ANALYSIS OF DEBRIS MITIGATION SCENARIOS IN TERMS OF COST AND BENEFIT

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ABSTRACT

Appropriate measures for minimising and controlling the debris environment have been clearly identified in the past. This paper addresses the cost / benefit ratio of debris mitigation. The costs are determined by the system and subsystem modifications and the fuel needs for orbit manoeuvres associated with debris mitigation. The benefit can be expressed in spacecraft that will not run into a damaging collision due to debris mitigation. Direct and indirect benefits are considered. The analysis was performed by an upgraded version of the long term debris environment model LUCA. First results are presented. A significant impact on the cost benefit ratio is the bandwidth of the growth of the future population due to uncertainties related to the traffic models, statistical effects, etc. The related bandwidth is quantified and it is shown, which spatial regions could be subject to uncontrolled population growth taking into account also economic considerations.

1. INTRODUCTION

A study program concerning the cost and benefit analysis of debris mitigation has been initiated at the Technical University of Braunschweig. The reason for this kind of study is not the question, whether debris control and minimisation is necessary or not. There is no doubt among the debris experts that future space flight must include the avoidance of mission related objects, the prevention of explosions in space, de- and re-orbit of spent upper stages and payloads.

Both methods to introduce debris mitigation as a kind of standard space flight procedure, i.e. by internationally agreed upon and binding principles (IADC, UN) or by informal agreements based upon national regulations, are possible. But the first method may be subject to longer discussions and negotiations. In any case, space flight industry and satellite operators must contribute to the process of defining debris mitigation standards. And this is under way.

However, the necessity of debris mitigation is not always clear to satellite operators and space industry. They are responsible to the share holders and this, of course, is reflected by a different view concerning the debris problem. The economic benefit [1] of investing in debris mitigation is the key point of their considerations. This benefit can be expressed by

- the mission costs due to space debris in a business as usual (no mitigation) scenario compared to the missions costs considering debris mitigation
- the time until the investment in debris mitigation will lead to effectively reduced mission costs

Both aspects are a function of the point in time of debris mitigation implementation. Typically, cost and benefits of debris mitigation can be quantified as given in Fig. 1.

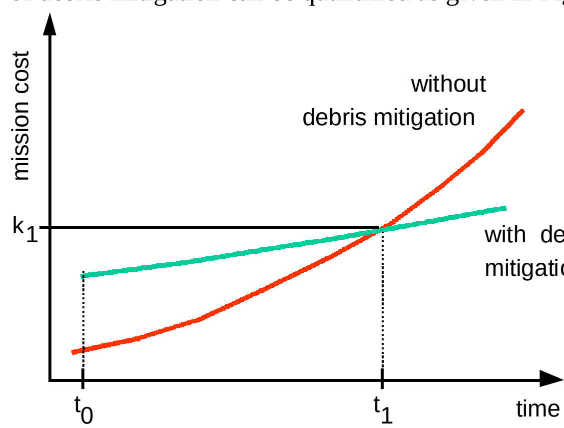

Fig. 1. Principle cost net benefit of debris mitigation due to mitigation implementation time

The point in time t0 depicts the implementation of debris mitigation measures, t1 is the break even point. In any case, there will be a certain phase (t1 – t0) until the break-even point is reached. Until then, the costs of debris mitigation have no direct economic benefit.

The methods used for the analysis of the possible future environment are becoming more and more sophisticated. However, due to all the unknown parameters in the traffic models, statistical effects, etc., a certain bandwidth has to be considered in the population trend curves.

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This principle bandwidth is shown in Fig. 2. It can be seen, that the uncertainties are growing with time. This does not improve the accuracy of the cost analysis. The same applies for all the uncertainties concerning future space flight activities, such as launch rates, launch sites, mission profiles, launcher technology, and types of payloads. But the goal should be to convince space flight industry and satellite operators to invest in a limited and controlled future debris environment.

One of the major concerns in this connection is that probably someone could bear the costs for debris mitigation who not will have a direct benefit from his investment, but others.

