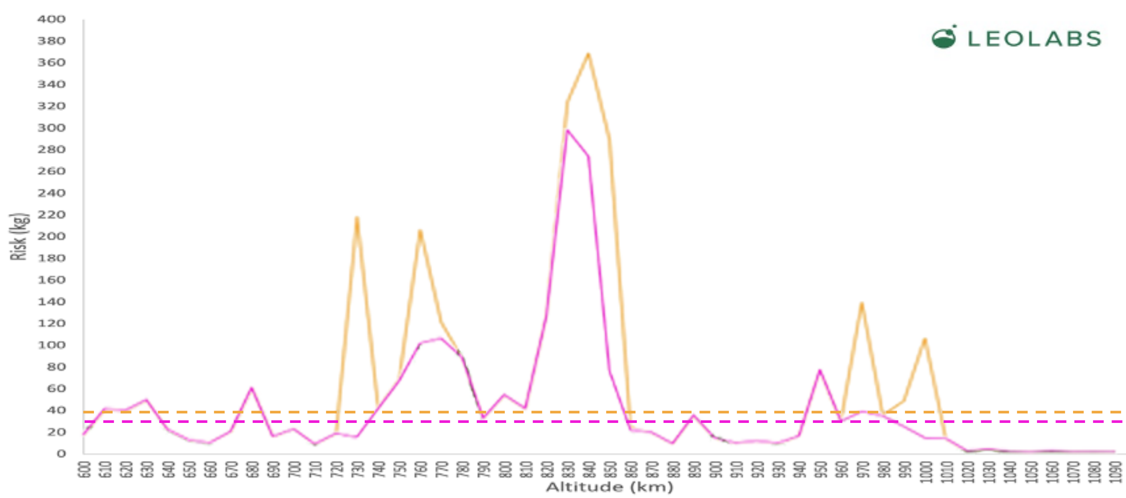

Fig. 3 — Aggregate risk pressure by altitude before (gold) and after (pink) removal of 10 debris objects

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[1] In shorthand, one can say that "the most likely events to occur is likely not the next event to occur."

This is illustrated with a simple scenario in which the top 10 statistically-most-concerning objects identified in Fig. 1 are removed (i.e., the objects with the greatest aggregate risk per object) and the analysis re-run without them. Fig. 3 overlays the resulting pressure with the ten objects removed (the pink line) on the pressure measurements derived using the original dataset (the gold line, taken from Fig. 2). The figure also shows the median values for each dataset with the dashed horizontal lines.

Table 1 shows the reduction in aggregate risk for each of the local maxima in LEO.

Table 1 — Reduction in aggregate risk from removal of top 10 objects

	Altitude band				
	730 km	760 km	840 km	970 km	1,000 km
Before	218.3	206.3	369.9	139.2	106.1
After	13.8	100.1	272.0	37.5	12.8
Reduction	94%	51%	26%	73%	88%

Examining the change between the datasets, it can be seen that all of the local maxima were reduced but the 840 km peak was not affected as much as others; it is still the region of greatest aggregate risk. Of the top 10 objects, there were only two SL-16 rocket bodies removed, and this is the class of objects causing the spike at 840 km. It should also be noted that of the ten objects removed, six are rocket bodies and four are non-operational payloads.

Having thus established a measurement for evaluating the benefit of debris remediation, we now turn our attention to examining the pragmatic aspects of conducting such activities, and some of the associated constraints.

3. ACTIVE DEBRIS REMOVAL

Physical active debris removal (ADR), the capture and disposal of debris objects by a servicer spacecraft, is one option for debris remediation. There are other strategies to address the threat from debris, but ADR is the most technically mature approach and, unlike some other remediation proposals, provides for the permanent mitigation of debris-generation risk posed by the presence of large derelict objects. In addition to ClearSpace, there are a host of other companies that include debris removal as part of their roster of in-orbit services. ClearSpace is currently under contract with ESA to perform the first debris removal mission; Astroscale, a Japanese company, has a contract with the Japanese Aerospace Exploration Agency to inspect, and likely remove, an object from orbit; and in the United States, Starfish Space, Kall Morris, and Rogue Space are all incorporating debris removal as part of their business plans. The US Congress is currently considering a bill, the ORBITS Act, that would direct the US government to explore ADR and conduct disposal missions. Other techniques, including laser ablation [6], attachment of de-orbit systems, and just-in-time collision avoidance mechanisms, while promising, are not yet as advanced as ADR, and still face significant technical, economic, and regulatory hurdles [6].

The authors note that we do not advocate ADR as the *best* strategy for addressing the issue of space debris. By far the most cost-effective and reliable manner to address debris is to prevent its creation in the first place. We consider careful spacecraft design and testing, operational attentiveness to hazards, and reliable passivation and disposal at end-of-life to be less costly, and therefore preferred measures to mitigate the threat from debris. Nevertheless, ADR is the logical choice to explore for enhancing these other efforts, and for cases when best efforts in prevention have failed.

