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Cost and risk assessment for spacecraft operation decisions caused by the space debris environment ☆

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A R T I C L E I N F O

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A B S T R A C T

Space debris is a topic of concern among many in the space community. Most forecasting analyses look centuries into the future to attempt to predict how severe debris densities and fluxes will become in orbit regimes of interest. Conversely, space operators currently do not treat space debris as a major mission hazard. This survey paper outlines the range of cost and risk evaluations a space operator must consider when determining a debris-related response. Beyond the typical direct costs of performing an avoidance maneuver, the total cost including indirect costs, political costs and space environmental costs are discussed. The weights on these costs can vary drastically across mission types and orbit regimes flown. The operator response options during a mission are grouped into four categories: no action, perform debris dodging, follow stricter mitigation, and employ ADR. Current space operations are only considering the no action and debris dodging options, but increasing debris risk will eventually force the stricter mitigation and ADR options. Debris response equilibria where debris-related risks and costs settle on a steady-state solution are hypothesized.

1. Introduction

The presence and creation of debris due to human operations in orbit is an ongoing problem. It is recognized that the continuation of current trends in launches and long orbital lifetimes of satellites will only increase the density of debris in both Low Earth Orbit (LEO) and High Earth Orbit (HEO) regimes, such as geosynchronous (GEO) [1–4]. This has led to increased use of passivation techniques to avoid on-orbit break-ups, improved spacecraft shielding against small object impacts, and the mitigation guidelines of a 25-year lifetime rule for LEO and sub- or super-synchronous graveyard orbit for GEO. Active Debris Removal (ADR) has also been suggested, and widely studied, as a possible method for reducing debris density. However, ADR techniques considered in the literature, such as robotic re-orbiting [5–8], electrodynamic tethers [9,10], laser ablation [11–14], ion shepherd methods [15–18], tethered tugging of large LEO debris [7,19–24], harpoons or nets to capture debris [7,25,26], and electrostatic tractors [27–30], are economically costly, technically challenging to develop, and often overshadowed by political hurdles [31,32]. More recently, Just-in-time Collision Avoidance (JCA) concepts are discussed where the orbit of a large debris object is nudged with an intercept mission to avoid collisions with operating assets or other debris objects [33]. Such technology could be more cost effective than ADR, but requires highly accurate debris tracking and leaves the debris in orbit.

There are many important research papers discussing the projected growth of space debris in the near Earth environment, such as the often cited studies by Liou

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0094-5765/

published in References [1] and [2]. Here, the LEO debris population greater than 10 cm in size is modeled for the next 100–200 years, showing that even with an optimistic 50% mitigation compliance rate, the LEO debris population could double over 200 years. Reference [34] shows the debris doubling over 100 years if no mitigation methods are implemented. While such figures are alarming to space debris researchers and experts who understand that these results represent mean trends, the worst-case scenarios could be much more severe. Convincing the general public, policy makers, and research funding agencies that action is required now to control this debris hazard remains a challenge. For example, operators today are able to fly satellites in their desired LEO or HEO orbits with only minimal concern regarding space debris avoidance. When asking unmanned satellite operators how often they need to make an additional maneuver to avoid debris, the common answer is that this almost never happens. If there is a warning of a possible conjunction, the uncertainty of the miss distance is often so large that the warning is ignored, or the conjunction is accounted for in regular orbit maintenance maneuvers, thus not expending additional fuel. Therefore, considering that space debris strikes have had a minimal documented impact on current satellite operations, doubling or tripling debris-related risk – especially 100–200 years in the future – is unlikely to convince policy makers or operators to demand strong space debris mitigation and remediation policies over the next decade. There are significant on-going efforts to better attribute many anomalies and failures of unknown cause to their trigger.[1] some of these anomalies may have been caused by non-trackable debris, the true current space debris threat has not yet been captured or communicated.

Reference [35] discusses the need to consider near-term ADR (remediation) developments and stronger end-of-life disposal guidelines (mitigation). The complexity of considering LEO space debris risks is shown by how the fragment sizes and orbit types impact the risk to the space operator. Vance proposes in Reference [36] an economic metric by which competing debris removal methods are evaluated for the highly populated sun-synchronous orbit regime. However, this orbit-specific analysis only considers cost due to the economic value of the satellite, and the environmental cost if the satellite experiences a fragmentation collision. Risk costs of the de-orbit maneuver, costs incurred by precision tracking of the debris to be removed, and political cost considerations are not included.

Thus, this paper investigates a means to bridge the divide between space debris researchers that support near-term action (begin ADR within a decade) to control the space debris population, and most space operators that are successfully operating satellites without demanding stronger mitigation and remediation methods. In particular, this study highlights the complex decision logic that space operators face when considering the total space debris-related cost. The available debris response options during a mission are classified under one of the following categories:

1. Make no mission changes in response to space debris.
2. Respond to conjunction warnings by dodging close-approach debris or using JCA.
3. Follow current or more stringent end-of-mission *mitigation* guidelines.
4. Begin active debris removal or *remediation* in the orbit regime of interest.

Currently only elements of options 1 or 2 are employed in the operator community. Implementing shorter post-mission orbital lifetimes (element of option 3) can have a significant impact on the commercial viability of launch operation if it is not uniformly adopted. Elements of option 4 are discussed and researched, but economically viable and proven solutions are at least a decade away from being flight ready. The natural question arises: At what point is the total space-debris-related cost large enough to warrant options 3 or 4? This paper considers a high-level decision logic from an operator's point of view on how to respond to a space debris threat including not only direct mission-related financial considerations, but also indirect costs such as tracking or debris avoidance analysis, environmental and political considerations. While earlier studies focus on the overall space debris growth, the impact to the individual space operator can vary by orders of magnitude depending on where the satellite is flown, the mission duration, and the mission objectives (e.g., high-value commercial communication satellite versus low-cost CubeSat technology demonstration).

The paper outline is as follows. First, the present-day status of the LEO and GEO debris environment is reviewed. Next, the overall space debris costs and associated response decision factors are discussed, illustrating how these can vary drastically across mission types. A mission scenario case study illustrates how different mission types are impacted very differently by space debris, leading to the current range of operator responses to debris-related risk. This is important when trying to bridge the divide between space debris researchers and operators/policy makers. A fundamental question is asking whether common mitigation guidelines for all LEO operators make sense. Another important aspect to consider is what happens if stronger mitigation or ADR measures are implemented. In particular, would these ADR efforts continue indefinitely, or could the debris control methods stabilize to new operational equilibriums? Finally, the possible operator responses and costs to the debris threat are reviewed and discussed.

2. Present day space debris congestion

LEO is the most studied orbit regime for orbital debris – this is because it is the most densely populated regime (using spherical shell densities), as illustrated in Fig. 1, and many commercial, government, and military satellites are in this regime. GEO has the next largest spherical density, while Oltrogge states that its volume density can be as critical as

[1] http://www.integrity-apps.com/events/scaf/.

