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SPACE DEBRIS MITIGATION MEASURES AND COST ISSUES

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ABSTRACT

The space debris environment is highly dynamic. There are processes that cause an increase in the object population. The most significant is the fragmentation of spacecraft. Other processes lead to a reduction of the object population. The most important influence is the residual drag of the atmosphere on Low Earth Orbits (LEO) which causes many objects to descend. It would be preferable if at least a balance between both processes could be achieved so that the number of objects in space may not increase further. Overall, however, a continuous increase in the number of space debris objects is observed. Computer simulations show that the rising trend will continue in the future due to two causes. On the one hand, the number of objects in space continues to increase due to spaceflight activities. Particularly on sun-synchronous orbits (SSO), this leads to a high accumulation of debris. On the other hand, the probability of catastrophic collisions in SSO increases. Due to the high collision velocities resulting from the particular impact geometry on satellites or rocket bodies in SSO, high-energy collisions are expected on these orbits. The resulting debris will lead to a further increase in collision risk. It is therefore advisable not to release any more debris on SSO. However, it is expected that even in the case of a suppression of all future explosions, an increase in orbital debris generation will occur due to accidental collisions. Therefore, the implementation of further mitigation measures like controlled de-orbiting or active removal is reasonable. The implementation of mitigation measures is costly. The discussion of preliminary cost estimations is the subject of this paper.

INTRODUCTION

On Low Earth Orbits (LEO) particularly high collision velocities may occur. The potential risk of space debris is caused by the high kinetic energy that can be released in a collision. The collision velocities on LEO are in the order of ten kilometers per second. A risk for an operating spacecraft exists for a particle diameter of about one millimeter. At this size, a satellite structure can be damaged. A particular risk is posed by objects that are larger than about one centimeter. Such objects can put a satellite out of operation. They penetrate every structure, even if it is covered with multiple walls for protection. Generally it is not possible to protect structures against impacts of objects that are larger than about one centimeter. Currently there are about 700,000 man-made objects larger than one centimeter on all Earth orbits. The number of objects larger than one millimeter is estimated to be 200 million [9]. The number of objects in the sub-millimeter range is several trillion. The most dangerous objects exist between one and ten centimeters in diameter. They are too small to be tracked and too big for protective measures.

A significant amount of the larger orbital objects is continuously tracked by sensors. The catalog of orbital data generated from these measurements includes about 16,300 objects (s. Fig. 1) [10]. This orbital data is published and made available for analysis purposes. The cataloged objects, however, make up only a small fraction of the actual space debris population. The existence of smaller objects is known from sporadic measurement campaigns [9]. But their orbits cannot be tracked. The number and the orbital distribution of small objects must be described by statistical models. These models must have the capability to reproduce the sporadically obtained measured data. Especially in the millimeter and centimeter range there are large uncertainties due to missing data. The latest version of the European space debris model, called MASTER-2009 was developed under ESA/ESOC contract at the Institute of Aerospace Systems, Technische Universität Braunschweig. The simulated distribution of orbital debris is shown in Fig. 2 to 4.

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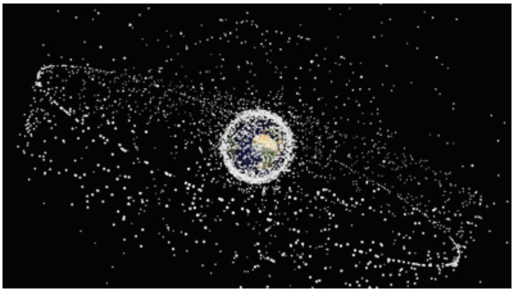

Fig. 1: The number of cataloged objects is 16,300.

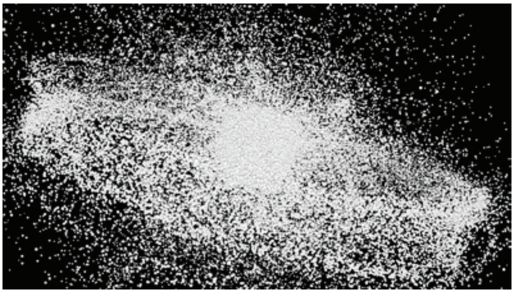

Fig. 2: The number of objects larger than one centimeter is about 700,000 according to MASTER-2009.