ADR is simple in concept, yet technically, economically, and politically challenging. A servicer spacecraft is designed with a payload that provides a capability to capture and control a client debris object. As an example, the ClearSpace-1 mission is depicted in Fig. 4.[2] After launch, the servicer maneuvers to the orbit of the intended client, conducts rendezvous and proximity operations that facilitate the inspection and characterization of the client, and then executes a final approach and capture. Once the servicer and client are conjoined, the servicer takes control of the orbit and attitude of the rigidized stack. For objects in LEO, the servicer then lowers the orbit, and the client is either released at an altitude that will decay significantly faster than before, or escorted into the atmosphere in a controlled reentry of the stack, targeting uninhabited areas on the Earth for any debris that survives reentry.

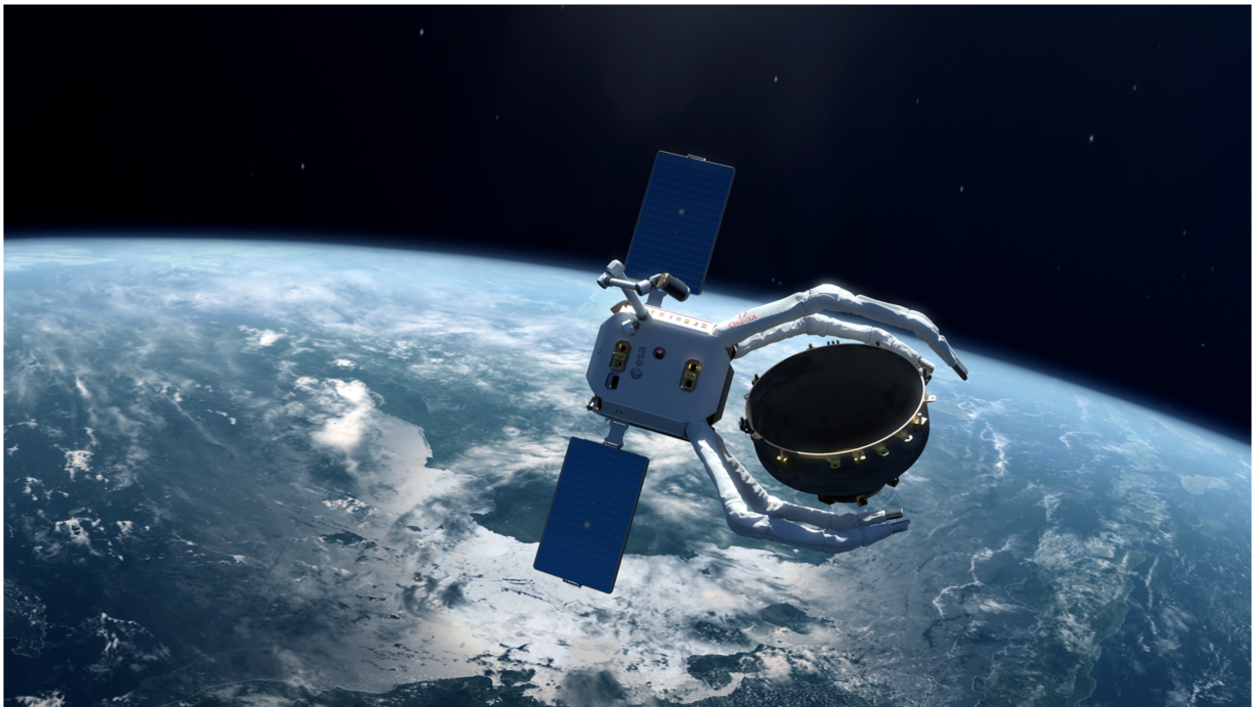

Fig. 4 — Artist's rendering of the ClearSpace-1 mission. Credit: ClearSpace

Naturally, the details of the operation are more complex, but they can largely be ignored for the purposes of this discussion. What are harder to ignore are the cost barriers to ADR, which must be balanced against the benefits to gauge the overall cost-effectiveness of any debris removal initiative. In the following section, that balance is discussed.

4. SOME PRAGMATIC ADR PROGRAM CONSTRAINTS

The benefits of debris removal are described in one sense in section 2, where we identify the most dangerous objects based on their mass and the risk pressure of the orbits they occupy. The objective of removing the most dangerous objects is to eliminate their potential to generate additional, more numerous and lethal nontrackable (LNT) objects. A collision between two large spacecraft will result in a cloud of trackable debris of hundreds or thousands of objects and an amount of nontrackable debris that is an order of magnitude higher (see for example the discussion by Murtaza, et al., of debris generated by the 2007 Chinese anti-satellite test. [7]). These objects, undetected and traveling at speeds of kilometers per second, pack enough energy to turn an operational satellite into a piece of debris without warning. Most operators, even those in crowded orbits, manage conjunctions with larger objects

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[2] The figure illustrates one example of a capture system; several are in development. This is that with which we are most familiar, and the "claw" provides a useful metaphor when contemplating ADR.

through coordinated collision avoidance measures. However, the risk from LNT debris is one that can only be managed through impact-tolerant design practices and by managing the environment itself.

As illustrated with the simple ADR campaign described above, the value of a removal program can be evaluated by evaluating the "pressure" relief it provides in the surrounding environment. However, there are pragmatic considerations that will constrain the execution of such a program, so it is useful to be able to compare different removal scenarios in designing a practical and cost-effective campaign.

