An actuarial modifier for underwriting OOS satellite insurance: Space debris mitigation

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Abstract. Increasingly, insurers are reluctant to provide coverage for certain specific risks such as on-orbit collision damage or LEO-orbiting satellites whereby the probability of loss is ambiguous. The latter portends the risk for satellite encounter with space debris, and the former foretells not only spacecraft damage but debris production as well. With hundreds of satellites on orbit, the loss of one or a few may not cripple the entire constellation, or fundamentally change the dynamics of the business model based on the utility derived from satellite performance. Insurers are already pulling out of the market for LEO due to the risks of collision and space debris. General market consensus indicates current premium volume about half of what it should be. As insurers' exodus from space continues, the whole insurance sector appears to lag behind a booming space industry. However, insurers accept or reject risks based on how stability and profitability were realized from the actualization of their business model. This paper suggests active debris removal will promote stable performance reliability of satellite operations that will underpin insurance market stability and profitability. The specialty space operations sub-segment, on-orbit servicing satellite infrastructure, appears to be emerging to stabilize insurance market with the capability to repair, refuel, and reposition non-functioning satellites. Increased stability of on-orbit satellite operations results in extended satellite lifetimes and reduced LEO-laden debris to modify the actuarial basis for underwriting premium coverage of LEO-orbiting satellites.

1. Introduction

Underwriting capacity is the maximum amount of liability that an insurance company agrees to assume from its underwriting activities. Underwriting capacity represents an insurer's ability to retain risk. It's important for an insurance company to calculate and maintain its underwriting capacity so it will be able to pay out claims to customers when needed so as to avoid insolvency. The insurer diligently seeks to determine if it's profitable to offer coverage and then, based on its research, establish a price. This price is known as the premium, and it is charged in exchange for taking on the risk of covering the applicant against loss.

Insurers offer policies covering the satellite from manufacturing through launch and orbit.[1]

Pre-Launch	Third-Party Liability	Launch	On-Orbit
		Launch Plus One Year	
Covers damage to the satellite or launch vehicle during manufacturing, transportation, assembly, and processing phases prior to launch	Protects satellite operators from claims from third parties for injury or property damages arising during the pre-launch, launch, or on-orbit phases	Covers loss, damage, or failure of the satellite between intentional ignition of the rocket and separation of the satellite from the launch vehicle	Covers complete or partial failure of the satellite during its operational lifetime after separation from the launch vehicle and is usually renewable annually

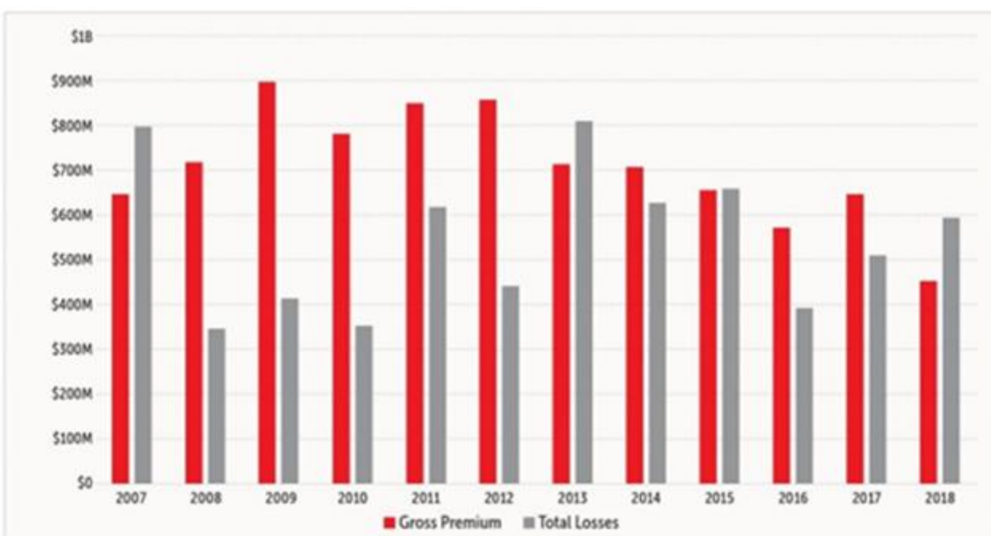
Source: AON Risk Solutions, "Insuring Space Activities." Aon.com, Aon plc, October 2016,

Models of risk sharing under expected utility maximization invariably conclude that the entire risk should be split according to the risk preferences of the parties to the exchange. The optimal contractual forms do not include coverage limits but involve deductibles and coinsurance above some level. Only in the case of a regulatory constraint requiring insurers to sell a policy with a prescribed actuarial value has it been shown that there will be policy limits [1]. Huberman, Mayers, and Smith [2] develop coverage limits when demand is influenced by limited liability under specific assumptions about the nature of the risk, but this does not explain insurers' reluctance to offer policies with unlimited exposure. Striking the right balance is essential to maintaining and improving the financial health of the insurer. In other words, a company's underwriting capacity, or the maximum amount of acceptable risk, is a crucial component of its operations. An insurance company's profitability hinges on the quality of its underwriting. The role of an insurance company is to provide protection against the risk of financial loss. It could be the risk that a satellite will not perform the task it is built to do, which could happen because of a variety of circumstances (such as failure of the launch vehicle, failure to reach a proper orbit, or operational failure of the satellite itself. Without insurance, many smaller companies, and especially startups, would not be able to absorb the risk of doing business because the stakes can be very high—a single failed launch can result in payload losses of hundreds of millions of dollars. As military and civil space customers become increasingly reliant upon such companies, they must understand the commercial sector's ability to sustain failures while maintaining solvency and operations. Although the government does not buy insurance for its own satellite launches (as the government turns to the private sector for launch and satellite services), it is important for government stakeholders to maintain heightened awareness of key drivers and issues facing the satellite insurance market [3].

Stone's behavioral theory of insurance proposed that constraints of stability and survival are used by insurance companies for acceptance or rejection of risks, where *stability* meant regularity in corporate profits over time, and *survival* referred to the specification of a maximum probability that aggregate losses exceed surplus. Factors affecting premiums can be internal to the mission or external in the broader market and can be both technical and nontechnical [4].

2. Commercial Satellite Insurance

Commercial satellite insurance has been around since 1964. Until the 1980s, commercial enterprises were unwilling to self-insure such high valued assets that were subject to relatively high loss frequencies. Market capacity soared in 1990s from $300M to almost $1.2 B in 1999, well in excess of $175M-$250M coverage that NASA-required for most satellites to as much as $500M coverage [5]. The history of the satellite insurance market indicates that crises and booms in profitability and prices repeat in a manner suggestive of cycles. Some aspects of the satellite insurance market are volatile (e.g. claims) or cyclical (e.g. rates), while capacity is both volatile and cyclical.