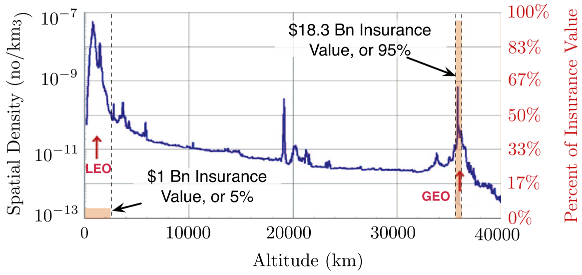

Fig. 1. Density of debris population from LEO to GEO regimes, reproduced from Reference [37], compared to insurance values provided in Reference [38].

LEO [39]. GEO is critically important for commerce and Earth observing, with pivotal assets existing for many organizations. This is illustrated in Fig. 1 by comparing the debris spatial densities to the orbit regime insurance values discussed by SwissRe in Reference [38].[2] 95% of insured satellites systems reside in GEO, and such costs must be considered when evaluating the economic impact if a satellite is struck by debris. Although this paper focuses on the LEO and GEO regions, the issues, risks, and costs associated with debris relate to other orbital regimes as well.

Fig. 2 illustrates the altitudes and inclinations of LEO rocket bodies and spacecraft with masses above 50 kg [34]. Note that these objects are not evenly spread out over the orbit altitudes and planes; rather, distinct banding is observed. This illustrates that the LEO risks are focused in select orbit regimes. The sun-synchronous region is illustrated as it has a very high economic value for commercial remote sensing and imaging satellites, as well for some military reconnaissance systems [38]. This region also has the highest debris collision hazard – the annual probability of collision of a 10 m^2 satellite with 1 cm debris or larger exceeds 0.8% [38].

There are several excellent studies of the LEO debris environment, many emanating from NASA's Johnson Orbital Debris Program Office and ESA's Space Debris Office [1,2,34,40–43]. Reference [44] highlights the variability in these debris forecast studies. For brevity, the following can be summarized from these studies:

1. The number of debris is increasing, and appears to have rapid growth in certain altitudes [4,41].
2. High inclination orbits are most densely populated, especially around 600–800 km and 1000–1500 km altitude [34,40].
3. Large debris objects drive growth, but smaller objects (0.5–10 cm) pose the largest hazard to active satellites because they are numerous, have significant energy, and cannot be tracked [45].

As of February 2014, the GEO regime contains approximately 1145 large-scale, unclassified, and trackable objects larger than 0.8–1.0 m in effective diameter, 760 of which are uncontrolled derelict objects that actively contribute to longitude-dependent congestion levels across the GEO ring [46,47]. In addition to this large-scale, catalogued debris population, significant populations of uncatalogued objects at sizes as small as 10–15 cm have been detected in GEO optical observation campaigns, and are hypothesized to be indicative of undetected fragmentation events in this regime [38,48,49]. Recent studies of the GEO environment illustrate that GEO debris congestion—and the resulting probability of collision—is non-uniform in longitude and time (both time of day and time of year) [50,51].

Fig. 3 depicts the number of longitude-dependent near-miss events per day within 50 km for a projected five-year forecast, assuming an idealized “no future launches” scenario. While 50 km may appear like a large distance, larger than the typical GEO orbit determination accuracy, the high value of GEO satellites has many operators studying objects at even larger distances. As shown in Fig. 3, longitude slots in the vicinity of the two gravitational wells at 75E and 105W are subject to upwards of 5–6 close calls per day with uncontrolled debris objects, in contrast to the longitude slots over the Atlantic and Pacific Oceans, which experience a maximum of only 1–2 close calls per day at this miss distance. Longitude-dependent debris congestion patterns, and alternative debris flux descriptions that provide higher spatial and temporal resolutions [51], are central to mission assurance and space situational awareness activities in the GEO ring, and have critical implications for both the direct and indirect costs incurred by operating a satellite in the GEO debris environment.

An open question regarding space debris is, what is a sustainable debris environment [52]? The studies to date consider the effort required to keep the debris at current levels. This is true for both pre- and post-2009 studies. The acceptable debris environment simply shifted after 2009. However, is the current space debris level required for sustainable space operations? Could the debris grow 50%, or double, while still keeping space operations economically viable? This important question is not addressed in this paper, but must be considered when doing a cost/benefit analysis of debris mitigation and remediations efforts.

3. Debris considerations for operators

3.1. Operator debris response considerations

Fig. 4 outlines the high-level weighted cost considerations that a satellite operator must consider to determine how to respond to the orbital debris environment threat. In this discussion, the term “cost” does not relate to monetary objects exclusively, but can relate to political implications and mission risks, as well. Thus, the cost structure shown in Fig. 4 provides a total debris-related cost function that considers a heterogenous set of “debris costs”, each weighted considering the associated orbit regime and satellite type. The mission-related responses (right side) are grouped into four categories. The first two are short-term reactive responses to an immediate debris threat during a mission and include: (1) no action is made during a mission in response to debris, and (2) a trackable debris threat is reduced through a maneuver. The next two

[2] The Technical Report is available at http://media.swissre.com/documents/Publ11_Space+debris.pdf.

are proactive, long-term responses that seek to avoid the possible creation of future debris including: (3) a following of stricter mitigation guidelines, and (4) using ADR to reduce the long-term debris in an orbit regime of interest.

The multitude of debris-related costs a space operator must consider are discussed in detail throughout the remainder of this Section. Interestingly, the answers to the questions in Fig. 4 can vary strongly from one operator to another as illustrated in Table 1. The table columns indicate the following considerations:

Thrusting: Considers the cost of having to implement thrusting. This would have a strong weight on small satellites that typically don't have thrusting, or very little fuel. On most other bodies this weight is low as these satellites already have thrusting capabilities. De-orbiting rocket bodies after they deliver their payload would require a lot of fuel, thus the strong weight.

Downtime: Considers the impact if mission operations have to be suspended to address debris issues. This has a strong weight for commercial or military satellites.

Insurance: Space insurance costs are heavily weighted towards commercial GEO satellites. Small satellite operators don't often purchase insurance. While the US government satellites don't typically carry insurance, some other countries' governments do purchase satellite insurance.

Mitigation: Considers the costs to implement current mitigation guidelines. This is a large challenge for CubeSats and small satellites, and limits them often to lower altitudes. For commercial launch providers, the cost of de-orbiting their spent rocket bodies has a significant impact on their competitiveness.

Debris tracking: This is mostly covered by the US Air Force, but other countries are starting to develop their own space situational awareness programs [53].

Debris analysis: Considers the labor time and costs of analyzing possible debris threats.

Risk of de-orbit: Considers the risk of debris causing damage on Earth. This is negligible for small satellites, strong for LEO satellites, and has no weight on GEO satellites.

Reputation Loss: Considers the political and professional impact if the operator's satellite causes damage to another satellite.