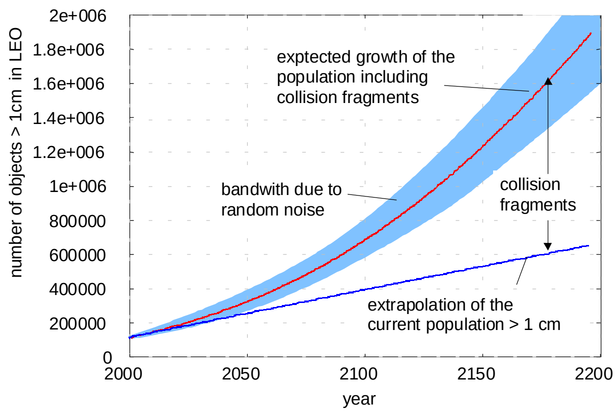

Fig. 2. The principle growth of the future debris population > 1 cm in LEO without any debris mitigation

2. DEFINITION OF COST AND BENEFIT

The mission costs and the benefits with and without debris mitigation consists of a number of items. It is difficult to quantify these items in a common sense. Hence, the following gives an overview, including quantities where applicable. An example of an expense profile for a mission is given in Fig.3. It can be seen that any changes in the system design should be implemented at an very early stage of the project. This is why missions already in preparation can not be subject to cost-effective debris mitigation measures.

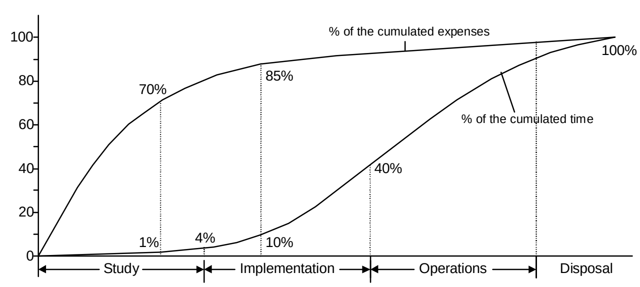

Fig. 3. Characteristic expense profile of a mission

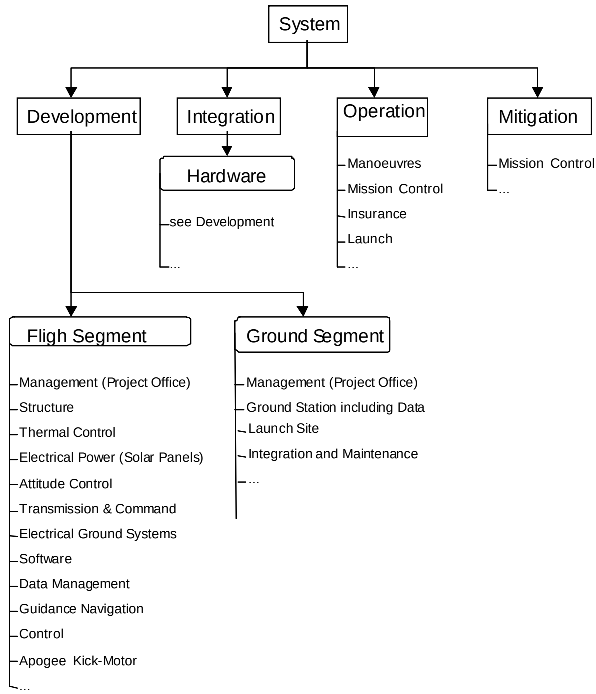

Fig. 4. Life cycle of a mission and related cost items

Fig. 4 gives an overview on the life cycle of a mission and related cost items. Generally, all cost items can be subject to changes due to debris mitigation, depending on the related requirements and the state of development, when debris mitigation is introduced into planning.

2.1 Mission costs due to the debris hazard

Mission costs can be increased by orbital debris hazards concerning the following items:

- total loss of operational launcher/spacecraft at any time of the mission due to a collision
- damage on operational launcher/spacecraft at any time of the mission due to debris impact
- operational costs and extra fuel (lifetime/mass penalty, respectively) for collision avoidance including the costs for debris detection, for selected missions
- shielding development, mass penalty, replacement for selected missions, e.g. ISS
- extra insurance rates

The above type of costs are already part of the mission costs. Their relevance will increase with an increasing debris population. Shielding and collision avoidance has been set to the list, even if they are called passive debris mitigation measures also. In this sense they protect selected missions, the limitation of the debris population is a 2nd order goal. From the investor's point of view the increased survivability of his mission is given and required from general safety (in case of manned missions) or economic reasons.