One such consideration is debris ownership. A cursory review of the most dangerous objects shows that many are the responsibility of launching states[3] that have somewhat strained relations with the nations where ADR appears to be of most interest.

International agreements on outer space, unlike those that might seem analogous in the maritime domain, do not address the notion of salvage. Provisions of maritime law permit the mitigation of hazards of navigation from an abandoned or derelict vessel via salvage by a state actor or private entity. While ownership of the salvaged vessel does not change, a salvor is entitled to a reward from its owner for its salvage, with the extent of the compensation based both on the costs to the salvor and the level of the salvor's effort [8]. No explicit permission is required to salvage an abandoned vessel in international waters.

In space, as at sea, ownership remains essentially in perpetuity with the operator and/or launching state of an object but, crucially, no contact with a derelict object is permitted without prior approval of the owner. There is no case law on this topic for space assets, unlike the centuries of accumulated maritime precedents, but it may be possible for an object of unknown provenance to be disposed of without consequence to the remover, if good faith efforts were made to identify the owner in advance of the disposal.

There are reasons for the lack of a legal framework for salvage in space, not least of which is that some owners may have reason to obscure the operational status of their spacecraft or to prefer that others not approach them in fear of the information that could be gained through inspection or manipulation. The proscription of one country's retrieval of another's derelict objects, however, presents a real and formidable barrier to debris removal activities. It is likely that the nations associated with the free-market democracies will have the greatest interest in conducting ADR for the purposes of enhancing the sustainability of LEO, but the most attractive potential client objects may remain beyond their grasp without advances in international diplomacy.

A similar barrier is posed by third-party liability.[4] International liability for space objects is assigned to its launching state, which may transfer some or all to commercial operators through licensing provisions. Naturally, the liability for an ADR servicer lies with its launching state and the service provider, but there is no international agreement covering liability for the stacked objects nor for the client object after its release; it must be negotiated between the launching states of the servicer spacecraft and client object, and between the service provider and client object owner. While a successful ADR mission would reduce the overall risk of incurring any damages, and thus be advantageous to the parties responsible for the client object, organizations tend to be very conservative in their willingness to actively alter their risk profile in areas with as little case law as space debris.

[3] "Launching State" is a legal term of art that identifies states responsible for space objects according to the terms of the UN Outer Space Treaty. It is used more casually here and throughout to refer generally to the state or states assigned that responsibility for a given object.

[4] It is perhaps worth noting that ongoing discussions of liability among operators, regulators, insurers and others require significant time and effort, but that actual liability risk for an operator or licensing state for on-orbit damages (as opposed to damages on Earth or in the air) requires assignment of fault, which is a standard that appears very difficult to meet in most realistic situations.

To investigate how ownership and liability might influence debris remediation efforts, the objects with the highest debris-generating potential can be filtered by nation. Fig. 5 shows for each country the aggregate risk for all derelict objects above 600 km (based on all conjunctions between January 2022 and August 2023). Surprisingly, Chinese hardware in LEO has a dramatically higher debris-generating potential than objects owned by any other nation. Russia, France, India, and Japan each present similar average debris-generating risk, and the US, while lower in overall risk, shows up relatively high on the number of conjunctions scale . The list of countries ranked by aggregated risk of their objects starkly highlights the necessity of working across international borders and against prevailing diplomatic alignments to produce improvements in the orbital risk environment. In the meantime, however, we can apply filters and re-expand the list to evaluate the population client objects most likely available to a program led by the US and its most friendly allies. Fig. 6 shows the number of conjunctions as a function of debris-generating potential for derelicts in LEO, above 600 km, excluding Russian and Chinese objects. These represent objects that could more realistically be considered for a joint, international program.