Space environment: Considers the risk either operating in a high-density debris environment, or the risk to other operators if the operator's satellite causes a large debris field.

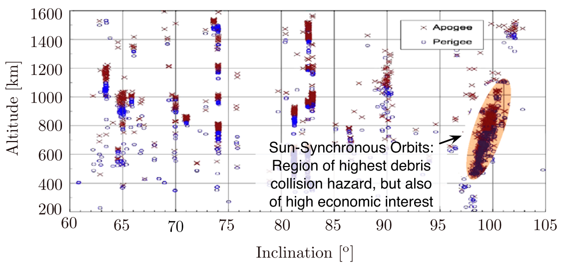

Fig. 2. Illustration of the LEO debris hazard [34] and regions of high economic interest.

Currently the practice is to either not consider space debris, or account for possible conjunction events in their regular orbit correction maneuver planning, as illustrated in Fig. 5. Prior to the Iridium/Cosmos collision in 2009, the response was mostly to do nothing. Even now, the spacecraft operators and insurance industry do not appear overly concerned with addressing space debris. Malfunctions known to be related to debris are currently still rare [54]. In contrast, space debris research is strongly arguing for increased space debris mitigation or remediation. Operators of low-risk assets with short mission lifetimes are less concerned with debris and therefore typically choose the no action response. As total debris hazard related risk increases, it is necessary to maneuver through the debris field, or increase the spacecraft shielding, increasing all related costs and risks. These approaches are *reactive* since operators are only responding to the current debris environment. As the debris-related risks rise to a critical level, likely driven by major catastrophic events such as collisions, the total costs will justify pursing stricter mitigation than the current IADC standards. If the environment becomes significantly more hostile to space operators, ADR may be required, thereby increasing the costs to remediate the debris environment considerably. These latter two approaches actively attempt to alter the environment, providing a *proactive* approach to risk reduction.

Current technology status makes mitigation costly and remediation all but unaffordable – this leads to a strong

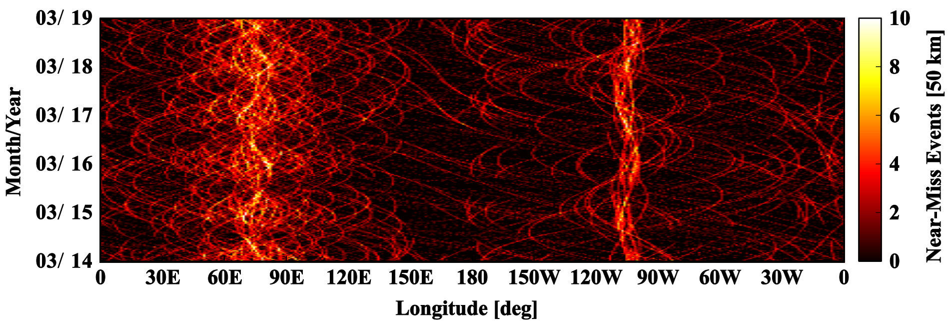

Fig. 3. Forecasted longitude-dependent debris congestion in GEO regime.

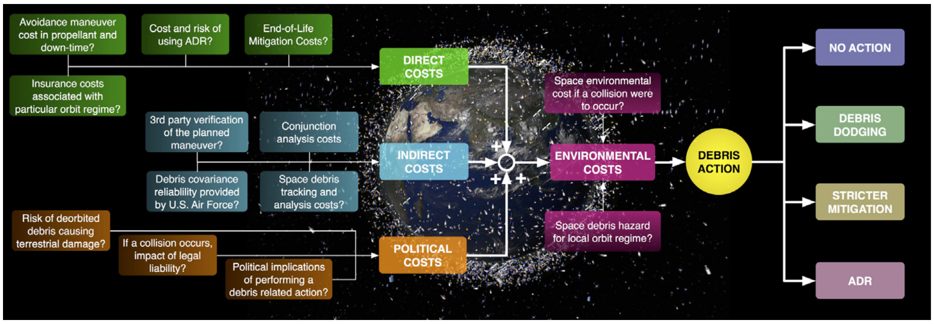

Fig. 4. Illustration of the cost considerations leading to a space debris response decision.

Table 1
Representative weighting for various debris hazard impacts on mission types using the coloring. [red] – strong, [medium red] – medium, [light pink] – low and [white] – no weight

	Direct Costs				Indirect Costs		Political Costs		Space Env. Costs
	Thrusting	Down time	Insurance	Mitigation	Debris Tracking	Debris Analysis	Risk of De-orbit	Reputation Loss	
CubeSat	strong	low	no	strong	no	no	low	medium	low
SmallSat	strong	medium	no	strong	no	low	medium	medium	low
LEO COMM/Science	low	medium	low	medium	no	low	strong	medium	medium
Commercial Sat	low	strong	low	medium	no	low	strong	medium	medium
A-Train Science	low	medium	medium	medium	no	low	strong	strong	strong
Rocket Bodies	strong	no	low	strong	no	no	strong	low	strong
Military LEO	low	strong	low	low	strong	medium	strong	strong	medium
GNSS	low	strong	low	low	no	low	no	low	low
Military GEO	low	strong	low	medium	strong	medium	no	strong	strong
GEO COMM/Science	low	strong	strong	medium	no	low	no	strong	strong

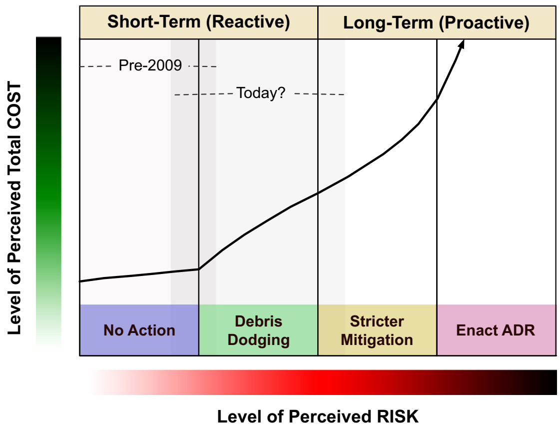

Fig. 5. Trend showing that as perceived debris-related risk increases, so does associated operator costs.

uncertainty in this debris response cost function. As outlined by McKnight in Reference [35], such advanced technology development can take many years, even a decade. Further, the funds required to achieve the technology readiness level for ADR increase dramatically as the development time is decreased. Thus, there is a large risk associated with waiting until the daily operator costs associated with space debris are large, and then seeking a mitigation/remediation solution over a short period of time. Seeking ADR technologies that have a broader impact will facilitate their development, and spread out the costs over a range of mission operations such as orbital servicing, or autonomous refueling. The current space debris mitigation requirements are a step in the right direction, but do they go far enough? Instead of worrying about active removal, or increased costs of tracking an ever-growing debris population, what are the costs associated with requiring a greatly reduced post-mission satellite disposal time (e.g., proposing a 10-year reentry rule for certain LEO satellites, instead of the current general 25-year standard)?