2.2 Costs due to debris mitigation

Debris mitigation in terms of minimisation and control of the debris environment can have an impact on the following cost items:

- mission and spacecraft (re)-design for spacecraft passivation and minimisation of mission related objects (MRO)
- design costs, operational costs and extra fuel (lifetime/mass penalty, respectively) for de- or re-orbit at end-of-life (EOL)
- design costs, operational costs and extra fuel (lifetime/mass penalty, respectively) for collision avoidance including the costs for debris detection
- shielding development and mass penalty

Shielding and collision avoidance has been set to the list also. Here, the limitation of the debris population is a 1st order goal. By avoiding a collision with a larger object or increase the survivability of the system by shielding a controlled de- or re-orbit at EOL can be ensured. From the investor's point of view, the increased survivability of his mission is given, but not required in any case.

2.3 Benefits due to debris mitigation

The benefits due to debris mitigation, compared to a business as usual scenario, are as follows

- reduced loss of operational spacecraft
- reduced damage on spacecraft
- reduced shielding mass
- reduced number of collision avoidance manoeuvres
- reduced insurance rates
- preserving the possibility of future missions in currently used orbital regions and those not yet used, preventing collision cascading in the far future

Some or all of the above items may not touch the investor`s mission directly. An unmanned spacecraft in 900 km altitude does not have any benefits, if the safety of a space station requires less shielding mass. On the other hand, the spent spacecraft or its fragments would soon or later pollute the station's environment.

As stated in connection with Fig. 1, there will be no economic benefit for the investor until the break-even point is reached. The last point of the above list may not convince an investor, since it is relevant outside his interest in terms of the orbit region or time interval. Especially the prevention of collision cascading, which according to Fig. 2 may set in after 2100, is not of interest from the economic point of view as of the year 2000. The fact that the collision cascading process can only be stopped, if one controls the growths of the number of large objects as soon as possible, may be clear to everyone. But no economic figure can be correlated with this finding, since the benefit will be entered into the books very late.

3. QUANTIFYING THE COSTS

In the following, some examples will show the difficulties and the bandwidth in quantifying costs that may occur in the future due to the debris risk and due to debris mitigation measures.

3.1 Business as usual

Fig. 5 depicts a business as usual scenario of the future development of the objects larger than 1 cm in LEO. The MASTER'99 population [3] has been used as initial population. Here, one single Monte-Carlo-run is analysed, not the average of a complete series of runs, since any random development is as probable as another. This is to show how specific the future debris environment may develop due to a huge number of parameters not known at present. In the example presented here, a growth factor 2.3% per year linearly has been chosen for the basic population.

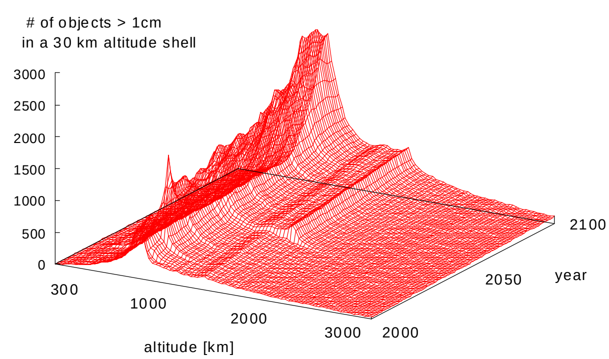

Fig. 5. Example for a business as usual simulation of the future debris population > 1 cm in LEO, 2.3% per year growth of the basic population assumed, overview

The breakdown of the overall population growth is given in Fig. 6. It can be seen, how conservative the scenario is. In reality, the future debris population could develop conservatively. In the above simulation, the collision fragments will not dominate the population in this Monte-Carlo case. According to Fig. 2, this would occur later and outside of any economic interest.

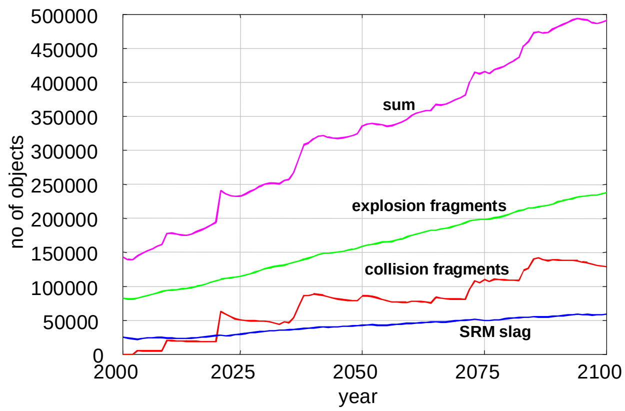

Fig. 6. Example for a business as usual simulation of the future debris population > 1 cm in LEO, 2.3% per year growth of the basic population assumed, population breakdown

The number of destructive collisions has been determined to be 34 (68 colliding objects) based on the above simulation. In order to quantify the direct cost related to these events, Tab. 1 gives a detailed collision description.