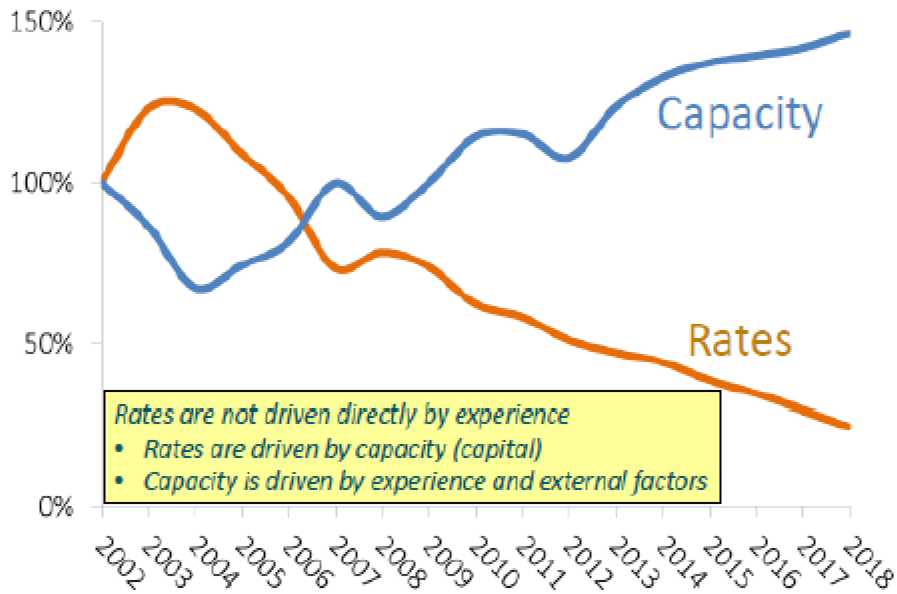


SOURCE: SERADATA

SPACENEWS GRAPHIC BY ROBIN MCDOWALL

In a syndicated insurance market, insurance premium rates vary inversely with the underwriter's capacity—the supply of coverage that insurers are willing and able to provide. When capacity is high, rates are low, and vice versa. Factors that affect capacity for the space industry include general insurance cycles, macroeconomic trends, launch and satellite failures, and changes in the commercial space industry. While aggregate premiums collected have generally outweighed annual losses since the early 2000s, the difference between premiums collected and maximum exposure (the value of the single largest policy for that year) has decreased over time. Since 2016, total premiums collected annually could not have covered claims on the largest policies in any of those years, opening up insurers to potentially substantial losses had these large claims occurred. This development represents a turning point in the stability of the industry. This is an issue for low-frequency/high-risk lines of business such as satellite insurance [6].

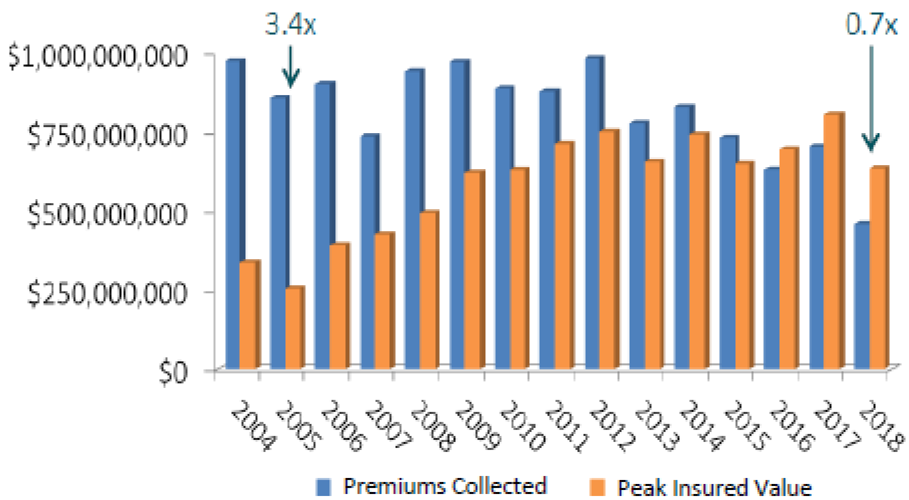
Insurance risk may be estimated by using the widely published launch missile failure data (as a referenced control for satellite failure) and making a learning curve analysis to compare cumulative launch failures to the number of starts. This launch failure data is of only limited statistical value and should not be associated with the loss experience of the insurers. However, it does provide a basis for risk analysis and the development of customized insurance programs. The whole risk management process should be divided into three steps: risk identification, risk analysis/risk valuation, and risk control. Describing risk provides measures and opportunities for identifying, minimizing, and avoiding risk. Risk identification considers whether new risks have arisen, whether existing risks have changed in scope, or when previously unknown risks were identified. Risk analysis and valuation determines if the small number of insurable events, their technical heterogeneity and the wide spread of insured values, the incomplete data or the lack of cost-effective means to obtain information, complicate the risk analysis process. To obtain the two critical measures, loss frequency and amount of loss, auxiliary measures are being used, such as *probable maximum loss* (PML) [7].



Change in Capacity and Rates Since 2002. *As rates decrease, capacity has historically increased. (Source: Kunstadter, Christopher. "Space Insurance Update 2019," International Union of Aerospace Insurers)*

On the other hand, as rates increase, capacity typically decreases. Higher premiums could hurt satellite operators' bottom lines, and a significant rate increase would be an incentive for some operators to self-insure, especially as satellites become smaller, cheaper, and more expendable. While large companies with significant financial backing can "self-insure" their satellites, this is not an option for smaller or emerging companies [8].

With limited data on evolving satellite technology, insurers assess risks and make informed underwriting determinations. Worse-case scenarios obligate insurers to pay out peak insured values resulting in a negative-supply shock, whereby premiums increase across the insurance market. Given the changing technology environment, space underwriters create customized databases of satellite and launch vehicle heritage. Moreover, they rely on extensive databases to give them the tools they need to respond to the fast-moving space technology environment of the twenty-first century [9]. To avoid limits which are too high on a satellite that is losing value, capacity limits are gradually lowered. Hence, coverage is granted for a certain period in reasonable relation to the satellite's life expectancy. For new satellites the policy period is usually limited to three years. For policy annual renewals, the insurer often asks for a *health certificate*, requiring reassessment of the satellite's technical condition and prior functional disturbances. Since potential flaws may be discovered during the test period, launch insurance covers such losses. Major risks of in-orbit insurance include mostly partial losses, specifically defined in the policy. Therefore, underwriting on-orbit insurance focuses on life expectancy and reliability estimating the of the critical systems and components [10].



Aggregate Premiums Collected vs. Maximum Exposure. *The gap between peak insured value and market premiums has narrowed since 2004, and premiums have not been sufficient to cover the peak insured value since 2016. (Source: Kunstadter, Christopher. "Space Insurance Update 2019," International Union of Aerospace Insurers)*

The increased participation of private companies in satellite and launch operations—a domain once reserved for governments—represents a paradigm shift in space activity. NASA's commercial cargo program and other federal contracts have helped fuel the growth of the commercial launch sector, which has also attracted significant venture capital backing [11]. Heavy competition in both satellite operations and launch services over the past two decades has led to innovation in space technology and a lower cost of entry into orbit, especially with the advent of small satellites. A company seeking to create and launch a satellite into orbit can do so faster and for less than ever before. While these developments represent breakthroughs for an industry that has traditionally embraced the status quo, the increasing number of less experienced operators and untested technologies poses new challenges for insurers. Including tests, new launch vehicles fail 25 percent of the time on each of their first and second launches [12].

There is considerable empirical evidence suggesting that ambiguity (i.e., parameter risk) impacts pricing decisions by actuaries and underwriters and their desire to provide coverage. Increasingly, insurers are reluctant to provide coverage for certain specific risks such as on-orbit collision damage or LEO-orbiting satellite insurance where the probability of loss is ambiguous. Such behavior may be deemed safety first but seems to complicate an expected utility approach [13]. Three different categories distinguish satellites according to their use: scientific satellites (e.g. research of the earth and its immediate surroundings, astrophysical measurements, and space observations); military satellites; and, task-oriented satellites (e.g. communications, earth explorations, weather and navigational satellites). Only the latter category indicates an insurable risk on the insurance market. Communication satellites losses in function results in their devaluation. For a risk manager every single satellite and space project is a new risk; only some individual aspects are comparable to previous risks because of their technical differences. Risk control elements such as risk avoidance and risk reduction particularly should play a significant role in satellite and space technology. Risk analyses are the foundation for measures to maintain high standards of quality, hence important for achieving a superior standard of safety and reliability. In 2018, according to the Space Launch Report, a total of 114 rockets were launched into space, from which the space insurance industry, as a whole, collected$450 million in premiums and paid out$600 million in claims [14]. Space insurers complained not making a lot of money.