3.2. *Direct costs*

There are a multitude of direct costs associated with operating in the debris environment around Earth. A *direct* cost is considered a cost associated with a particular launch, satellite, or operation of a specific satellite. These values can change dramatically across ranges of mission types.

While the “no action” during a mission approach costs nothing for operators, there are often related direct costs with increased satellite shielding. Such protection provides the operator with a risk reduction relative to the lethal, yet Non-Trackable (LNT) debris objects. Many of the larger, more capable satellites consider maneuvers or “dodging” debris. A strong concern with performing debris avoidance maneuvers is the fuel costs and the possible satellite down-time, reducing science return and revenue. The satellite down-time can be a stronger cost to commercial operators than the fuel usage. For smaller science satellites that only have a small amount of fuel aboard, it can be more costly to consume fuel, resulting in significantly shorter mission lifetime as illustrated in Table 1.

Orbital debris has built up over the years because it is less costly to abandon the spacecraft than choosing "mitigation" or post mission disposals. It is *directly* expensive to operators and launchers to perform mitigation operations. Even for government payloads, contracts are often awarded based upon lowest price, thus it is more competitive to not have mitigation costs. In a study by Adilov et al. [55] they demonstrate that choosing to create debris leads to less overall direct cost to operators, and higher profits. They further point out that, for commercial applications, it is more competitive to have more operational assets than necessary. This means that it is, again, more profitable to create debris. If an asset is lost, it will be replaced adding further mass and objects in orbit, increasing debris growth. While this description is based upon a simple economic model, this is supported by actual practices of companies that have reduced mitigation practices due to their expense [56].

Spacecraft insurance is another direct cost to be considered. First-party policies insure against the failure of the asset, while third-party policies covers satellite owners for suits that may be filed by third parties in the event that their satellite hits another satellite and damages that other satellite.[3] While many of the smaller satellite operators don't carry insurance, the larger commercial, and some non-US government satellites, do carry first party insurance with a world wide combined insurance premium cost of about $800 million per year. Third-party insurance is still rarer, only larger commercial satellites in LEO and GEO carry it, with the world-wide insurance premiums summing to about $20 million per year (see footnote 1).

However, though space debris rarely factors into the current insurance cost premiums, insurance companies are beginning to consider debris [38,57]. The worst LEO debris-related mission risk is about 0.8% [38], while the total on-orbit failure risk is about 1.5%. Rocket bodies, after having delivered their payload to orbit, may still be covered by third party insurance for 30 days to one year. Thus, rocket body operators debris cost concerns don't end with the mission termination. For third-party spacecraft insurance the premium would be lower if there is a way to avoid a collision as the insurance risk is dominated by collision concerns. With first-party insurance the concerns are dominated by mechanical breakdown issues with the satellite itself, rather than with debris-related collisions. The incremental risk is small enough to be ignored for now (see footnote 1). However, this could rapidly change if there is a catastrophic collision of a large, insured satellite. Thierry Colliot is quoted as saying "You can potentially lose the premium of a whole year in one single event" [58]. With the increased liability of the launch vehicles, satellite insurance rates have been dropping, leaving very thin margins and higher risk if a failure would occur.[4] The insurance costs illustrate how the space debris costs are driven by outlier event.

3.3. Indirect costs

An *indirect* cost is one that occurs due to generally having debris in orbit, but is not unique to the particular mission. Examples include the cost of tracking debris, or staffing for debris-related analysis. Unfortunately, the natural progress towards creating more orbital debris distributes *indirect* costs to all entities that utilize satellites. Perhaps one of the largest costs, that has yet to be well understood, is the cost to the US Air Force (USAF). While the USAF tracks all visible objects in orbit for its own Space Situational Awareness (SSA) defense reasons, the creation of debris further stresses this organization. This affects operators because the USAF freely provides tracking, conjunction, and some Collision Avoidance (COLA) analysis for most satellite operators today [59]. With the Iridium–Cosmos collision, the collaboration between the USAF and operators around the world has increased. Still, the USAF is not obligated to provide information to operators and these indirect costs get distributed to US citizens. The community is currently dependent upon US government cooperation. Implementation of more precise and smaller debris tracking is a costly undertaking. Several nations are investigating improving their own space situational awareness capabilities [53]. The US government accountability office May 2011 report [60] outlines the significant fiscal and managerial challenges of expanding the SSA capabilities. Space debris growth is mentioned as one of the drivers for needing improved SSA. The US SSA-related investments over 2006–2015 sum up to about 5.3 billion US dollars. This does not include the costs of operating the existing SSA programs and facilities. However, factoring out the specific debris-related cost components is very challenging as many of these SSA systems have non-debris-related functions as well.

The analysis of a conjunction, often automated, and maneuver planning can be considered indirect costs to the mission operator [61]. Conversations with DigitalGlobe indicate that the cost of monitoring JSpOC warnings, analyzing them, and occasionally planning COLA maneuvers (less than 10 per year), is about 15% of the cost of one full time engineer. The creation of the automated analysis system costs more, but it was a one-time cost for the company. Further, COLA maneuvers do not reduce lifetime of the spacecraft at this point because they can be built into the normal station keeping maneuvers. Assuming DigitalGlobe is similar to many other LEO operators, it is a tangible, but minimal, indirect cost to operate in the current debris environment. This is the major reason why there are strongly conflicting responses to the current debris environment between operators (little to no response) and the space debris research community.

3.4. Political costs

There are five United Nations treaties on outer space. For example, the 1972 Liability Convention[5] specifies that

[3] Information obtained in conversation with Chris Kunstadter.

[4] http://tinyurl.com/pmr53n9.

[5] http://www.unoosa.org/oosa/SpaceLaw/liability.html

nations are internationally responsible for in-space or on-Earth damage caused by their space objects [62]. The 1975 Registration Convention[6] declares that states will register and report the launch of space assets. Art. VIII of the 1967 Outer Space Treaty[7] provides that States keep under their jurisdiction the space objects that they have registered.

Unfortunately, there is no clear legal obligation for various states to exchange information to avoid collisions. Thus, except for specific bi-lateral agreements, the US Air Force can stop its dissemination of information at any time. Articles II, III and IV of the 1972 UN Liability Convention define several forms of space debris related liability: absolute (objective + unlimited) liability for the damage caused by a space object on the ground, fault liability for the damage caused by a space object to another space object or to a human being in outer space, and joint liability for damage caused by space debris resulting from a first collision with another space object. While there is a framework to hold state or entity accountable for accidental/purposeful creation of debris and damages to assets (on Earth or in orbit), the enforcement of such liability remains a considerable challenge [59].