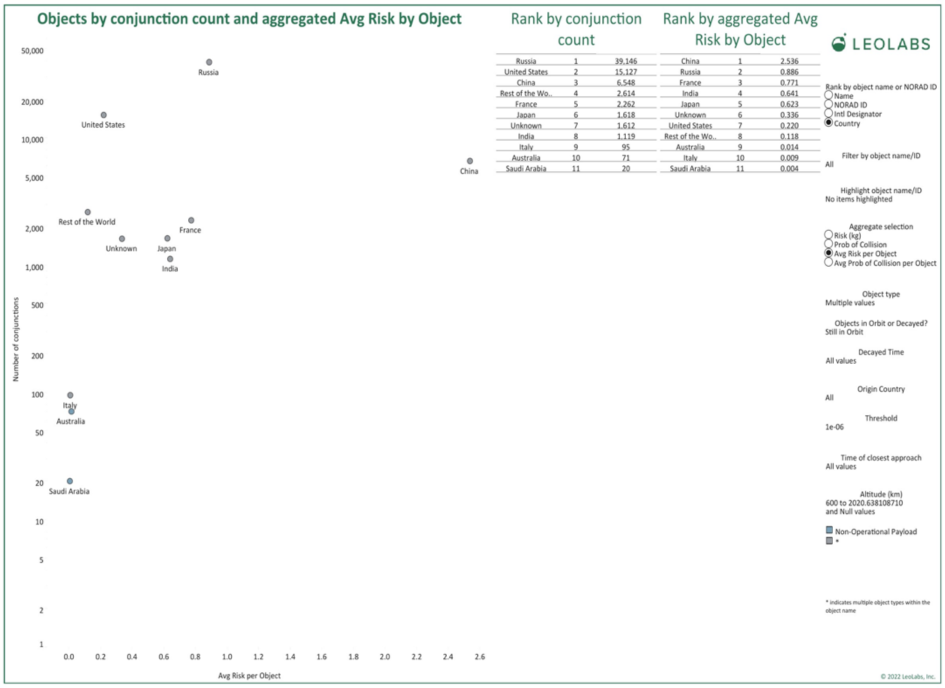

Fig. 5— Risk aggregated by launching state

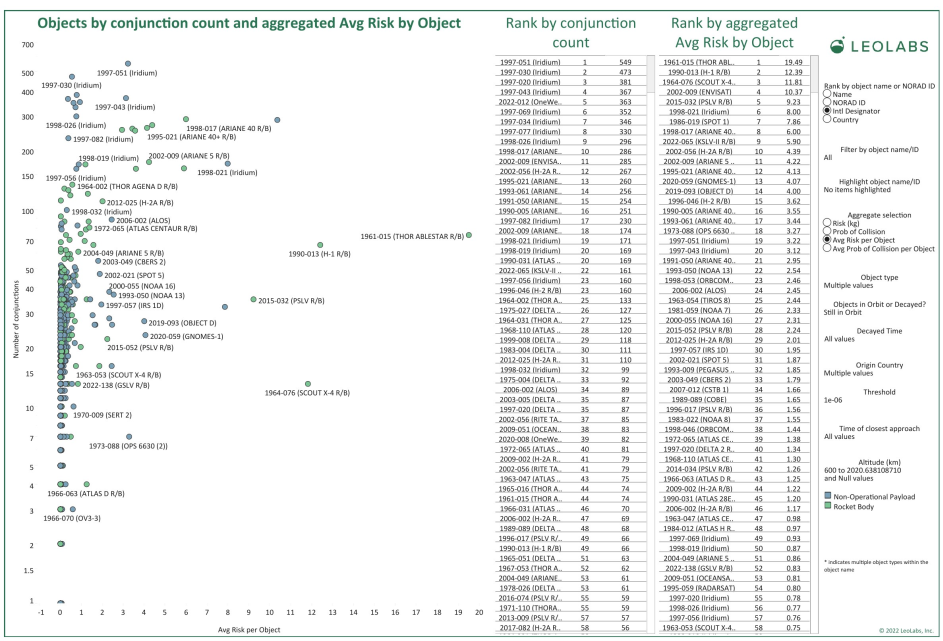

Fig. 6 — Risk of individual objects, excluding those of Russian and Chinese origin

5. THE COSTS OF ADR AND HOW TO MITIGATE THEM

On the cost side of the equation, ADR is an expensive prospect. Despite the significant reductions in cost for both building and launching spacecraft during recent years, for most operators, getting an operational satellite into orbit remains as a major, capital-intensive prospect. The larger the satellite, the more expensive; the longer the spacecraft must last, the more expensive; the more unique the satellite, the more expensive. For a servicing mission, add in the technical complexities involved in finding, identifying, approaching, and safely capturing another spacecraft, and then maintaining control of the combined stack and transferring it into the atmosphere, and the cost builds quickly. While recurring costs will come down with market adoption, bespoke missions will still require some level of non-recurring development, and the price tag for ADR services will remain high without concerted effort to drive down costs wherever possible.

At the same time, commercial operators are likely to be highly price-sensitive in their uptake of ADR and other in-orbit services. While operators of large commercial constellations such as OneWeb, Starlink, and Kuiper, for example, are highly motivated to maintain a clean operating environment, satellite communications is a highly competitive industry that requires operators to watch their financial margins closely. For these players to find significant value in outsourcing the disposal of their retired satellites, ADR service providers will have to optimize every aspect of their services.

For governments and institutions that have or are considering a commitment to mitigating debris, and who find themselves responsible for some of the most dangerous objects, the financial burden may be less of a barrier. This may translate to them becoming early adopters, but they will be just as interested in maximizing the value proposition for the services they procure.

Therefore, for ADR to become an effective part of the toolkit for maintaining a safe and sustainable orbital environment, techniques must be found to optimize the cost-benefit ratio for disposal missions. By far, the largest cost of such a mission is the development and launch of the servicer spacecraft, and as the launch industry is currently demonstrating, the biggest cost reductions are to be found in re-using one's assets, so our principal challenge is to enable an ADR servicer to perform multiple removals.

While the arms of the ClearSpace servicer illustrated in Fig. 4 can reopen to release its client to reenter the atmosphere on its own, and thereby free the servicer to perform another removal mission, there are a number of additional challenges to optimizing servicer reuse. Chief among these are meeting reentry hazard requirements while enabling the servicer to remain in orbit, and replenishing consumables.