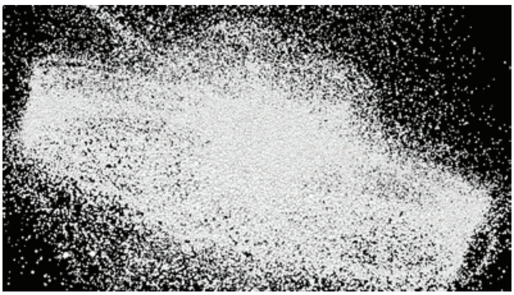

Fig. 3: The number of objects larger than one millimeter is about 200 million according to MASTER-2009.

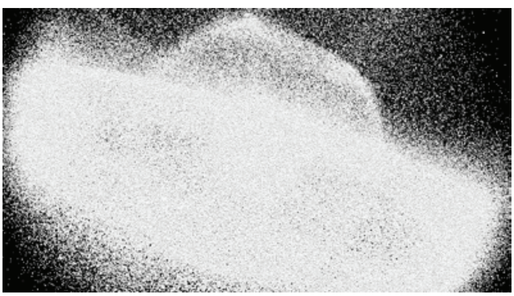

Fig. 4: The number of objects larger than one tenth millimeter is several trillion according to MASTER-2009.

The amount of debris has increased significantly in the recent past, due to further fragmentation events. The three most important were the Cosmos/Iridium collision, the destruction of Fen-Yun 1C and the explosion of Briz-M. The impact of events on the spatial density of the reference period May 1, 2009 is shown in Fig. 5 to 7.

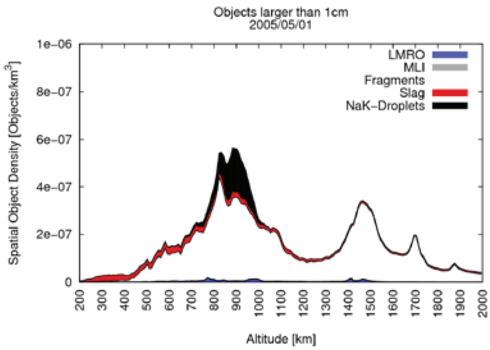

Fig. 5: Spatial density of debris larger than one centimeter in 2005 according to MASTER-2009.

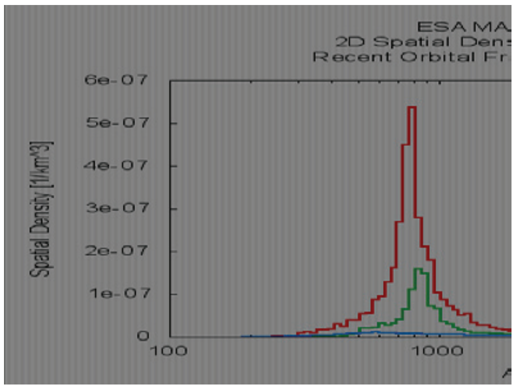

Fig. 6: Spatial density of debris larger than one centimeter in 2009 of three recent major events according to MASTER-2009.

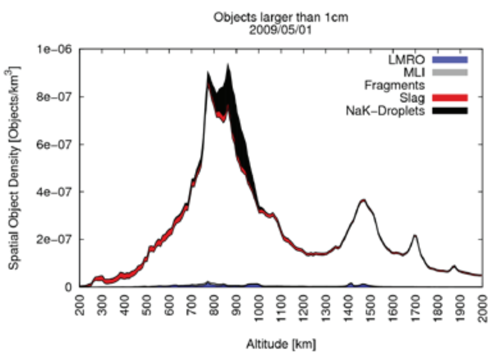

Fig. 7: Spatial density of debris larger than one centimeter in 2009 according to MASTER-2009.

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HIGH RISK ORBITS

It is important to identify the main risk factors for the most important orbits. For these orbits it is useful to implement regulations on the mitigation of space debris. The highest spatial object density exists at altitudes near 900 km. (Only in the micrometer size range, the highest density is found near 1000 km.) This can be shown by simulations. Below 900 km, the orbital lifetime of objects decreases due to the atmospheric drag, leading to a reduction in spatial object density towards lower altitudes. Above 900 km altitude, space activities decrease so that less debris is produced here. Generally speaking, the collision risk increases with the spatial object density. So the highest risk of collision with debris exists on nearly polar orbits, especially sun-synchronous orbits near 900 km altitude. In polar or near polar orbits the probability for head on collisions is very high. In this case the collision velocity equals two times the orbital velocity resulting in extremely high kinetic energies.