Nations and companies attempting to adhere to the IADC's 25-year de-orbit guideline for LEO encounter liability concerns stemming from the 1972 Liability Convention, because this guideline promotes uncontrolled re-entry, and as a consequence, potential terrestrial damage. Article II of the 1972 Liability Convention affirms that "a launching State shall be absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft in flight." Thus, although the 25-year de-orbit guideline reduces the potential for on-orbit collisions with other space objects, this guideline does not reduce the collateral possibility of on-ground damage incurred during re-entry, for which operators may be held liable per the 1972 Liability Convention. Several large defunct satellites in sun-synchronous orbits have decay times that are much larger than 25 years. For the operator this means the ground damage liability concern has been moved many decades away. The immediate cost and risk to the operator appear to have been reduced, but only if ignoring the growing risk of these large debris objects colliding with other space objects [63]. Fig. 6 demonstrates the number of cataloged object re-entrees throughout the history of space operations. This will likely increase with greater adherence to the IADC guidelines.

Further, previous debris-related events have shown that most of the political embarrassment from causing damage is minimal. One example, the re-entry of COSMOS 954 in 1978, scattered radioactive debris over about an 800 km Section of Northern Canada due to a malfunction in the boost system for its nuclear reactor. The cost of clean-up was around $14 million, and the Soviet government only paid $3 million of that [65]. While it was evident that the debris was from the USSR, their payment and liability was minimal. However, if the operator is trying to deorbit their satellite, care must be taken to avoid the debris hitting populated areas, or causing general damage. Some countries, such as France, are enacting

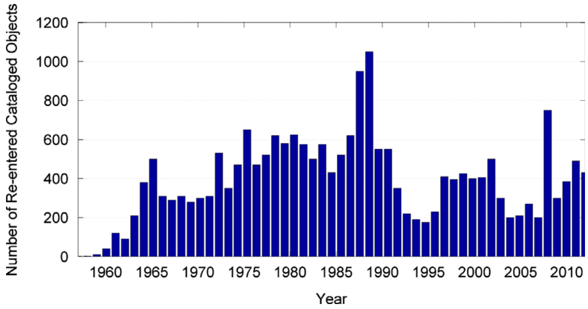

Fig. 6. Cataloged objects that have re-entered, replicated from Reference [64].

strict liability if debris causes terrestrial damage after any attempt of debris mediation or remediation.[8] While to date the direct human harm due to re-entering space debris is virtually zero [66],[9] if falling debris causes a death, it may significantly alter the discussion about liability, especially in the effected country. As a result, operators must consider the risk and political cost of deorbiting an object and the risk of doing terrestrial damage, versus the risk of leaving the object in space for many decades. Reference [67] discusses how the current guidelines, stating an acceptable casualty limit for random reentry of $E_c = 10^{-4}$, is actually hindering development of space debris solutions. While many of the large LEO debris objects already exceed this casualty risk mark, developing ADR strategies that can guarantee this guideline after an active mitigation or remediation maneuver will significantly drive up the debris removal technology costs. Thus, if this guideline prevents cost-effective debris removal technologies to be developed, it will lead to a higher casualty risk as the existing large LEO objects will reenter, uncontrolled, in a few decades. Reference [67] proposes a relaxed "interim provision" guideline that allows for the first generations of space debris removal technologies to be tested.

Another example is the Chinese 2007 anti-satellite (ASAT) test which was the most catastrophic fragmentation event recorded. Statements were made by several space faring nations[10] that expressed the concern for such actions. This ASAT test was performed at a higher altitude where the debris will remain for decades. The US conducted an ASAT operation of their own[11] shortly afterwards. Because this ASAT action was performed at a low altitude to destroy a hydrazine tank on-board a malfunctioning spacecraft, the atmospheric drag has removed most of the associated debris. These two events have greatly raised the awareness of risks and political costs of performing ASAT operations. However, at the time, beyond some space debris experts expressing concern, there was very little popular awareness of the issues, or political fall-out. However, in the last few years there has been an increase of popular articles,[12] and the movie *Gravity* that dramatizes the threats of space debris. If another large debris field generating high altitude ASAT

[6] http://www.unoosa.org/oosa/SORegister/regist.html
[7] http://www.unoosa.org/oosa/SpaceLaw/outerspt.html

[8] http://tinyurl.com/pdlwsfs
[9] http://tinyurl.com/k7emxdo
[10] http://news.bbc.co.uk/2/hi/asia-pacific/6276543.stm
[11] http://tinyurl.com/qxfs4xp
[12] http://tinyurl.com/nlbwpao

were performed today, the political fallout and costs to operators would be higher than with these tests. A high altitude ASAT test by any country could be both a political "black eye" and impede further collaborations between the country performing the test and the rest of the space-faring community.

Looking at the Iridium–Cosmos collision in 2009, there were no legal repercussions for the Russians or Iridium space operators, although Iridium lost a functioning spacecraft. At the time of the collision, the two bodies were not expected to collide.[13] In fact, they were not even among the most likely space objects to collide that day. Iridium ended up maneuvering into the Cosmos' flight path, and this collision has helped increase the communication between the US Air Force and satellite operators. Possible conjunctions events are slightly more transparent, and planned maneuvers can be verified a priori to avoid a resulting conjunction event. This satellite-to-satellite collision naturally resulted in direct costs to Iridium, but also indirect costs to users of space, specifically the USAF. Many operational lessons have been learned since the Iridium–Cosmos collision. Today's political costs, if an operator were to maneuver into the path of another object, are expected to be higher because of the improved tracking data being provided, and the increased awareness of space debris hazards.

Next, consider the multi-ton spacecraft Envisat which is no longer operational, but remains near the popular A-train obit. As discussed earlier, this sun-synchronous orbit region has the highest risk of colliding with other debris, and is in a heavily populated zone of expensive, commercial satellites. The loss of the ESA Envisat satellite in April 2012 has prompted many in the European Union to consider ways to actively remove this object from orbit due to its large size and high orbit.[14,15] With ESA attempting to follow international guidelines and publicity of this event in space debris circles, there appears to be a genuine effort to consider ways to remove this object from orbit [26,68–70]. Besides considering the technical challenges of moving Envisat, the political costs would be considerable if Envisat were to collide with another operating satellite, and cause a massive debris field in the highly commercial sun-synchronous orbit regime. This appears to be one of few current debris concerns where a potential political black eye is causing some ADR research in Europe. In the end, even these political costs are not high enough to currently warrant funding an Envisat ADR mission, but the pressure is mounting.

3.5. Environmental costs

Both ESA and NASA have looked into the predicted mean number of collisions expected, in LEO, over the next hundred or two hundred years [1,71]. Without changes to current-day practices, it is expected that there will be over 35 collisions in the next 100 years. Increased mitigation adherence will significantly lower this, to about half as many collisions ($\sim$15).

It can be argued that these studies are not really representative because they are mean values. Outlier conditions, such as the Iridium–Cosmos collision, will drive the debris population, not the mean [63]. For example, if there were two collisions back-to-back, this will cause many more challenges versus if there is only one collision within 15 years. Mean growth studies are not a good illustration of how good, or bad, the space debris environment will be.