3. On-orbit Satellite Constellation Insurance

LEO comprises all orbits with average altitudes below 2000 km, the 250-450km subset of which known as manned spaceflight corridor where ISS is located. LEO is also where large communications satellite constellations are located, including (as of 2011)

Satellite Constellation	Number of Satellites	Altitude (km)
Iridium	66 comsats (and seven spares)	790
Globalstar	32 comsats	1,414
GeoEye	3 imaging sats	705 and 681(2)
Digital Globe	3 imaging and remote sensing	770, 496, and 450

Source: Chrystal, P., McKnight, D., Meredith, P. L., Schmidt, J., Fok, M., & Wetton, C. (2011). Space debris: On collision course for insurers?. *Swiss Reinsurance Co. Publ., Zurich, Switzerland*

Space imaging systems, cloud computing, networking and storage, as well as machine learning algorithms are all included in the system that analyzes, monitors, and forecasts data and trends of interest. Advances in these categories, particularly those relating to and supporting smallsat constellations, improve the accuracy and the application of these analyses and forecasts. The miniaturization, interchangeability, and component standardization characteristic of smallsats has changed the priorities of satellite systems. The assured systems performance and affordability allow more constellation systems to be orbited, enhancing survivability and access opportunities to space. Future systems engineering endeavors will result in increased utility. Increased greater cosmic data collection, shrinking electronics and sensors, increased efficiency of satellite constellation management, and availability of flexible short-term/ low-cost missions are the expected outcomes. New technologies reduce the potential financial losses of launch vehicle or satellite failure. Some operators—especially legacy companies with large capital reserves—would likely have less incentive to purchase insurance and would in effect become self-insured. However, smaller startups entering the space market could still benefit from the safety net of insurance coverage, particularly if a small number of satellites represent a large part of a company's total assets [15]. Persistent surveillance capabilities of smallsat constellations provide accuracy and development of analysis, applications, algorithms, and models [16].

Although these industry developments pose new risks, they also represent a long-term industry trend toward cost-effectiveness, efficiency, and resilience that is unlikely to reverse, as competition increases. If these new technologies reduce the potential financial losses of launch vehicle or satellite failure, some operators—especially legacy companies with large capital reserves—would likely have less incentive to purchase insurance. They would in effect become self-insured. Smaller startups carry more risk per satellite: if something goes wrong, a smallsat operator is more likely to lose a capability. Consequently, they are more likely to buy on-orbit insurance, 23% of self-insure by depending upon the versatility of their large constellations to pick up the slack if necessary [17]. As with classic satellite insurance, constellation insurance policies typically define an expected performance, and the coverage is structured to compare the actual performance with what is defined under the policy. In some cases, there may be high levels of interdependence between satellites compared to individual satellites. In common with classic insurance products for individual satellites, the underlying policy is an all-risk policy negotiated to cover loss, damage, malfunction or any defect impacting operations. Satellite constellations often contain spares to providing redundancy in case partial loss in performance. Operators of such constellations in effect alternatively self-insure on-orbit liability.

Case1.

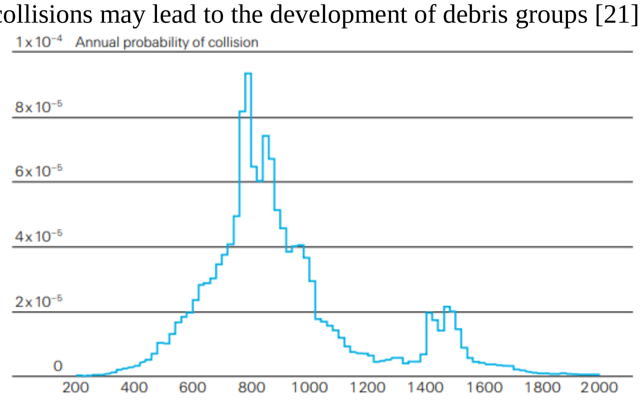
Planet Corp."The constellation has enough redundancy built into it in terms of the numbers of satellites that we don't need to insure the performance of any specific satellite." — Mike Safyan, Planet's vice president of launch and global ground station networks.(Credit: iStock/SpaceNews).The same is true for Planet, which has about 150 Dove cubesats as well as 13 SkySats, larger satellites that the company obtained when it acquired Terra Bella (formerly Skybox Imaging) from Google last year. Mike Safyan stated, "Once we started launching large quantities of Doves to sun-synchronous orbit, those launches were insured against launch and deployment failure. The constellation has enough redundancy built into it in terms of the numbers of satellites that we don't need to insure the performance of any specific satellite," Safyan said of its Dove satellites. Planet has considered insurance for its SkySat fleet given the smaller number of them and the higher individual value of each satellite.To date, we haven't felt the need for in-orbit performance insurance, and part of that is because for these smallsat constellations, redundancy is already built in with the numbers of satellites in orbit."[18]

	Technical	Nontechnical
Internal considerations	♦ Mission requirements and concept of operations • Operating environment (orbit) • System architecture, subsystem design, and redundancy systems ♦ Experience of the operator, manufacturer, and launch provider ♦ Anomaly resolution process in place	♦ Contractual considerations • Spacecraft purchase and launch services agreements • Performance specifications ♦ Financial considerations • Business plan • Exposure analysis • Asset valuation • Loss calculation, policy terms, and conditions
External considerations	♦ New commercial entrants • Less experienced satellite operators and launch service providers with new development philosophies ♦ New technology • Electric propulsion • Phased-array antennas • Onboard processing • Optical intersatellite links ♦ New architectures • Larger constellations of smaller, less expensive satellites	♦ Insurance market considerations • Quantification of potential loss scenarios • Perceived risks and recovery bias • Frequency vs. severity of losses • External events that could drain insurance capital: natural disasters, and terrorism • Political policies and environment ♦ Macroeconomic considerations • Global interest rate environment

Source: Kunstadter, Christopher. "Space Insurance Update 2019," International Union of Aerospace Insurers

With the large total losses of the 1980s in mind, the insurance industry addressed the question as to whether these complex technical satellite and space travel systems are manageable from an insurance perspective [19]. When underwriting space operations, insurers must consider a multitude of factors, which include technical and nontechnical aspects of the individual program in question, all of which affecting premium rates for a given launch [20].

In 2018, there were still nearly 3,000 scrapped satellites in orbit, excluding rockets at the final stages, fairings and other hardware [2]. There are greater than 15,000 large objects in orbit around the earth. However, only 7% of these are active spacecrafts, 17% are non-functional spacecraft, and 13% are rockets in orbital phases. These launch missions have overwhelmed our space environment. Kessler [3] proposed that the concentration of objects in near-earth orbit (NEO) may reach a critical level in the future, which will cause cascade effect, where some major collisions may lead to the development of debris groups [21].



Four major LEO commercial constellations in different debris environments. (Source: Collision risk derived from data provided by NASA)

In sun-synchronous orbit within LEO, the annual probability of collision of 1 cm size debris with a $10m^2$ satellite exceeds 0.8%. This is the largest debris collision hazard anywhere in Earth orbit. The annual collision risk for a $10m^2$ satellite across LEO is plotted highlighting the range of risks. Note that the annual collision risk at 750-900 km is on average seven times greater than at 500 km.