Staying in Orbit — Today most industry standards and most regulators alike require that the probability of ground or in-air casualties from the atmospheric re-entry of an object stays below 10^{-4}. For small spacecraft, this is often achievable by designing for demise, i.e., designing the spacecraft such that little-to-no material survives reentry. The determination of ground casualty risk is normally performed by modeling the spacecraft reentry using software approved by national space agencies. Client objects that do not meet this standard are typically required to be disposed of via controlled reentry, targeting an uninhabited area on the ground for the impact of any surviving pieces. An ADR servicer delivering such a client to its demise is thought to have to escort it into the atmosphere and deorbit as well and preclude re-use.

However, it is also the position of most regulators and industry standards bodies, to the extent that they have considered the issue, to assign the same requirement for a client object of an ADR mission, regardless of the original risk from re-entry of the object, meaning that if the risk from the client object is greater than 10^{-4}, a controlled re-entry must be performed, requiring the servicer to be single-use.

Consider a notional ADR mission to remove a debris object from an orbit that will result in naturally decay in approximately 50 years. When modelled, the debris presents a ground casualty risk of 10^{-3}. A simplistic way of modeling the lifetime risk of fragmentation of a space object is:

$$R_l = R_y \cdot T$$

where R_l is lifetime risk of fragmentation, R_y is risk of fragmentation per year, and T is the number of years the object is in orbit. Presuming that the risk of fragmentation of our notional object is 10^{-3} per year, that gives R_l a value of 5%. If an ADR mission is performed to reduce the orbit life of the debris object to five years and then allow it to decay naturally from there, the lifetime risk of fragmentation is reduced to 0.5%, reducing the in-orbit hazard from the object by an order of magnitude. On the ground, assuming the Earth's population grows over the 45 years that would separate the two re-entry scenarios, the ground casualty risk not only is not higher than that presented by the debris object in its original orbit, but it is actually *lower* because there are fewer people at risk in five years than in fifty. Performing the ADR mission as describe, therefore has a significant positive safety effect in orbit, and small positive safety effect on Earth, but today it would likely not be allowed by regulators.

Despite the risk reduction offered by this operational concept, regulators may not be persuaded by the benefits of bringing forward in time the random re-entry of a large object, and other strategies may be required to enable a servicer to remain in orbit.

Controlled de-orbit normally would normally result in a final maneuver to lower the perigee of the stack's orbit to approximately 40 km, depending on the apogee, resulting in an expected dispersal of debris limited to an area approximately 3000 km across, which is the lesser, latitudinal extent of the South Pacific Ocean Unoccupied Area, at which controlled de-orbits are often targeted. For a servicer to remain in orbit after placing its cargo on such a trajectory would require extraordinary performance. With the final perigee-lowering maneuver being conducted at the orbit's apogee, it is at least theoretically possible to execute this burn, release the client, and then initiate a maneuver in the opposite direction to raise the perigee again enough for the servicer to survive in orbit and seek out its next client.

Another, more plausible option is to release the client on an "assisted re-entry" trajectory, a concept that was recently demonstrated by ESA with their Aeolus spacecraft [9]. At the end of its useful life, it was left with insufficient fuel on board to perform a controlled re-entry of itself. Thanks to careful planning and judicious conservation of fuel reserves, the operators were able to dispose of the spacecraft safely without executing a fully controlled de-orbit. To achieve this, they targeted a perigee that would assure re-entry within two orbits of the final maneuver and timed the operation such that the terminal ground track traversed minimally populated areas. This tailoring of the potential dispersion area enabled operators to keep the re-entry casualty risk below the 10^{-4} standard. It is likely that this technique can be employed by ADR missions and permit the servicer sufficient margin to remain in orbit.

Fig. 7— Artist's rendering of Aeolus prior to disposal. Credit: ESA

Replenishing consumables — The principal mission limitation for a mission offering transport services is fuel. Another key enabler to servicer re-use is the capability to refuel the spacecraft. If a servicer must carry fuel to rendezvous with several different objects and transport them to a disposal orbit, the fuel to access the balance of the remaining client objects is part of the mass that the servicer must move each time it makes an orbit change, whether alone or in a stacked configuration. If that mass can be offloaded until it is needed, maneuvering becomes nimbler and more efficient.

Consider for instance a notional set of three 5,000-kg clients orbiting at 700 km altitude. If a 2,000 kg servicer is launched to 500 km to perform assisted de-orbits of these clients without refueling, it would have to carry almost 1,800 kg of fuel to complete the removals. Each additional removal adds a mass penalty as the entire fuel mass for the program must be carried on board, including the fuel mass needed just to move the fuel. If instead the servicer is launched with a refueling depot staged at 500 km, it need only move its dry weight and approximately 800 kg of fuel before returning to replenish, permitting a fuel savings over the course of the three removals of around 30%. While this scenario does not account for the mass of the fuel tanker, the more missions that can be performed, the greater the savings in fuel mass that is available through refueling, making the use of a fuel depot more cost effective.