With the recent Chinese ASAT test and Iridium–Cosmos collision, the number of new objects created was equivalent to about 16 years of launches [35]. It can be said that years of successful mitigation can be negated by one collision [59]. In this way, collisions, and the associated increase in space debris density in the associated orbit regime, can be considered a *enhancer/multiplier* for all previous costs. This is also the case for indirect and political costs which are enhanced by the space environment weight factor.

DigitalGlobe created an automated conjunction analysis tool (at cost to the company) that analyzes the JSpOC conjunction reports. This tool was created only *after* the Iridium–Cosmos collision, emphasizing that collisions increase infrastructure costs. If there are enough conjunction events per day, a dedicated analysis team may be required, increasing costs to operators further. Further, more collisions will eventually cause insurance rates to increase on satellites. The SwissRe report already indicates that the rates for GEO satellites are being reconsidered to account for growing space debris [38].

If a collision were to occur in heavily populated orbital regimes, such as the sun-synchronous orbits or GEO, this would have even greater effect. A collision in GEO will distribute debris throughout the entire belt within a day [72]. As illustrated in Fig. 3, the GEO gravity wells will causes some of this debris to be focused on these regions, increasing the local-longitude conjunction likelihood even further. A collision in the commercially popular sun-synchronous orbits could result in costly direct costs to locally operating satellites, and make future operation in such sun-synchronous orbits more challenging. Both of these narrow orbit regimes are special in that the operators are flying there to take advantage of particularly favorable orbital physics. These mission types are not possible by simply moving the GEO satellite to a lower orbit, or changing the plane of the sun-synchronous spacecraft.

4. Operator responses to space debris

This paper considers two reactive and two proactive operator or policy maker responses to the threat of space debris. The reactive options are to ignore space debris, or to track debris and perform collision avoidance maneuvers if required. The two primary long-term, proactive avenues are to improve the debris environment either through stronger mitigation efforts or commencement of active debris removal (ADR) missions.

[13] http://celestrak.com/events/collision.asp
[14] http://tinyurl.com/6tja2t7
[15] http://tinyurl.com/kq96x5x

4.1. No action related to space debris threat

Many LEO satellite operators do not respond to debris hazards because (a) their spacecraft does not have any maneuvering capability, or (b) they do not consider the conjunction information reliable enough to justify the cost of an avoidance maneuver. Inherent in the later consideration is the impact of spacecraft shielding. This provides some level of security to the operator that the satellite could withstand impingements with very small debris.

The no action option is certainly the most economical response during a mission, but also the one with a high risk. There is a growing population of small- and nano-satellite missions that have no propulsion capability. These missions are often high-risk technically and designed for a short mission duration. When considering all the risks that might terminate their operation, the probability of being hit by debris is not a driving consideration.

Some satellites with maneuvering capabilities still choose not to respond to debris conjunction threats and rely on shielding to handle the small debris. Regarding large debris threats, operators might arrive at this no-action response because they don't have access to conjunction data, feel the uncertainty of the conduction prediction is so large (often 10's of km or more) that they cannot justify the cost of an avoidance maneuver, or they choose to avoid additional maneuvers to retain fuel for other mission objectives and simply accept the higher mission risk. As illustrated in Fig. 5, prior to the Iridium–Cosmos collision this “no-response” decision was the most common response.

4.2. Dodging space debris

The “debris dodging” response considers moving an operating spacecraft to avoid another space object, or changing the flight path of debris to avoid a collision. Since the Iridium–Cosmos collision many operators' response to debris threats have evolved. The medium- and large-debris conjunction assessments are more reliable and transparent, and the 2009 event raised the awareness of debris collision risk. Thus, since 2009, an increased number of operators is choosing to make orbit corrections to effectively weave through space debris field. Conversations with LEO and GEO space operators showed that these corrections are commonly integrated into the regular orbit maintenance maneuvers. Thus, typically no additional fuel is expelled, but the direction of the burn is slightly adjusted. However, note that these maneuvers are only possible with respect to tracked debris (10 cm and larger). About 98% of LEO debris falls into the LNT category, and thus cannot be dodged. While this dodging strategy only avoids about 2% of LEO debris, it does help avoid the large-on-large collisions that are a major source of the small LNT debris.

Dedicated collision avoidance maneuvers will use up some of the mission fuel reserves, and are currently very rare. The conjunction uncertainty would need to be rather low for such a decision. Or, if the mission is of high value (commercial satellite, costly science satellite, etc.) the operator may choose to perform a burn despite large conjunction uncertainty.

Weaving and dodging about the medium- and large-sized debris is currently an affordable option for the space operators because the various indirect costs, such as tracking and cataloging the debris, is not currently charged to the space operators. However, if this should change in the future, and operators would have to pay for good tracking data (pushing infrastructure costs onto operators), the cost balance would shift in favor of proactive debris responses.

A recent development is the concept of Just-in-time Collision Avoidance (JCA) technologies [33]. Here short-notice (within days or hours) intercept methods allow a large debris object to be nudged, thus avoid hitting another large debris object, or an operating satellite. While this method can be cost-effective in avoiding an immediate large-on-large fragmentation event, this method only moves the debris, and does not remove it from orbit and future conjunction events. However, it could provide critical near-term large debris protection to a space operator willing to fund such an action.

4.3. Stronger mitigation implementation and/or practices

Mitigation is the process of reducing the likelihood that a specific object will cause more debris. Unlike the earlier two actions, it is not a response to an immediate debris threat. The first, and most widely used, mitigation practice involves passivation where rocket bodies and satellites that have reached end-of-life dump fuel, short out batteries, and effectively reduce the amount of on-board stored energy (they should also have captive mechanism features). Prior to the ASAT tests and the Iridium–Cosmos collision, it was post-mission explosions due to stored energy that caused the most debris growth. Passivization minimizes potential break-ups in orbit. Most space agencies have their own passivation guidelines, and their common implementation has greatly helped reduce the small debris growth.

The second mitigation practice, that is generally not as widely followed, is to implement post mission disposal. The most widely referenced general mitigation guidelines are the United Nation's (UN) IADC and Committee on the Peaceful Uses of Outer Space (COPUOS) Mitigation Guidelines. The well known LEO 25 year deorbit and GEO 235 km reorbit come from these guidelines. These guidelines are good step in the right direction because they focus on limiting the generation of future debris. However the guidelines, again, can be challenging to enforce. Some countries, such as France and Belgium, have legislation making the guidelines binding for their space operators. For most countries the COPUOS guidelines are not binding and have a recommendatory value.