Table 1. Destructive collisions occurring in business as usual simulation according to Fig. 6

Type of objects involved in a destructive collisions	**total (operational) number**
payloads	19 (4)
rocket bodies	17
others	8
collision fragments	13
explosion fragments	11

There are 4 operational satellites out of 19 payloads involved. The related mission times have been one year and less. This means, from the economic point of view, the loss of 4 operational satellites right after their launch within a time frame of 100 years. All others colliding objects are not of commercial interest. Furthermore, there are 13 collision fragments involved. This might by the evidence for reaching the critical density.

3.2 De-orbit and explosion prevention

Fig. 7 shows how lifetime reduction to 25 years for rocket bodies and payloads and the prevention of explosions would control the future debris environment. Again, a single Monte-Carlo run is analysed as an example. For this case it was assumed that both measures are implemented immediately. The number of collisions is reduced to 14.

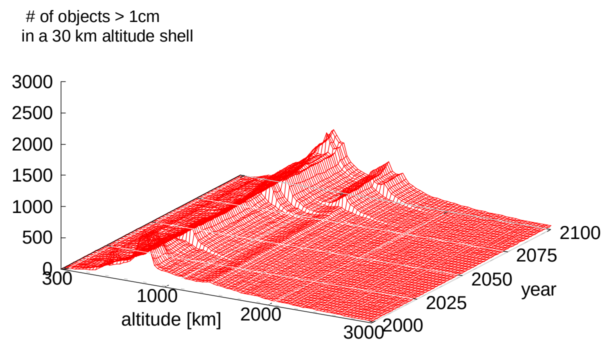

Fig. 7. Example for future debris population > 1 cm in LEO, immediate de-orbit and explosion prevention

Fig. 8 shows the related development of the sub-populations. At the year 2080 explosion fragments, collision fragments, and SRM slag contribute a third each to the total population.

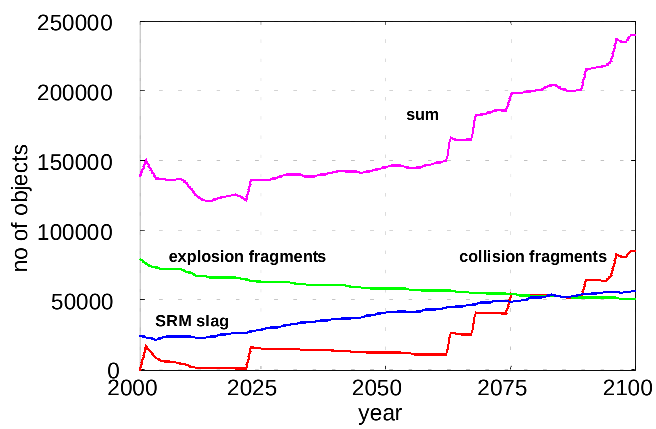

Fig. 8. Example for the future debris population > 1 cm in LEO, immediate de-orbit and explosion prevention

Table 2. Destructive collisions occurring in a mitigation simulation according to Fig. 8

Type of objects involved in a destructive collisions	**total (operational) number**
payloads	12 (4)
rocket bodies	8
others	3
collision fragments	2
explosion fragments	3

Tab.2 shows that the number of operational payloads is, by chance, the same as in the business as usual case. The related mission times are 1 to 7 years. Hence, no economic benefit is not given. The collision fragments involved occur after about 100 years.

The effort for the lifetime reduction of the payloads is summarised in Tab. 3, not taken into account the design costs as stated in section 2.2. The maximum propellant mass fraction tolerated for the lifetime reduction was 20%. Although the scenarios are not identical, the results are comparable to those obtained in [2].