INSTABILITY OF THE LEO POPULATION

The occurrence of catastrophic collisions can be expected in regions where the highest spatial density of debris objects exists. Using the long-time simulation tools LUCA (Longterm Utility for Collision Analysis), it can be examined on which orbits catastrophic collisions can be expected. The locations of future catastrophic collisions were calculated assuming a business-as-usual scenario and using an initial population from the ESA MASTER model. Fig. 8 shows the increase of the spatial density.

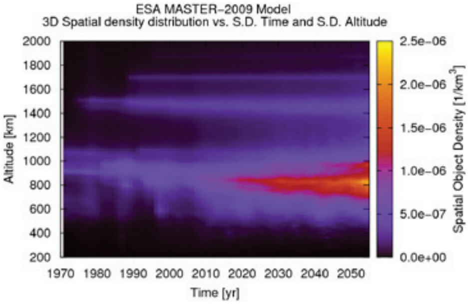

Fig. 8: Spatial density of objects larger than one centimeter versus time on LEO according to MASTER-2009.

The highest concentration of orbital debris can be found in 900 km orbital altitude. At this altitude the highest probability of collision exists. Looking at orbital inclinations i, mostly sun-synchronous satellites ($i \approx 98°$) are expected to collide with Russian objects at $i \approx 82°$ (s. Fig. 9). This will lead to very high-energy head-on collisions at twice the orbital velocity near the Earth's poles. Many of them may occur as catastrophic collisions. Today, catastrophic collisions are still not a big problem. On average, they occur every 5 to 10 years. But if spaceflight activities continue in the current way, collisions will occur more frequently and may become the dominant effect in the generation of space debris in the future.

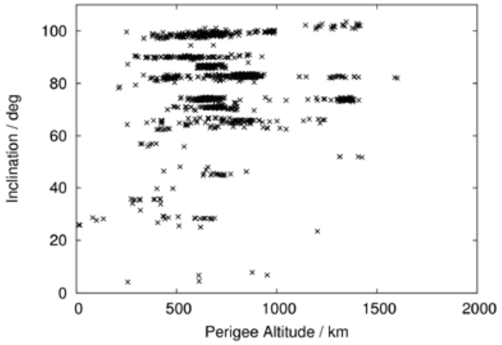

Fig. 9: Location of catastrophic collisions from eight Monte-Carlo runs in future business-as-usual scenario; collision orbit altitude and inclination.

The simulations indicate that with the increasing number of active and decommissioned spacecraft, the likelihood of catastrophic collisions will increase. If the released debris in turn trigger catastrophic collisions, this can lead to a cascading increase in the generation of debris. This collisional cascading effect is also known as a collision chain reaction effect or Kessler Syndrome [2,3].

MITIGATION MEASURES

There is awareness of the risk that arises from the generation of orbital debris. Workshops and conferences are being held with the sole purpose of discussing possible methods for active debris removal. Recommendations are available for the introduction of mitigation measures. Examples of such guidelines are the IADC's (Inter-Agency Space Debris Coordination Committee) Space Debris Mitigation Guidelines [6]. The goal of such recommendations is to keep the space environment in a state that allows the use of all the important orbits in the future. The IADC guidelines in particular recognize that there are certain orbit regimes which are more important than others and which should therefore be protected. The two so called 'protected regions' which have been introduced are a LEO region which spans from Earth's surface up to an altitude of 2000 km and encompasses all declinations and the geosynchronous region which is defined as the geosynchronous altitude ±200 km and a declination band between -15 and +15 degrees from the equator. One option for mitigating space debris is to reduce the number of objects which are produced

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during or after a mission. The other possibility is to remove objects from the protected orbit regions either by performing end-of-life maneuvers or by other measures. Options which belong to the first category are prevention of mission related objects (MRO), prevention of solid rocket motor slag or passivation. Measures which belong to the second category are the reduction of the orbital lifetime, insertion into disposal orbits or active removal. It is important to note also that not all approaches are applicable to all objects. All of them have their own warrant. The applicable ranges and the effectiveness are briefly outlined in the following sections.