As discussed previously, it is currently more cost-effective in the short-term for companies to create debris – i.e. not clean up their end of life satellites. Therefore, with the increasing commercial activities in orbit (both LEO and GEO), there is little short-term fiscal incentive to push for better mitigation practices. This enforces the concept of a *global* means for enacting and enforcing the use of mitigation measures on all missions. If instituted globally, all contractors are equally impacted and will remain commercially competitive. What this does not mean is that all mitigation policies need to be the same for all orbit regimes. For example, GEO and LEO already have different guidelines. As illustrated in Fig. 2, the LEO debris distribution is focused in a finite set of orbit regimes. It is conceivable that refined mitigation guidelines are developed for particular LEO regions.

Jakhu suggests that the only way for these mitigation methods to be effective is to have binding international legal agreements that are reflected in the domestic laws of space-faring nations [59]. This would require international cooperation across many interests and domestic policy to be made that could be unpopular within the space community, due to increased regulations. Laws such as The French Space Operations Act from 2008, while well meaning, could remove competitiveness for French commercial entities, since the rest of the world is not restricted by similar laws. The challenge is that, economically, instituting mitigation regulations appears to be an “all or nothing” effort where the only way for any company to internationally be competitive is for all nations to have similar regulations.

Current mitigation guidelines have been shown to not be enough to reduce debris growth in LEO [34] and there is debate about whether the GEO rules are a reasonable solution [73]. Further, adherence to the 25 year rule for LEO is weak [74]. Only 15% of the high debris criticality index spacecraft (often in high sun-synchronous orbits) are being maneuvered to have a decay time less than 25 years. In GEO, operators are much better at self-regulating and appear to be improving with their efforts to comply with post-mission IADC disposal guidelines. It should be noted that the fuel cost to reorbit the end-of-life GEO satellite is only about 11 m/s, much less than the 100's of m/s required to deorbit LEO satellites. This could explain the higher compliance rate at GEO. Using re-orbit statistics compiled from ESA's annual *Classification of Geosynchronous Objects* reports [47], Fig. 7 illustrates compliance to the IADC re-orbit guidelines since they were introduced to the international GEO operator community in 1997 [75]. Fig. 7(a) shows the number of GEO satellites annually that (1) reached the end of their operational lifespans, (2) attempted re-orbit to an IADC-compliant disposal orbit, and (3) successfully achieved the minimum periapsis altitude increase stipulated in the IADC guidelines. The margin between the number of assets that reached end-of-life and those that re-orbited into an IADC-compliant disposal orbit has decreased since 1997, indicative of a growing international desire to preserve the long-term utilization of the GEO ring. Fig. 7(b) provides a breakdown of the compliance data in Fig. 7(a): during 1997–2013, approximately 50% of GEO satellites that reached end-of-life were repositioned into IADC-compliant disposal orbits before deactivation, and 30% attempted post-mission disposal, but were unsuccessful in achieving the IADC's minimum periapsis altitude increase. Interestingly, 53 GEO satellites were abandoned without any re-orbit attempt during this time frame, the largest contributor being Russia (33 abandoned). The political costs to Russia

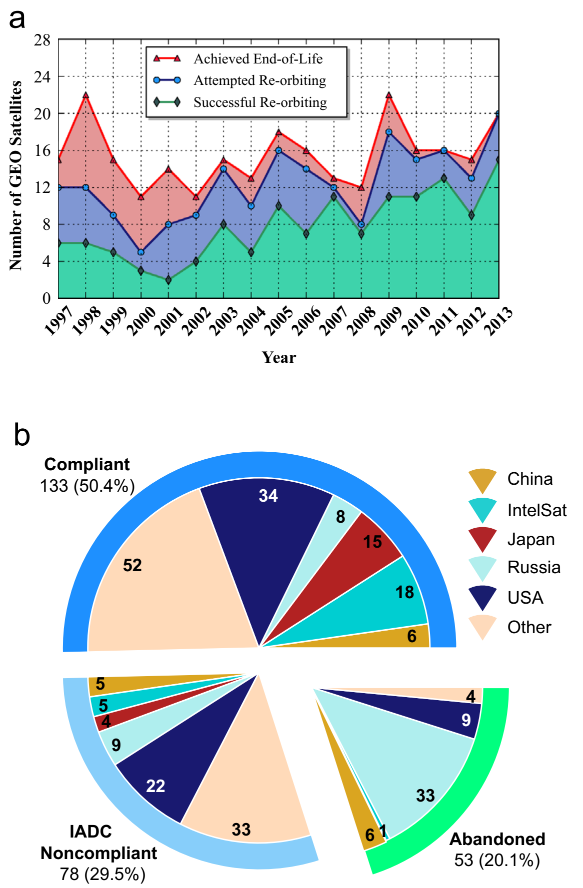

Fig. 7. Compliance to IADC guidelines for post-mission disposal of GEO satellites [47]. (a) Annual GEO disposal guideline compliance since introduced. (b) Compliance to GEO disposal guidelines by entity for 1997–2013.

contributing 62% of the abandoned GEO satellites over this time period has been negligible. This illustrates that for the near-term it is cheaper to generate debris, than try to follow debris mitigation guidelines.

The natural question arises, how can LEO operators be encouraged to act more like GEO operators? Debris mitigation is a key element to an economically sustainable space debris environment. The high GEO operators' compliance rate is facilitated through:

1. *Awareness of the debris-related mission risk*: The low risk tolerance of GEO operators, as shown by the lion's share of the space insurance being at GEO, and the narrow operating regime about GEO make the operators sensitive to space debris issues.
2. *Availability of low-cost debris mitigation solution*: It only requires about 11 m/s of Δv to boost a satellite to a super-synchrounous disposal orbit.
3. Avoidance of the myriad of legal concerns about causing extremely rare terrestrial damage, as the satellites do not re-enter the Earth's atmosphere.

In contrasts, many LEO missions are lower-budget and more risk tolerant. Even for insured commercial satellites, the operators engage in "debris dodging" to avoid trackable LEO debris, often not realizing they are avoiding only 3% of the potentially lethal LEO debris population, and thus have about the same chance of their mission pre-maturely terminating due to a collision with a LNT object.

The fuel efforts required to deorbit are significantly larger, around 100's of m/s for a sun-synchronous spacecraft. Low-cost solutions to deorbit end-of-life satellites is critical. However, such technologies, such as drag or tether devices, will result in a passive re-entry. This raises concerns with about causing terrestrial damage. A LEO operator may chose to simply abandon a satellite in orbit, rather than doing an active deorbit and assume the legal risks. Thus, to encourage LEO operators to comply better with debris mitigation guidelines, it is key to continue to educate them on the true current and future debris risk, while providing access to low-cost and low-liability deorbiting solutions.

Another important question is whether more aggressive rules should be applied for particular orbit regimes (much shorter than 25 years after end of life – LEO, reboosting of objects significantly beyond 235 km – GEO). At the 6th European Conference on Space Debris in Darmstadt, Germany, McKnight voiced the idea of using shorter post-mission disposal times such as 10–15 years. These measures might stabilize the debris population without needing ADR. Such stronger mitigation guidelines would increase the mission costs of most space operators, thus common enforcement would be critical. While there has been progress on improving mitigation, the slow pace of acceptance, especially in the countries that are the largest contributors to debris, makes it appear that the political and economic costs are (perceived as) currently more than the cost of increasing debris.