The number of satellites orbiting around the earth is increasing, many of which to soon reach end of their lifetimes (EOL) . GEO satellites will have to lift themselves up to a higher altitude (I,e, graveyard orbit). LEO satellites will de-orbit to a lower altitude where atmospheric drag causes them to re-entry within 25 years EOL. Satellites are incapable of such operations because of malfunction or lack of fuel. At present, no obligation requires a satellite operator to purchase liability insurance when the launch provider's coverage expires. However, satellite operators in LEO planning to re-enter their satellite constellations at end-of-life may be required by US Government to carry third-party liability insurance policy with a de-orbiting endorsement up to maximum insured of $500M [22].

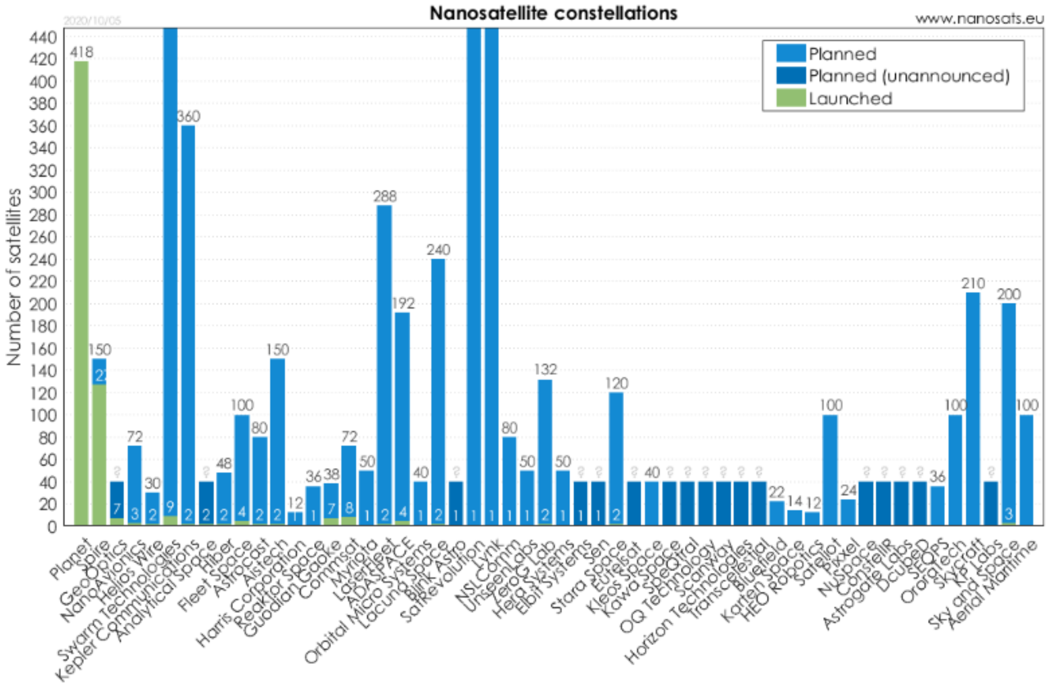
year	Succeed to Reach GEO	Fail to Orbit	Rocket Bodies	Reach EOL	Successfully Re-orbiting	Re-orbiting Ratio(%)
1997	35	0	-	17	7	41.2
1998	29	3	-	21	7	33.3
1999	22	6	-	12	4	33.3
2000	43	4	-	11	3	27.3
2001	22	1	-	14	2	14.3
2002	28	3	-	11	4	36.4
2003	28	0	-	16	8	50
2004	19	1	5	13	5	38.5
2005	22	0	3	18	10	55.6
2006	29	2	2	16	7	43.8
2007	25	3	2	13	11	84.6
2008	30	2	4	12	7	58.3
2009	30	1	3	21	11	52.4
Total Average	28	2	3.2	15	6.6	44.1
5-year Average	27	1.6	2.8	16	9.2	57.5

As for the end of 2009, some satellites have been re-orbited successfully, i.e. the graveyard orbit complying with the IADC (the Inter-Agency Space Debris Coordination Committee) re-orbiting guidelines. Integrating and analyzing the data of different information sources, the annual launching and re-orbiting GEO satellites, together with the GEO satellites which reached the EOL(end of life), are analyzed [23].

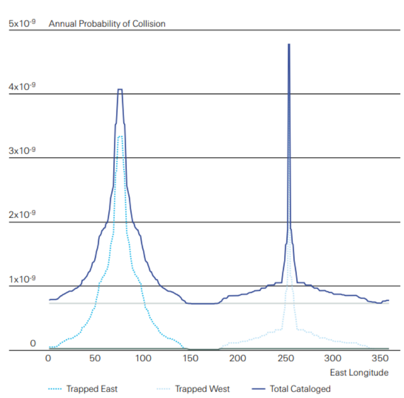
More than half (57%) of in-orbit population is fragmentation debris. Non-operational satellites and spent rocket bodies together make up only 25% by number while they contribute over 90% of the mass of the in-orbit population. The number of objects in-orbit drive the current collision hazard while the mass in-orbit future collision hazard since this mass provides a potential source for future debris-generating collisions. Non-operational payloads have either completed their design lives or malfunctioned prematurely. The typical mission lifetime in GEO is about 15 years. Spent (or derelict) rocket bodies are components of a multi-stage expendable launch vehicle used to place a satellite into orbit that are left in-orbit after a completed launch mission. The lower launch vehicle stages are designed to re-enter over the ocean uninhabited land areas. Currently, fewer spent rocket bodies deposited in GEO than being released after satellite deployment. Mission debris is hardware released as part of the normal deployment and operations of a spacecraft [24]. Fragmentation debris is created when payloads and rocket bodies explode due to onboard self-destruct devices, over-pressurized propellant tanks, and accidental collision between orbital objects. To date, nearly 200 known debris-producing events have occurred in space [25].

4. Current Insurance Market

In 2016, premiums were the lowest they had been in 15 years. After approximately 10 years, the satellite value declined enough such that insurance no longer made sense. Could on-orbit servicing extend this timeframe or even create an uptick in the value? Smaller fleets carry more risk per satellite: if something went wrong, a small fleet operator was more likely to lose a capability [26]. In a LEO constellation with multiple satellites orbiting the Earth multiple times a day, and with potential areas of concentration (over the poles), collision risk was clearly a significant additional consideration for insurers [27]. The annual probability of collision for any station kept satellite as a function of longitude can be calculated.



The market for insuring cubesats has changed significantly over the last five years [28]. In describing the cislunar space domain, satellite operations may be discussed comparatively in terms of old space and new space. Prior to the time of satellite constellations (new space), a space system would consist of 1-2 satellites operated by space-faring governments or large organizations for purposes of either national security or national infrastructure. Typical satellites within a constellation may have a mass less than 200 kg built by startups representing more than 90 countries. Satellite constellations are dispensed into orbit from space launch vehicles they rideshare to space. Their operations depend on such concerns as how to extend serviceability, provide satellite replenishment, and manage end-of-life strategies. Additionally with satellite constellations, LEO space domains of their operations are more crowded and show a greater probability for collision.



The annual probability of collision from catalogued population for a station-kept satellite at the center of a geopotential well exceeds 4x 10^9, the equivalent of one chance in 250 million of a collision between an operational satellite and a catalogued object over a year's time. The probability of collision between any two of the estimated 2200 non-catalogued objects larger than 10cm increases to 7 x 10^6 per year or one chance in 150,000 each year [29]. Complicated maneuvering around operational assets and de-orbiting or re-orbiting become standard practices.