Reduction of the orbital lifetime

The goal is to remove large objects with high orbital life-times from orbit and cause them to re-enter, so that they cannot serve as collision partners in the future. A direct re-entry trajectory is desirable from a debris mitigation stand point, but it is often not feasible for various reasons. On the one hand, it requires a large amount of fuel and is therefore costly. Another reason is that special conditions must be met in conducting controlled re-entries which may also be complex as-well as costly. Reducing the orbital life-time may also mean that an object is maneuvered into an orbit which will cause it to re-enter within a defined time frame. The IADC Space Debris Mitigation Guidelines for instance propose a 25-year time frame. Both cases are only applicable to satellites on low Earth orbits. Using this method for higher orbits would cause high costs related to the significant re-entry burn and also temporarily increase the collision risk between the objects on re-entry paths with operational satellites on lower orbits.

Disposal orbits

Satellites in geostationary orbits are transferred to an elevated disposal orbit, where they remain. This option is also possible in the LEO region and has been used for certain mission types such as the Russian RORSAT (Radar Ocean Reconnaissance Satellites). A significant part of GEO satellites have performed such end-of-life maneuvers in the past decade.

MRO Prevention

Satellites should avoid releasing objects during their mission. Examples of such objects are instrument covers or explosive bolts. Many of these objects are relatively large and can trigger catastrophic collisions.

Slag Prevention

Solid rocket motors typically use aluminum to enhance the effectiveness of an engine. This aluminum oxidizes during the burn and may remain in orbit for significant amounts of time as slag particles reaching diameters of several centimeters or as sub-millimeter sized dust particles. The release of slag particles can be prevented, if motors with solid fuel are replaced by liquid engines. This reduces the number of objects in the centimeter range and lower size regimes. Although these objects do not seem to cause catastrophic collisions this mitigation measure makes sense, because the slag particles are the second largest contributor to the object population in the centimeter range.

Passivation

The object generation due to unintentional fragmentations of spacecraft or upper stages is the main contribution to space debris [5,9]. The causes are on board energy sources. Most of the fragmentations involve an explosion of the propulsion systems. By removing the residual energy it is possible to reduce the number of such fragmentation events. This can be done, for example by releasing residual fuel and oxidizer through a valve into space [1]. The fragmentation of satellites due to battery explosions almost never occurs today, but has been an important contribution in the past [7]. Also the rate of fragmentation events which can be traced specifically to remaining propellants has decreased noticeably. In spite of measures obviously being taken to passivate space craft, accidents still occur as was seen in February 2007, when a malfunctioning Briz-M upper stage exploded on a highly elliptic orbit with almost its entire propellant still on board [4,7].

De-Orbiting

Decommissioned heavy satellites and upper stages, which are exposed to a high collision risk, are the main drivers of the collision chain reaction effect. For such spacecraft, it may be useful to perform a controlled de-orbiting maneuver. The object is re-entering at EOL above a certain geographic region, for example an uninhabited sea area. This method is useful for heavy objects. Such objects should not perform an uncontrolled re-entry, to avoid that they may fall into populated areas.

Active Removal

Currently, a further measure is discussed. It is the active removal of larger objects with high orbital lifetimes and which reside in orbits with very high spatial object density. The background will be outlined in this work. The reason for the discussion lies in the imminent onset of the collision chain reaction effect especially on sun-synchronous orbits [5]. These orbits are used by many Earth observation satellites. The measure involves the removal of objects that are already in orbit. A recovery vehicle would dock with such objects and maneuver them into a re-entry trajectory.

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REMOVAL OF COLLISION PARTNERS

A catastrophic collision can be triggered in principle by projectiles with sufficiently high kinetic energy for destroying a target object. Generally, projectiles with diameters of about 10 cm have this capability [8]. The number of these projectiles is much higher than the number of target objects. To reduce the probability of catastrophic collisions, it makes sense to remove those target objects with the highest collision risk. In a first step, this requires the establishment of a priority list.

Priority Targets

In order to achieve a maximum benefit-to-cost ratio for each individual ADR mission, potential targets within the critical orbit region have to be ranked by defining an appropriate priority criterion. The top 500 of these potential target objects are shown in Fig. 10.