Pluck the low-hanging fruit — While refueling is a way to make more efficient use of fuel, the most valuable fuel is the fuel that doesn't need to be launched. Reducing the total mileage a servicer must transit, particularly when ferrying a massive client, will save fuel, time, and money. For example, at first blush, a servicer with a fixed amount of fuel can retrieve twice as many clients that reside at 600 km as it could if the same clients were at 1,200 km. Of course, the benefit of retrieving lower objects is offset to some extent by the potential benefit of removing longer-lived objects that reside in higher orbits, so this trade should be carefully considered when selecting ADR clients.

Single out one inclination — It is straightforward to raise or lower an orbit, or to alter its eccentricity, phasing, or ascending node. Comparatively, it is very resource-intensive to change the inclination of a satellite. For example, changing the inclination of a servicer from 45° to 50° requires a change of velocity, or delta-V, in excess of 30 times that required to raise the same spacecraft from a circular orbit at 500 km altitude to an orbit at 1000 km altitude. That difference in delta-V translates directly to a difference in fuel required, and therefore in mass, and therefore in cost to construct, launch, and replenish. To avoid incurring such extreme costs, multiple clients for a single servicer should whenever possible be selected from similarly inclined orbits. Indeed, depending on the amount of fuel required for desired inclination change, it might be *less* costly to build and launch a second servicer than to enable the inclination change on a single servicer.

Select clients based on structural similarity — Many of the capture systems under development are adaptable for use with a variety of client objects. Consider again the claw from Fig. 4, which is designed to capture the launch adapter pictured, but can be envisioned capturing other shapes with minimal modification, as its analog in the children's arcade game is tasked to do. However, the massive objects topping our list of dangerous objects have dramatic differences in configuration and mass properties among different classes of objects and will require different capture mechanisms, if not entirely different servicers. To enable a single servicer to perform multiple disposal missions, the clients for a given servicer should be of the same design class. The coarseness with which a class is defined will need a detailed assessment, but the overall shape and size, the client mass, and the type of capture interface required will be among the considerations. For example, rocket bodies might constitute one or two classes, perhaps depending on mass variations, and large satellites that share similar launch vehicle interface hardware that might be used for capture might be another.

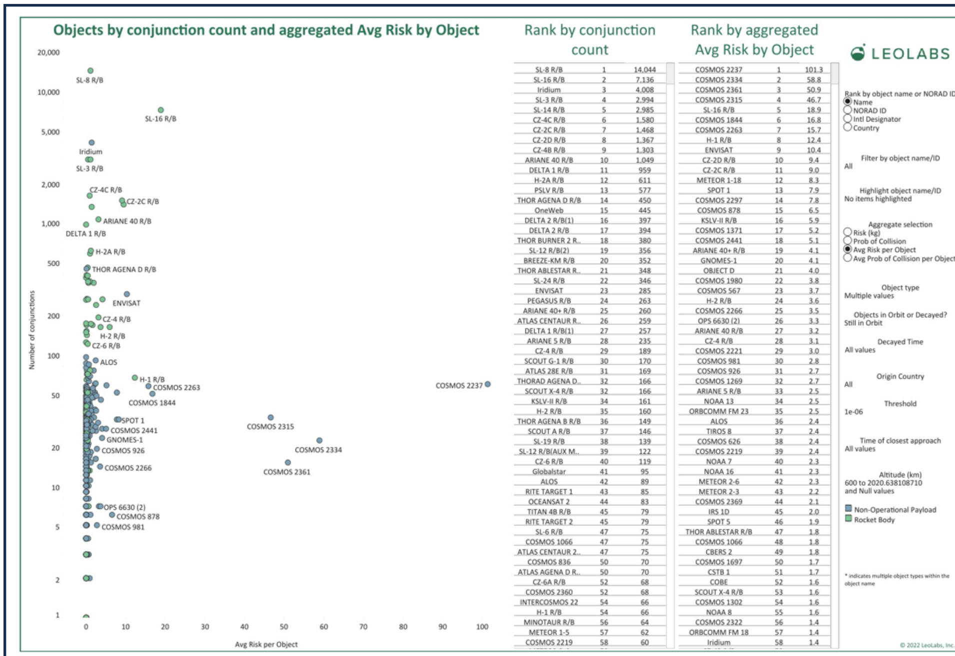

Fig. 8 — Objects grouped by type

Here again, LeoLabs' conjunction dataset can be filtered to illustrate these considerations. In Fig. 8 the average risk per object is aggregated by "families" or object types (e.g., a SL-16 rocket body, an Iridium satellite; note that for this analysis, only rocket bodies were grouped collectively, while payloads are not.) This aggregation highlights several important points. First, despite the tendency to focus attention on rocket bodies, the top four objects in the plot are non-operational payloads. Each of those four Cosmos satellites has a much greater debris generating-risk than an average SL-16 or SL-8 rocket body. Second, despite their moderate aggregate risk, the two families of SL-8 and SL-16 rocket bodies have a very large number of close encounters with other objects and a moderate aggregate risk, so should still be seen as the two richest sources of ADR client objects.

Given this set of considerations, the ideal ADR program would use a refuellable servicer capable of multiple disposals. It would pursue the removal a group of structurally similar client spacecraft in orbits that share an inclination at the lowest practicable altitudes.