In a previous qualitative empirical study of space insurance market, published quotations were collected and manually coded from a sample of 16 satellite operators and 16 space insurance officers [30]. Most cited by satellite operators was inability to obtain coverage for LEO satellite operations and for collision risks.

# insurance underwriter entries = 43	# satellite operator entries =23
Increased claims to lower profits, increased new underwriting entrants, and failed satellite operations, lower rates due to cheaper launches and satellite values Changes=15	Response to Insurer rate increases, exclusion clauses or no coverage: Negotiate terms or self-insure. Responses =8
Insurer response to Insurance market inc. exiting and contract exclusions = 9	Lower insurance capacity; Total loss vs partial loss dilemma; No LEO or collision coverage; payout delay; no performance incentive; Changes = 10
Need transparency with satellite H/W, performace	Insurer collusion

The following cases are representative of the leading perceptions voiced in the space insurance market. There is growing concern about the increasingly crowded LEO being populated by constellations of hundreds of smallsats and the abundance of space debris produced. Consequently, insurers are reluctant to provide coverage for satellites orbiting in LEO.

Case1.

Since the beginning of the year, space insurance underwriter Assure Space is no longer offering policies covering collision risk for satellites operating in low Earth orbit, Richard Parker, Assure Space managing director, said at the Satellite 2020 conference. Assure Space continues to insure launches, satellites operating in geostationary orbit, satellites raising their orbit through low Earth orbit and missions to the international space station."But if someone comes to me and says, 'I want one year on-orbit coverage for a small satellite in low Earth orbit,' the answer is no," Richard Parker said. "I can't charge them today what I perceive the real risk to be." If a client still wants to buy a policy, Assure Space will write a policy that excludes collision coverage. "I won't pay in the event you have a collision in any circumstance," Parker said. It would not matter whether the client's satellite was involved in a collision or was hit by debris from a collision that occurred months ago [31].

Case2.

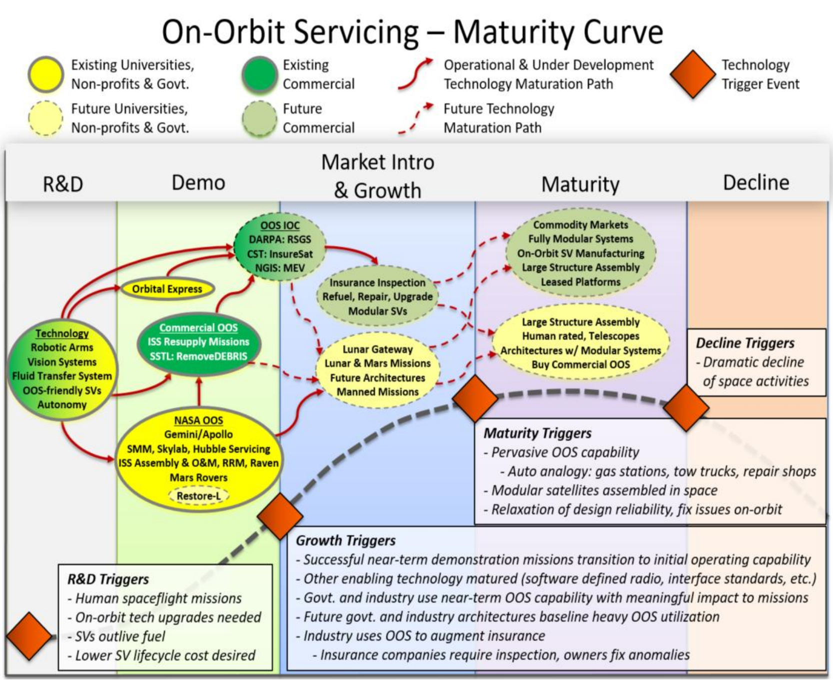
Unlike its single satellite insurance counterpart, the constellation insurance product is designed to consider the impact of losses within the overall network or system of satellites. Depending on the nature of the particular system, the failure of a single satellite or, more commonly, a series of failures across multiple satellites may impact the overall functionality of the constellation. In other words, the insurance product may be expected to respond to the sum of all parts (ie the satellites) that make up the whole (ie the constellation). The trigger for such coverage must therefore be carefully defined to cater for the individual requirements of the constellation owner/insured. To date, the issues of collision avoidance, situational awareness and de-orbiting of decommissioned satellites have formed a background part of insurers' overall risk assessment for both GEO and LEO insurance programs. In the future, the probability and consequence of collision are likely to become more primary considerations when underwriting this highly specialized class of business [32].

Case3.

Given the heightened probability of debris impact in LEO compared to GEO, insurers of satellites operating in LEO, especially in the most exposed regions around 800km should give additional consideration to damage to their satellites as a result of such debris impact. Depending on the terms of the policy, insurance coverage for a constellation would extend to loss, damage, malfunction or defect caused by a collision with space debris. The factors described above mean that the issue is of greater importance for insurers providing coverage for satellites or constellations in LEO as compared to GEO [33

5. Future Insurance Market

There are different aspects to insurance relevant for on-orbit servicing. The servicing vehicle may carry liability insurance, which would include launch and performance capabilities covering loss, damage, or failure. The satellite to be serviced may or may not be insured, but a contract with the servicer would outline expectations. Additionally, third-party liability insurance would cover damages imposed on an asset not involved in the servicing agreement.The availability of on-orbit servicing could one day lower premiums for satellites. Currently, premiums for on-orbit coverage are the lowest they have been in years, making it less likely for underwriters to lower them further. Satellite designers and operators may eventually know how insurers compare satellites having a conventional risk-mitigation profile to those having a contract with an on-orbit servicer. However, OOS technology needs to demonstrate greater maturity and readiness. Traditional satellites were not designed to be serviced, but the introduction of successful servicing could influence future designs. The amount and type of design change would depend on the intended servicer. For example, Orbital ATK claims that its MEV can interface with more than 80% of the satellites presently on orbit, limiting the need for substantial design changes [34]. National security space will likely see changes to its satellite designs and concept of operations as well. This indicates a shift from the status quo across multiple sectors. The insurance market, or any risk-management strategy, could potentially benefit from the proliferation of on-orbit servicing. Currently, the value of a satellite declines with time. Anomalies can occur throughout the lifetime of a satellite, and their impact on performance ranges from minor degradation to total loss of capability. Furthermore, 10% of anomalies occur within the first two months after launch—yet account for 36% of cases with full loss of capability [35]. Mechanical and electric power issues are the primary causes for loss—a likely area of focus for on-orbit servicing. Refueling alone could extend the life of a satellite, but is unlikely to increase its intrinsic value. The ability to do repairs or upgrades could conceivably improve upon the status quo, either by lessening the slope of the decline or by enhancing capability. If a satellite was built with a reliable bus, modular components, and the ability to get substantial software updates, the value could change with every servicing [36]. The opportunity for on-orbit servicing to have a unique symbiotic relationship with the insurance sector could provide ample assurance to this risk-averse base. The good news is that everyone recognizes the magnitude of risk in the space industry. Consequently, there are aligned incentives between commercial space companies and their insurers to mitigate risk and optimize performance [37].