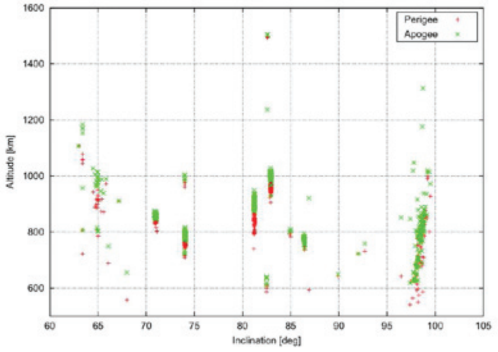

Fig. 10: Top 500 potential target objects.

This criterion is defined as a function of the collision probability and the mass of the target object. While it is clear that with increasing collision probability the ranking value should also increase, the mass indicates how many new debris objects will result from a catastrophic collision. Thus, an increasing mass implies an increasing risk to other objects. An alternative method to derive a priority ranking is based on the flux, which can be processed for each object using the ESA MASTER-2009 model. MASTER considers all relevant space debris sources and meteoroids down to one micron for historical as well as future populations. In this study only objects larger than one centimeter in size are considered for flux calculations, including cataloged objects, launch- and mission-related objects, explosion and collision fragments, solid rocket motor slag and sodium-potassium droplets. This is due to the fact that only objects greater than about 1 cm (mostly close to 10 cm) possess enough kinetic energy to cause a total fragmentation event. The ranking criterion shall be defined as a function of the flux and the mass of the target object. Only objects with a mass greater than 100 kg are considered for the determination of the ranking, neglecting those objects which spend only a small fraction of time in the critical region, e.g. objects in high-eccentricity orbits. The priority ranking shows, that there are a lot of geometrically similar rocket bodies among the top listed objects. The priority list of the top 20 target objects is shown in Tab. 1.

# Rank	Inc . [deg]	Perigee [km]	Apogee [km]	Mass [kg]
1	64.9	806.7	815.3	16800
2	98.6	787.8	789.2	8111
3	63.4	807.0	807.0	10000
4	97.8	270.9	1047.1	12900
5	71.0	849.2	852.0	9000
6	71.0	816.9	851.5	8226
7	71.0	845.6	852.8	8226
8	71.0	843.9	852.5	8226
9	71.0	846.9	848.3	8226
10	71.0	845.9	856.1	9000
11	71.0	839.1	852.1	8226
12	82.6	470.9	1236.7	9250
13	71.0	839.8	857.2	8226
14	86.5	740.5	763.3	661
15	71.0	835.9	857.5	9000
16	71.0	834.8	852.2	8226
17	97.7	632.2	656.0	8300
18	98.3	805.9	818.9	8226
19	71.0	839.9	855.7	8226
20	71.0	834.1	857.1	8226

Table 1: Priority list of the top 20 target objects with the highest probability of a catastrophic collision.

Cost Estimation De-Orbiting

A controlled de-orbiting of a satellite or upper stage is one option to re-enter a spacecraft. But for this task the spacecraft requires an onboard propulsion system. The propulsion system of a satellite is designed for the orbital operation like for example reaction control. The propulsion system performance is limited to this task. If a spacecraft needs an additionally velocity increment for the performance of the de-orbit maneuver without reducing the operational lifetime, then the existing propulsion system cannot perform this task. The satellite has to be equipped with additional or enlarged propulsion system components like fuel tanks or engines. It is assumed that a de-orbit maneuver is performed with an additional propulsion module due to the limited capability of the reaction control system. The size of the propulsion module is estimated from collected data on subsystem masses, based on regression analyses. The fuel mass is calculated as a function of the velocity requirement, assuming that at EOL the dry mass of the satellite including the propulsion module have to be de-orbited. The estimated mass of the propulsion module is used as an input parameter for the cost model. The

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result for the cost estimation of de-orbiting for the 20 priority targets is shown in Tab. 2.

# Rank	Delta-V [m/s]	De-Orbiting Cost [Mio. $FY11]
1	202.48	10.08
2	196.80	7.69
3	201.47	8.33
4	163.48	8.42
5	212.40	8.24
6	208.30	7.94
7	212.05	8.00
8	211.80	8.00
9	211.65	8.00
10	212.50	8.24
11	211.15	7.99
12	213.20	8.33
13	211.88	8.00
14	187.49	4.36
15	211.43	8.22
16	210.63	7.98
17	159.57	7.07
18	202.83	7.84
19	211.70	8.00
20	211.15	7.99

Table 2: Cost estimation for de-orbiting of the priority target objects, using a hypothetical onboard propulsion system.