6. THE COST OF REMOVING THE TOP 10 RISKIEST OBJECTS

To support a cost-benefit analysis comparing different debris remediation proposals, it is necessary to formulate a model that allows for the relative evaluation of cost. As seen above, servicer re-use is a key consideration so a simple model for the cost advantage of re-use is proposed.

The benefit of reuse is dependent on an array of variables, including the costs of servicer and launch, the amount of fuel required, the possibility for replenishment, the durability of the servicer, etc. We estimate cost reduction based on some simple assumptions in order to illustrate the relative value of reusing a servicer:

- The cost of designing, manufacturing, testing, and launching a single servicer is assigned a value of 10. It is assumed that a single servicer can complete two missions without refueling.
- The cost of a fuel depot on orbit is given a value of 7, in part because of the greater simplicity of the spacecraft and in part because of the likelihood that a depot can be launched as a secondary payload, reducing the launch cost. Each depot carries a sufficient fuel to supply the servicer for 9 missions.
- The cost of operating a single removal mission including mission planning and ground support, independent of how many missions will be performed, is assigned a value of 0.5. This includes operations for any fuel depot spacecraft, on the assumption that the marginal cost of operating a single additional satellite is very low.

With these notional cost parameters, the relative cost per removal for a variety of different scenarios is calculated, as depicted in Fig. 9, in which the maximum number of removals a servicer is capable of performing is specified by column, and the total number of removals for a program is specified by row. Thus, for example, the intersection of row 8 and column 5 reflects the per

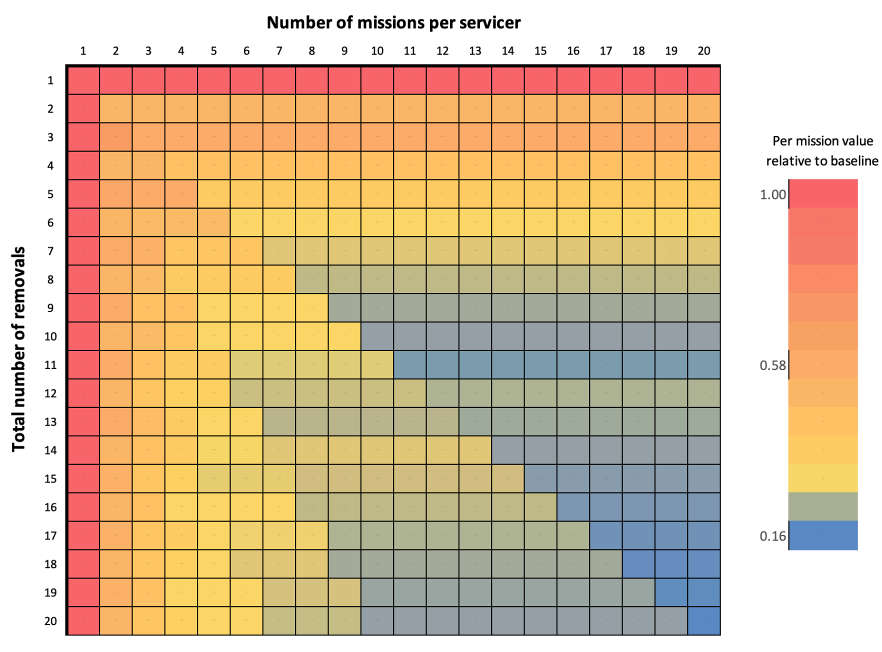

Fig. 9— The relative per-removal cost enabled by servicer re-use

mission cost of removing a total of 8 objects with servicers capable of each performing 5 removals apiece. Because each servicer only carries fuel for two removals, as one moves down column 5, there is an increase in cost for the 3rd removal, when the fuel depot is launched. Then there is another increase at row 6 when the re-use capability of the first servicer is exhausted and a second server is launched. In an actual mission plan, these discontinuities would almost certainly be addressed by either increasing the fuel mass on board the servicers to allow for optimized use of on-board resources, or by amortizing the cost of the fuel depot across multiple programs that could share the depot.

Despite such anomalies, the figure serves to demonstrate the reduction in the relative cost per removal as the reusability of the servicer increases. Based on this very simple model, the per mission cost can be reduced by two-thirds by using a single servicer for five missions, and by nearly four-fifths by using one servicer for eight removals.

We now return to the scenario depicted in section 2, wherein the top 10 objects with the greatest potential for debris creation were removed from the conjunction dataset to evaluate the reduction in risk pressure across LEO. Having established the benefit of such a removal, we look at the costs in light of the discussion on the optimizations for, and constraints on, ADR. As a baseline, we consider the case in which each removal requires a single-use servicer. The 10 items selected for removal are identified in Table 2.