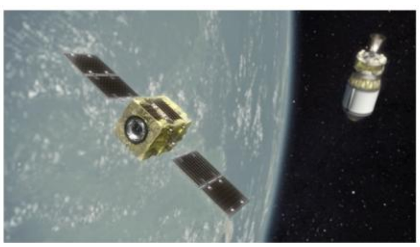
Capabilities necessary to service a satellite enables assessing the status of the satellite. Assessment of a technology is a key component of underwriting, once again making on-orbit servicing vehicles a potentially helpful tool for insurance companies. Furthermore, servicing could be used as a risk-mitigation tactic. Servicing or repair of a satellite could help to avoid catastrophic loss and could prevent the need for an insurance payout. In order to buy down risk, other factors to consider include

- ◆Metrics to determine when the capabilities are sufficiently mature.
- ◆Insurers to selectively determine which reliable and mature OOS capabilities necessary as a contractual mitigation strategy for adequate assessment.
- ◆Determination of a sufficient number of servicing vehicles needed for ready deployment [38.

The International Union of Aerospace Insurers reported that among its current topics of particular interest, or perhaps concerns, are LEO satellite constellations [39]. The current projected growth of LEO constellations adds thousands of new satellites into an already crowded and debris-filled domain [40]. This understandably adds more risk of collision and the possibility of interference. However, many of these large fleets reduce the risk of the service or mission failing. With hundreds of satellites on orbit, the loss of one or a few may not cripple the entire constellation, fundamentally changing the dynamics of the business environment. This is already causing insurers to pull out of the market for LEO. Assure Space, a space insurance underwriter, says that the company will continue to insure launches but will not insure LEO satellites for the near future. The managing director for Assure Space stated at a conference in March 2020 that he believes they are one to two years early but that eventually all space insurers will stop insuring LEO satellites. In his opinion, there is too much risk and too little being done about mitigating spac e debris or managing space traffic globally [41]. One thing to watch in the near future is how OOS and ADR missions may affect satellite insurance. The ability to fix, maneuver, or add fuel to a satellite on orbit decreases the cost of a failure and can increase the stability of the business case, if done in a responsible manner. This may allow for insurance premiums for satellites to lower, making insurance more accessible [42].

The large amount of space debris can cause serious security risks, especially for spacecraft in orbit. The harm of space debris to spacecraft is mainly caused by the huge kinetic energy of space debris when it hits. Specifically, it can be summarized as the following aspects [43]: (1) Changing the surface properties. The hits of high-frequency micro-sized space debris on the spacecraft surface may cause the optical lens surface to be frosted and unable to image. Or the radiation and absorption characteristics of the thermal control surface may be changed, resulting in a thermal control imbalance of the spacecraft. (2) Space debris itself with incredibly high speed and the surface material of the impacted spacecraft will vaporize and form plasma clouds, which will cause the spacecraft to malfunction. (3) The high speed collision between large space debris and the spacecraft will transfer huge kinetic energy to the spacecraft, which can change the attitude of the spacecraft and even the orbit. (4) Slightly larger debris will damage surface materials of the spacecraft or solar powered device. (5) When the energy of space debris is large enough, it will penetrate the surface of the spacecraft, causing serious damage to the spacecraft payload. More seriously, if the debris smashes into another object that is large enough, will produce a real explosion and thousands of further fragments. In addition, space debris can threaten the safety of astronauts and cause significant property damage.

European Code of Conduct for Space Debris Mitigation (ECCSDM) requires that satellites in the LEO protected region (< 2000km) are disposed of by destructive re-entry in the atmosphere within 25 years from their end of life [44]. Active Debris Removal technology constitutes a major part of on-orbit servicing sector for which ECCSDM will be executed. JAXA in partnership with an ADR startup Astroscale will remove some of the junk that exists on orbit.



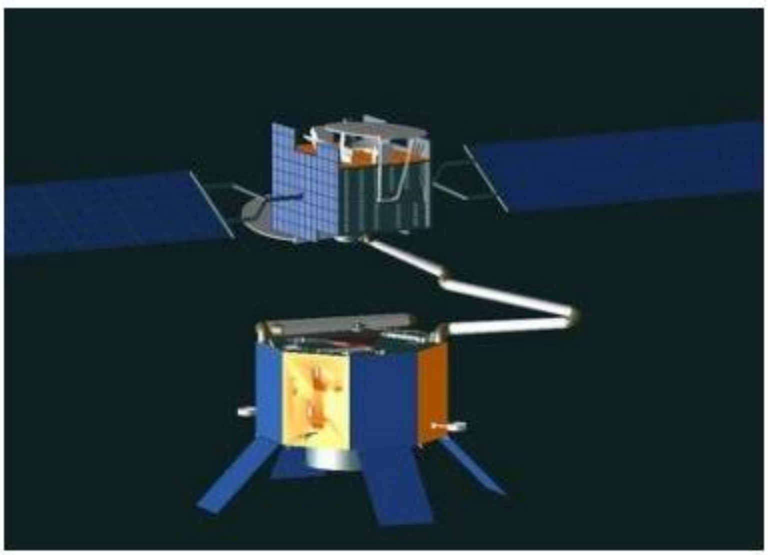
Source: Astroscale Selected as Commercial Partner for (Japan Aerospace Exploration Agency) JAXA's Commercial Removal of Debris Demonstration Project," Astroscale, Press Release, February 12, 2020, STS-51-A marked the first time a shuttle deployed two communications satellites, and retrieved from orbit two other communications satellites, Palapa B-2 and Westar Vl, for return to earth.. STS-51-A was the 14th flight of NASA's Space Shuttle program, as well as the second flight of Space Shuttle Discovery.

STS-51-A marked the first time a shuttle deployed two communications satellites, and retrieved from orbit two other communications satellites.

STS-51-A
Astronaut Dale Gardner achieves hard dock with Westar VI satellite
Credit: NASA

STS-51-A
Astronauts Gardner and Allen bringing Westar VI satellite into payload bay
Credit: NASA

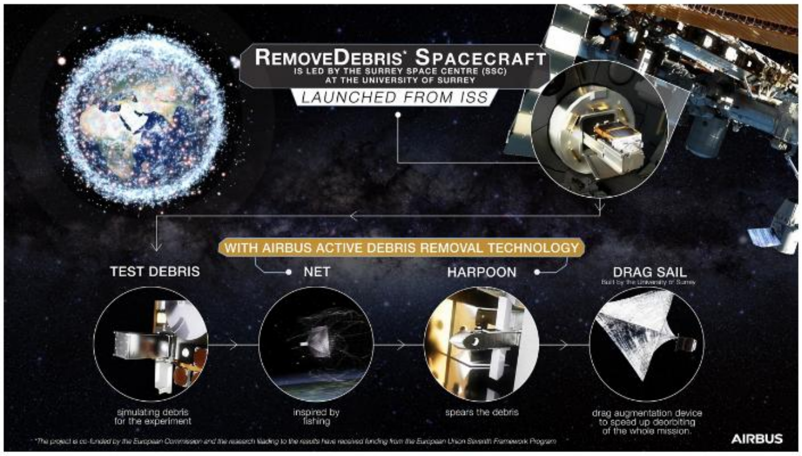
To safeguard the huge capital investments and the usability of the orbit itself, it will soon be indispensable to have adequate remote intervention means for the servicing and repair of satellites. Since the physical, technical and economic constraints of such a mission make servicing by astronauts impossible, robotised service vehicles will have to do the work. A robot-based Geostationary Service Vehicle similar to deep sea and nuclear servicing robots was being studied by European Space Agency [45].. A GSV would be unmanned, and the broad variety of tasks to be done, in combination with the unpredictable nature of the servicing tasks calls for a flexible and multi-functional flight segment. Robotic systems are the only means available to fulfill these needs. In addition a robot can be controlled in a telemanipulation mode by a remote ground operator.