Cost Estimation Active Removal

The cost estimate for active removal is based on the assumption that a sophisticated service satellite maneuvers a target object to a direct re-entry trajectory. The service satellite will be launched from Earth and maneuver into the orbit of the target object. After a rendezvous and docking maneuver (using for example a robotic manipulator), the service satellite shall perform a controlled re-entry maneuver together with the target object. For this, a maneuver is performed that lowers the perigee to 80 km. This allows the direct atmospheric re-entry of the target object along with the service satellite. The target object has to be selected from the priority list, resulting in a specific fuel requirement for each selected target. Another assumption is that the robotic manipulator has a constant mass of less than 100 kg. In this preliminary cost model, the total cost of the mission is taken into account, including the expensive development of the satellite. The size of the satellite depends on the fuel consumption. In this first cost estimating approach, it is assumed that the service satellite itself is lost during the mission. The result of the cost estimation is shown in Tab. 3. The result shows that active removal is about two orders of magnitude more expensive than de-orbiting with an onboard propulsion system.

# Rank	Delta-V [m/s]	Active Removal Cost [Mio. $FY11]
1	202.48	759
2	196.80	479
3	201.47	552
4	163.48	550
5	212.40	539
6	208.30	504
7	212.05	510
8	211.80	510
9	211.65	510
10	212.50	539
11	211.15	509
12	213.20	549
13	211.88	510
14	187.49	148
15	211.43	537
16	210.63	508
17	159.57	419
18	202.83	494
19	211.70	510
20	211.15	509

Table 3: Cost estimation for active removal of the priority target objects, using an expendable service satellite.

Electric Propulsion

There is the option being discussed to increase the performance of the service satellite by equipping it with ion engines to guarantee efficient maneuverability. One possible advantage of this technique would be the ability of the spacecraft to fly to several removal targets during a mission and thus to increase the effective use of the satellite. To investigate this, it is necessary to extend the cost model to ion engines. In evaluating the possible options for a cost effective removal of spent rocket upper stages and satellites, it is necessary to conduct a supplemental investigation. This investigation will deal with the question, whether a reusable, electrical propulsion module can be used on board the service satellite to remove a target object. Such a satellite may have cost saving options, due to its reusability and longevity compared to conventional chemical propulsion modules. A disadvantage of reuse is however, that no direct re-entry of the target object is possible. The target could only be moved close to the upper layers of the atmosphere. Then the service satellite has to be disconnected from the target and starts a long-lasting elevation maneuver to prevent not entering into the atmosphere and being lost. For the target object an uncontrolled re-entry has to be accepted in this case. It has to be discussed what remaining lifetime appears to be acceptable for the target object. In the case of using ion engines a cost model has to be developed, which includes the development and production costs of the propulsion module. Basically it can be assumed that the removal

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maneuver is independent of the delta-velocity due to the low fuel mass consumption, in contrast to chemical engines. However, the development and production costs of an electric propulsion module exceed that of chemical engines. It needs to be analyzed, whether a break-even point exists, where the cost due to mass increase of chemical fuel is higher than the hardware cost of an electric propulsion module. Above this point, ion engines may be cost effective.

SUMMARY

The cost estimate performed here was carried out for the top 20 target objects of the priority list. Here, de-orbiting is compared with the active removal. It turns out that de-orbiting is much cheaper than a subsequent active removal. De-orbiting is only possible if a propulsion module exists onboard the target object. In fact, this capability does not exist onboard the historic objects in the priority list. The cost estimates shown here for the top 20 objects is therefore purely hypothetical. The cost estimate for active removal is based on a preliminary cost model. It is based on the assumption that for each target object, an expendable satellite is developed and launched, and that the satellite is lost after one use. This is the most expensive option, which is conceivable. A cost reduction option could be to develop a standardized satellite type and reuse it. The satellite may then be used for multiple active removal missions. A further upgrade of the cost model is therefore required. This will give the basis for long-term simulations of the future debris environment and cost-benefit analyses.

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