Table 2 — The ten statistically-most-concerning objects

Rank	International designator	Object name	Class	Apogee altitude (km)	Inclination (deg)
1	2013-035B	CZ-2C R/B	Rocket body	745	98.44
2	1993-016A	COSMOS 2237	Payload	856	70.82
3	1996-052A	COSMOS 2334	Payload	1008	82.93
4	2019-063B	CZ-2D R/B	Rocket body	765	98.2
5	1986-008B	SL-8 R/B	Rocket body	997	82.95
6	1998-076A	COSMOS 2361	Payload	1013	82.93
7	1979-078B	SL-8 R/B	Rocket body	779	74.04
8	1995-032A	COSMOS 2315	Payload	1012	82.9
9	1990-046B	SL-16 R/B	Rocket body	855	71
10	1996-051B	SL-16 R/B	Rocket body	860	70.83

Inspection of this table reveals that this set of 10 client objects would likely be significantly modified by the application of the cost-reduction strategies outlined. These objects likely occupy at least three different classes of object: the SL-16 rocket bodies are significantly more massive than the SL-8 and Chinese-origin rocket bodies, likely therefore requiring a different class of servicer. The COSMOS payloads would require a third class of servicer.

Meanwhile, if a notional span of 0.25° of inclination is considered feasible for access by a single servicer, the ten objects would occupy four inclination cohorts, thus requiring at least four servicers. However, when the class of objects is considered as well, it is apparent that two of those inclination cohorts include a mix of two classes, meaning that each of those would require at least two servicers, for a total of six.

To address this scenario, however, the removal of the 10 statistically-most-concerning objects, we can only apply our optimizations to the client set, rather than selecting a client set to optimize cost. Thus, the following deployments are considered:

- one servicer to remove one small rocket body at 74.04°;

- one servicer to remove two small rocket bodies near 98.3°;
- one servicer to remove two large rocket bodies and one servicer to remove a payload near 71°; and
- one servicer to remove three payloads and one servicer to remove a small rocket body near 82.9°.

If we assume that the cost of the ADR program (C_{prog}) is the sum of the cost of the servicers, fuel depot spacecraft and operational costs of the servicers, then we can compare optimizations against the baseline. Given that the cost of a single removal by a single-use servicer (C_1) is indexed at 1 in the model discussed above, the per removal cost using a re-usable servicer disposing of two objects (C_2) is evaluated at 0.52, and a servicer disposing of three objects (C_3) is 0.59[5], we can see that using optimization techniques we can reduce the cost of the overall program of 10 removals by nearly one-third:

$$C_{baseline} = 10 \bullet C_1 = 10, \text{ and}$$

$$C_{prog} = 3 \bullet C_1 + 4 \bullet C_2 + 3 \bullet C_3 = 6.85.$$

Thirty percent is a significant reduction in costs. However, it is still about than three and one-quarter times the estimated cost of using a single servicer to remove ten objects:

$$C_{10} \text{ is } 0.21, \text{ giving } 10 \bullet C_{10} = 2.1.$$

Based on the constraints noted in sections 4 and 5, it is clear that a single servicer could not feasibly be used for this set of ten objects. However, it should be noted that in earlier forms of the top 50 statistically-most-concerning objects, the top 10 objects were indeed all SL-16 rocket bodies at an inclination of 71°; removal of that set of objects could potentially be conducted by a single servicer and would be expected to produce a significant reduction of the ensemble risk in the 840 km altitude band, though the diplomatic barriers to operating on those objects remain.

7. CONCLUSIONS

Perhaps the most interesting information to emerge from this analysis is the effect of removing the 10 most dangerous objects from orbit. As expected, all local risk pressures were reduced, but the area of highest pressure was the least affected of the critical altitudes. This presents an avenue for reconsideration of how to gauge the benefits of debris removal: is there more value in an overall reduction of risk to the LEO environment by individual object aggregate risk, or of a greater reduction in risk in the riskiest regions even if it means less impact on the most dangerous objects in LEO?

For all the benefit that can be demonstrated by removing key objects, it is also important to recognize the benefits that may go unrealized for diplomatic reasons. Most of the derelict objects with the greatest debris-generating potential do not belong to the industrialized democracies or their closest allies, which reenforces the importance of active diplomatic efforts to engage Russia and China in constructive dialog about debris mitigation. It also suggests that additional analysis is needed to optimize the cost-benefit tradespace for realistically achievable ADR campaigns by the US and its closest allies.

The cost of ADR can be optimized through strategies that we have outlined, and some of the effects of those strategies can be observed in their application to a program to remove the 10 objects with the greatest debris-generating potential. In fact, a reduction in cost of approximately one-third can be achieved, compared to the baseline program that was envisioned using a dedicated servicer for each removal. We propose future research in the area of optimizing the cost-benefit ratio of ADR by tailoring the client list according to the described constraints and evaluating the relative benefits of different ADR program scenarios on the degree of risk reduction effected by each.

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[5] Note again that the per removal cost is higher for the three removals than for two because of oversimplifications in the model around when refueling is required. In reality it would be the same or lower, depending on the details.

We continue to believe that assessing and aggregating the threat from individual debris objects is a useful way to describe the risk environment and that assessing a risk pressure according to orbit in LEO is a helpful way to contemplate the relative dangers and provides a framework for assessing the effectiveness of debris removal. Further, improvements in the cost-effectiveness of ADR can be won by optimizing ADR programs to minimize costs according to the physical, legal, and political constraints on the client population and evaluating the relative benefits of different prospective ADR programs according to their effects on the LEO environment.

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