— The GSV berthing an incapacitated GEO satellite

The RObotic Geostationary orbit Restorer (ROGER) studies focused on the need for and feasibility of a mission to control the threat from faulty satellites and large debris in the geostationary orbit. The geostationary orbit has a high commercial and strategic value and the satellite systems using it for telecommunication, TV broadcasting and weather forecasting represent a significant value in terms of capital investment and revenues. In order to preserve this resource for future satellite operations users have been encouraged over the years to re-orbit their satellites at end of life. This involves boosting the satellite to a graveyard region about 300 km above the GEO ring [46].

The RemoveDEBRIS mission has been the first mission to successfully demonstrate a series of technologies that can be used for the active removal of space debris in-orbit. The mission started in late 2014 and was sponsored by a grant from the European Communities. Surrey Space Centre developed the mission from concept to in-orbit demonstrations and terminated in March 2019. The mission was comprised of a main satellite platform (100kg) that was propelled to the International Space Station by a SpaceX Falcon 9 rocket, and then deployed by the NanoRacks Kaber systems into orbit. Technologies for the capture of large space debris, like tethered nets and harpoons, had been successfully tested together with hardware and software to retrieve data on non-cooperative target debris kinematics from observations carried out with on board cameras.



According to current estimates, there are more than 40,000 objects – equivalent to some 7,600 tonnes – of space junk floating in Earth orbit, posing significant collision threats to satellites and space stations. The RemoveDEBRIS project is aimed at performing key active debris removal (ADR) technology tests in search of the best ways to clean up space.

The German approach to serve, secure and de-orbit uncontrollable satellites is based on a robotic agent concept, a sufficient servicing satellite equipped with at least one manipulator. Primary mission goal is the capturing of a tumbling and non-cooperative client satellite with a manipulator on the servicing spacecraft and the re-entry (de-orbit) of the rigidly coupled configuration within a predefined orbit corridor. To achieve the envisaged goal a dedicated set of experiments has to be conducted where in general the complexity of the experiment execution will be stepwise increased over the mission period:

1. Far range formation flying experiments between servicing and client spacecraft have to be performed. This mission phase is characterized by methods of absolute navigation based on conventional GPS sensors and angle measurements provided by different ground stations. In addition the identification of dynamical parameters of the individual spacecrafts will be done during this phase.

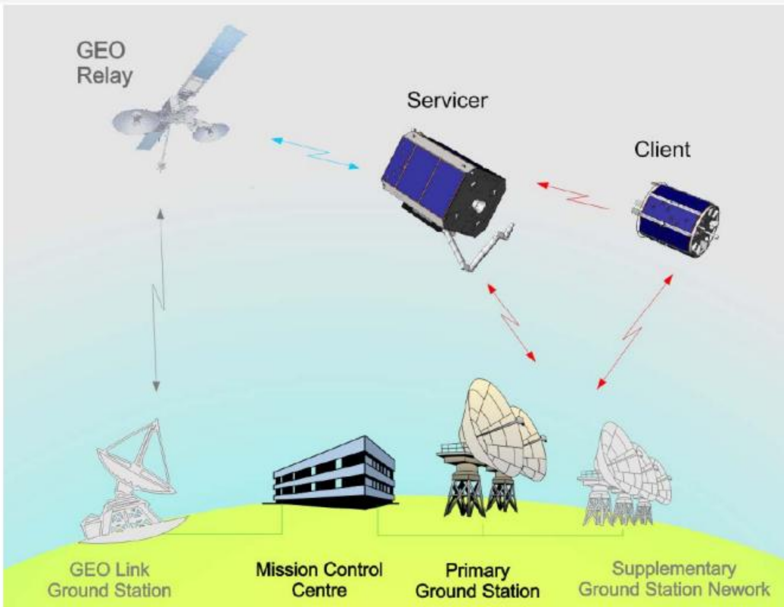
2. During the rendezvous phases the following experiments will be performed:
   - Approach of the servicing spacecraft to the non-cooperative client
   - Departure from the client
   - Execution of fly around and inspection maneuvers

   All these experiments are characterized by methods of relative navigation between servicing and client spacecraft, which are based on optical cameras or LIDAR sensors. They will be repeated several times under different illumination conditions.

3. The performance of the docking and berthing procedures between the servicing and the client spacecraft has to be demonstrated by different experiments. The berthing phase is characterized by grappling the client satellite using the so called manipulator end-effector of the servicing spacecraft and latching the client onto the berthing port. During the docking phase the servicing spacecraft approaches the client, inserts the docking interface of the client into the servicer's docking port and latches the client.

4. Finally, different flight maneuvers will be performed in a rigidly coupled configuration. They comprise

the execution of combined attitude and orbit maneuvers, the identification of dynamical parameters of the coupled configuration and the execution of special on-orbit servicing tasks with respect to the client. At last de-orbiting of the configuration rigidly coupled by the manipulator arm is foreseen, executed as a purposive re-entry within a given re-entry corridor [47].



DEOS Mission Ground and Space Segment Components (© STI, DEOS Mission Description Document, Space Tech GmbH (STI), January 2009)

One of the greatest challenges is how to reliably capture and remove a non-cooperative target, avoiding to generate even more space debris. To facilitate the development of active space debris removal, it is worth reviewing and comparing existing technologies on active space debris capturing and removal. TRL can be divided into 6 levels, 1 is basic technology research, 2 represents feasibility study, 3 represents technology development, 4 represents technology demonstration, 5 represents system / sub-system development, and 6 stands for system test or operation [48].

Table 3 Comparison of different ADR methods

Methods	Index		Orbit	Debris size	Removal cycle	Contact	TRL	Economy
Capturing removal	Manipulator		LEO~GEO	(0.1~1) m	Shorter	Rigid contact	6	Lower
	Tentacle		LEO~GEO	(0.1~1) m	Shorter	Rigid contact	6	Lower
	Tethered nets		LEO~GEO	(0.1~1) m	Shorter	Flexible contact	6	Higher
	Harpoons		LEO~GEO	(0.1~1) m	Shorter	Rigid contact	6	Higher
	Tethered space manipulator		LEO~GEO	(0.1~1) m	Shorter	Flexible contact	5	Lower
Propulsion deorbit	Laser	Ground-based	LEO	<0.02m	Short	Contactless	3	High
		Space-based	LEO~GEO	<0.02m	Longer	Contactless	3	Lower
	Ion beam		LEO~GEO	>0.1m	Longer	Contactless	3	Higher
	Solar radiation pressure		LEO~GEO	>0.1m	Long	Body contact	4	High
	Electrostatic forces		LEO	<0.01m	Longer	Contactless	2	Low
	Geomagnetic propulsion		LEO	>0.01	Longer	Contactless	1	Low
Drag augmentation	Inflatable deorbit		LEO	>0.1m	Longer	Contactless	3	Higher
	Expanding foam		LEO	>0.1m	Longer	Contactless	3	Higher
	Artificial atmospheric		LEO	>0.1m	Longer	Contactless	2	Lower

Conclusion

The volatility of cyclical space insurance market performance and insurers' reactionary adoption of exclusionary coverage of collision risks and other risks for satellite operations in Lower Earth Orbit have prompted greater autonomy of satellite operators in risk management. Declining spacecraft value and lower premium rates for their coverage decline frustrate insurers. The transformative impact of smallsats providing lower-cost missions and constellations, each with hundreds of smallsats sufficient with spares to consistently provide reliable mission performance through operational redundancy, empower the smallsat industry toward self-insurance. The growing threat of space debris for which space insurers based their exclusionary coverage for LEO satellites and collision risk is now addressed from within the satellite industry with technological research and development of active debris removal methods. On-orbit servicing satellites facilitate ADR with de-orbiting and re-positioning failed satellites to graveyard orbits. Other OOS satellites refuel, repair, and additively manufacture to replace damaged components. Hence, mission performance reliability is better managed and end-of-life extended. OOS satellites promote increased self-insurance for constellations of satellites. At the same time, OOS satellites appreciate in their value to the satellite constellation they serve. Therefore, the viability of space insurance market remains and encourages adaptation to a changing *spacescape* of satellite operations.