4.4. Remediation

If operators and policy makers cannot be convinced that mitigation regulations should be adopted, remediation appears to be the only other option for reducing growth to stabilize the debris density. While the ideal scenario will have nations participating in mitigation AND remediation, remediation is attractive because it can have very significant affects for small numbers of objects removed from orbit. Further, remediation can be performed readily unilaterally if satellite operators are moving their own debris. This is good because a single country, or small group of organizations, can directly improve the entire orbital environment and not necessarily need a world-wide policy effort.

The problem with unilateral implementation is that the direct expense of these systems to the organizations involved will be large. Even more troubling is that some ADR concepts could be considered a space weapon. Therefore, if a country like the US or Russia were to build an ADR system, there would be major concern about the use of this system. The creation of any ADR system would preferably be a public endeavor accepted by the international community [62].

Because there are 100,000's of centimeter or larger sized debris objects in LEO, the economic costs to deorbit large numbers of debris is daunting. A key driver in ADR technology developments is the economic viability. Otherwise, it can cost more to remove an object from orbit than it originally cost to put it into orbit. The economic hurdles to developing ADR solutions are considerable. However, the system costs can be reduced by considering that many ADR-related technologies have a broader use. For example, the autonomous rendezvous and docking GNC sensor systems required to approach passive space debris, the touchless actuation systems, the robotic grapplers, are also being developed for autonomous orbital servicing, asteroid capture systems, resupply missions, and space asset harvesting systems. By highlighting the broad use of to-be-developed ADR technologies, it is feasible to developed the required technological readiness level without investing large funds into a singular ADR concept.

It will likely be challenging for a single country to have space debris researchers convince their policy makers and/or population that the expense of an ADR system is worthwhile. However, it could be argued that ADR system development will provide vital new technologies with broad mission applications for that country or industry. This would make them a leader and key resource within the space-faring community.

One potential concept for funding of an ADR system (internationally or regionally) is to tax all operators that generate debris. Thus, there would be a tax associated with launching and the debris generation potential of the mission [62]. This would make the responsible parties for debris creation pay for the clean-up of space, but again, this cost structure will hurt competition without universal adoption.

A particular challenge with raising funds to implement space debris mitigation and remediation is that they do not return positive feedback [35]. This is because if mitigation and remediation measures work, there will be no major collisions. It is only the negative results, a collision, that are overly obvious. This makes costs associated with prevention less tangible. However, besides the well-known Iridium–Cosmos collision, there have been other cases where space debris has disabled a satellite, such as with Cerise [54]. Tracking such debris-related failures is critical to convincing policy makers that the debris models and forecasts are true. However, it is very challenging to determine if a satellite failed due to a collision with a small debris object. Satellites fail for many reasons, including space weather, mechanical failures, software glitches, etc. Recent satellite failure workshops are trying to share the histories of satellite failures to gain the data to track the exact causes.

But, as the perceived risk due to debris increases, direct costs to operators *will* increase because active responses will be chosen, and the indirect costs to all organizations will also increase due to the associated space situational awareness demands. Fig. 8 demonstrates this trend, and considers three scenarios. When it becomes necessary to enact "stricter mitigation", due to higher risk levels and/or government requirements, this will create a 'level-set' of cost to operators that will be difficult to reduce. This is because the costs for mitigation will likely be needed for all future operations to stabilize the debris population. If

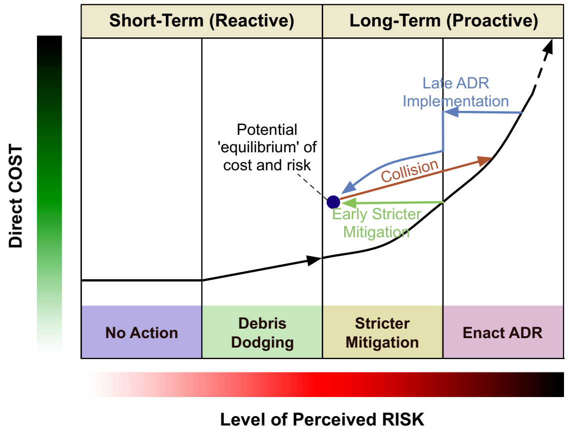

Fig. 8. Potential direct cost to operators as risk increases, and the trend in mitigation versus remediation.

the risk increases even more for a particular orbit regime, the total costs eventually increase enough that "ADR" becomes cost effective. Of course, the earlier ADR is implemented, the lower the cost for reducing risk. McKnight also makes this point in Reference [35].

The following three scenarios are considered. First, in the "Late ADR Implementation" scenario, assume the debris hazard risk in an orbit regime is allowed to grow to the point where even stronger mitigation measures will not sufficiently shrink it. The only option is to implement ADR to help remove objects that contribute to large scale debris growth [1]. The cost of such ADR technologies would be very high if this decision to engage in ADR is made with short notice [35]. A more economical approach would be to develop ADR technologies early on, possibly for other mission scenarios such as orbital servicing. Next, the interesting question is, how long will ADR measures be necessary? At some point ADR has removed enough objects such that the debris population is stabilized at a reasonable level. If the more costly ADR operations were to be suspended, would space operations reach an equilibrium where stricter mitigation is enough to stabilize the risk?

In the second scenario, consider the case where in an orbit regime the risk has grown large, but can still be made stable with stricter mitigation. For example, in sun-synchronous orbits, would a 10–15 year post-mission disposal time reduce the debris hazard risk without needing ADR? It is envisioned here as well that over time an operational equilibrium will be achieved.

Finally, consider the best-case scenario where with early thoughtful actions in an orbit regime an operational equilibrium with the debris hazard risk has been achieved. At first glance it may seem this avoids any need to develop ADR technologies. However, ADR capabilities would still be required to keep this orbit regime's debris stable. While the risk is held steady at a lower value, the risk is not zero. Collisions being unlikely does not imply they are impossible (see Iridium–Cosmos collision probability). A catastrophic collision can still occur, even in a low-risk environment, whose outcome would jump the local orbit regimes debris hazard risk to a much higher value. Again, early development of ADR technologies is needed to be able to respond to such outlier events.

5. Conclusions

This paper outlines the complex cost considerations associated with space debris hazards for the space operators. When advocating stricter mitigation or active debris removal solutions, these must be considered to yield effective guidelines for sustainable space operations. Further, operational equilibria are postulated where the debris mitigation costs and operational risks are balanced. However, such equilibria's would not be stable, as even a low probability of collision can result in an actual collision. For example, the 2007 and 2009 events caused the equivalent of 16 years of debris within only 2 years. With the increasing launch rates and incomplete mitigation implementations, a philosophical change in space operations is required.

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