Notes and References

[1] Raviv, A. (1979). The design of an optimal insurance policy. *American Economic Review* 69, 84-96).

[2] Huberman, G., Mayers, D., & Smith, C. (1983): Optimal insurance policy indemnity schedules. *Bell Journal of Economics*, 14, 415-426

[3] Hirano, N. &. Chaney, L. (2019).www.aerospace.org)

[4] Stone, J. (l973a). A theory of capacity and the insurance of catastrophe risks. *Journal of Risk and Insurance* 40.

[5] Gould, A. & Linden, O. (2000). Estimating satellite insurance liabilities. In *Casualty Actuarial Society*, 47-84.

[6] Hirano, N. &. Chaney, L (November 2019) *End of an era? Satellite insurance faces changing landscape*. www.aerospace.org

[7] Schöffski, O., & Wegener, A. G. (1999). Risk management and insurance solutions for space and satellite projects. *The Geneva Papers on Risk and Insurance. Issues and Practice*, *24*(2), 203-215.

[8] Harrington, A. (2017). Legal and regulatory challenges to leveraging insurance for commercial space. *J. Space L.*, *41*, 29.

[9] Interview Richard Rankin, Brandywinecreek LLC; August 20, 2019. Hirano, N. &. Chaney, L. (November 2019). *End of an era? Satellite insurance faces changing landscape*. www.aerospace.org

[10] Schöffski, O., & Wegener, A. (1999). Risk management and insurance solutions for space and satellite

projects. *The Geneva Papers on Risk and Insurance. Issues and Practice*, *24*(2), 203-215.
[11] Canis, W. (December 12, 2016). Commercial space industry launches a new phase. *Federation of American Scientists*,.
[12] Hirano, N. &. Chaney, L. (2019).www.aerospace.org); Kunstadter, C. *Personal Interview. June 22, 2018*.
[13] Berger, L..& Kunreuther, H. (1994). Safety first and ambiguity. *Journal of Actuarial Practice 1993-2006, 153*.

[14] Cao, S. (09/20/19). Rocket insurance is a complicated branch of the booming space industry. *Observer*

[15] Hirano, N. &. Chaney, L (November 2019). *End of an era? Satellite insurance faces changing landscape*. www.aerospace.org
[16] Johnson, S. & Rohrer, M. (2018). Small satellites impact global compliance. *Standards, Licensing and Data Access Technology-Build a Business Plan to Address these Impacts*
[17] Reesman, R. (2018). Assurance through insurance and on-orbit servicing. *The Aerospace Corporation Center for Space Policy and Strategy*.
[18] Chrystal, P., Mcknight, D., & Meredith, P. (2018). New space, new dimensions, new challenges. How satellite constellations impact space risk. *Zurich, Switzerland*
[19] Zocher, H. (1989). Raumfahrtversicherung von SchaÈden stark beansprucht. *Versicherungswirtschaft 44* (1), 63-69.
[20] Hirano, N. &. Chaney, L (2019).www.aerospace.org); Kunstadter, C. *Personal Interview*. June 22, 2018.)
[21] Zhao, P., Liu, J., & Wu, C.(2020). Survey on research and development of on-orbit active debris removal methods
[22] 18 U.S.T. 2410. (January 27, 1067). Treaty on principles governing the activities of states in the exploration and use of outer space .
[23] Xu, W., Lian, B., Gao, D., & Xu, Y. (October 18-22, 2010). A Space Robotic System Used for On-Orbit Servicing in the Geostationary Orbit. *The 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems.*
[24] Johnson, N. & McKnight, D. (1991). *Artificial space debris*. Krieger: Orlando, FL.
[25] NASA/TM-2008-214779. (June 2008). *History of on-orbit satellite fragmentations*, 14th Edition,
[26] Reesman, R. (2018). Assurance through insurance and on-orbit servicing. *The Aerospace Corporation Center for Space Policy and Strategy*.
[27] Global Aerospace (June, 2020). Space *insurance and the new era of space exploration..*

[28] Chrystal, P., Mcknight, D., & Meredith, P. (2018). New space, new dimensions, new challenges. How satellite constellations impact space risk. Zurich, Switzerland
[29] Chrystal, P., McKnight, D., Meredith, P., Schmidt, J., Fok, M., & Wetton, C. (2011). Space debris: On collision course for insurers?. *Swiss Reinsurance Co. Publ., Zurich, Switzerland*
[30] Freeman, R. H. (2020). Can space insurance underwriters keep up with a growing commercial space industry? In *ASCEND 2020* (p. 4200)
[31] Werner, D. (March 11, 2020). Assure Space won't cover collision risk in low Earth orbit. *SpaceNews*
[32] Global Aerospace (June 29, 2020). Space insurance and the new era of space exploration
[33] Global Aerospace (June 29, 2020). Space insurance and the new era of space exploration
[34] Reesman, R. (2018). Assurance through insurance and on-orbit servicing. *The Aerospace Corporation Center for Space Policy and Strategy*
[35] Kunstadter, C. (2017). Space insurance update 2017, *International Union of Aerospace Insurers*
[36] Reesman, R. (2018). Assurance through insurance and on-orbit servicing. *The Aerospace Corporation Center for Space Policy and Strategy*.
[37] Johnson, S., Corcoran, M., & Rohrer, M. (2017). *Platforms designed for big data provisioning with small satellite constellations.*
[38] Reesman, R. (2018). Assurance through insurance and on-orbit servicing. *The Aerospace Corporation Center for Space Policy and Strategy*
[39] Schenone, "2019 Space insurance update."
[40] Analytical Graphics Inc. (December 18, 2019). 10 Years of Planned Satellites - *Spacecast 28,*YouTube video.
[41] Debra Werner, "Assure Space won't cover collision risk in low Earth orbit," Space News, March 11, 2020.
[42] Rebecca Reesman, *Assurance Through Insurance and On-Orbit Servicing* (El Segundo, CA: Aerospace Corporation, February 2018)

[43] Grujicic M, Pandurangan B, Zhao C, et al. Hypervelocity impact resistance of reinforced carbon–carbon/carbon–foam thermal protection systems. Appl Surf Sci, 2006, 252: 5035-5050
[44] Rathgeber W, Remuss N-L, Schrogl K-U. Space security and the European code of conduct for outer space activities. In: Disarmament forum, 2009
[45] Visentin, G.. &Brown, D. (1998). Robotics for geostationary satellite servicing. *Robotics and Autonomous Systems*, *23(1–2)*, 45-51.
[46] Bischof, B., & Kerstein, L. (2002). Roger-robotic geostationary orbit restorer. *cosp*, *34*, 30.
[47] Rupp, T., Boge, T., Kiehling, R., & Sellmaier, F. (2009, September). Flight dynamics challenges of the german on-orbit servicing mission DEOS. In *21st international symposium on space flight dynamics* (Vol. 22). German Aerospace Agency Toulouse
[48] Shan, M., Guo, J., & Gill, E. (2016). Review and comparison of active space debris capturing and removal methods. *Progress in Aerospace Sciences*, *80*, 18-32.