Table 3. Lifetime reduction statistics for the mitigation scenario according to Fig. 8

Item	
payloads launched	4,920
payloads de-orbited to 25y lifetime	1,100
rocket bodies launched	3,680
rocket bodies de-orbited to 25y lifetime	1,390
total delta v required	420 [km/s]
average delta v required	0.17 [km/s]
average fuel mass fraction	10.2 %

Examples of the related orbits, which would lead to a lifetime of 25 years, are given in Fig. 9 in terms of perigee and apogee altitude. Fig. 10 indicates the fuel mass fraction required for lifetime reduction as a function of the apogee altitude.

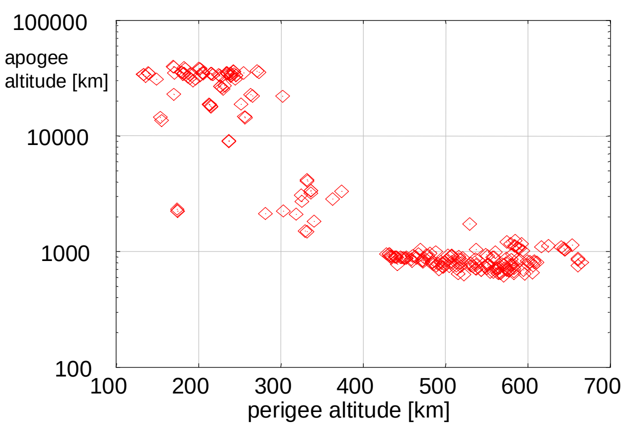

Fig. 9. Orbits leading to reduced lifetime for the mitigation scenario according to Fig. 8

Some other benefits shall be addressed in this connection. The net increase of objects > 1 cm will be limited to 100,000 objects by the above mitigation scenario, while business as usual in the same time may lead to an increase of about 350,000 objects. The benefits from this reduction are less mass for shielding, less non-destructive impacts (which also can lead to damage) and reduced collision avoidance manoeuvre frequencies. At this stage of the analysis, no quantities can be given for the related costs. This will be one of the results of the ongoing study.

The example shows that the cost benefit relation in this case is not very effective, if the next 100 years are considered. Obviously the benefit will occur later.

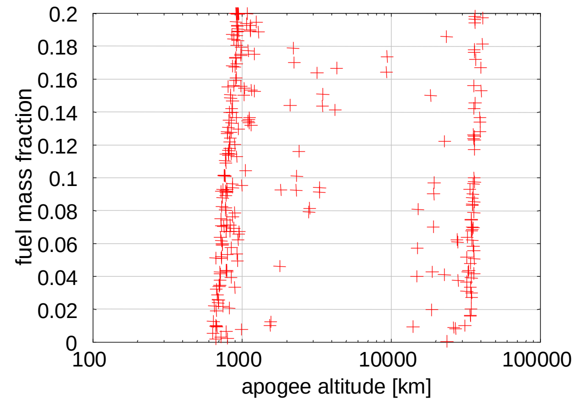

Fig. 10 Propellant mass fractions required to reduce the orbital lifetime according to Fig. 8

3.3 <u>Prevention of explosions and SRM slag</u>

A scenario has been analysed, were no de-orbit but the prevention of explosions and of further SRM slag generation were simulated. Fig. 11 shows that also this mitigation measures could lead to a certain control of the population. However, in this case the population peak at about 1,500 km reaches the same level as the 800 km peak after 75 years due to collisions. This of course is one random results. However, it indicates that these measures without de-orbit would not be sufficient on the long term, even if there are implemented immediately.

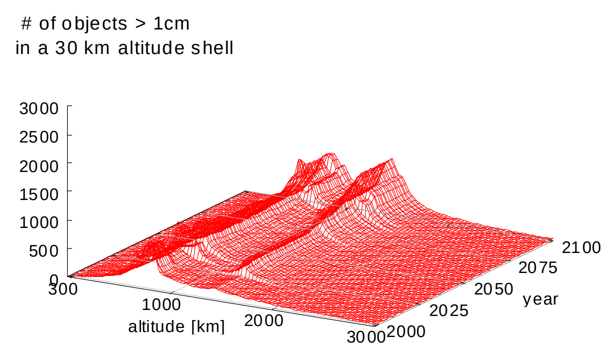

Fig. 11. Example for the future debris population > 1 cm in LEO, immediate explosion and SRM slag prevention

This is underlined by the population breakdown given in Fig. 12. It can be seen that collision fragments then would dominate the population after 60 years. This is due to the fact that neither explosions nor SRM slag are responsible for destructive collisions.

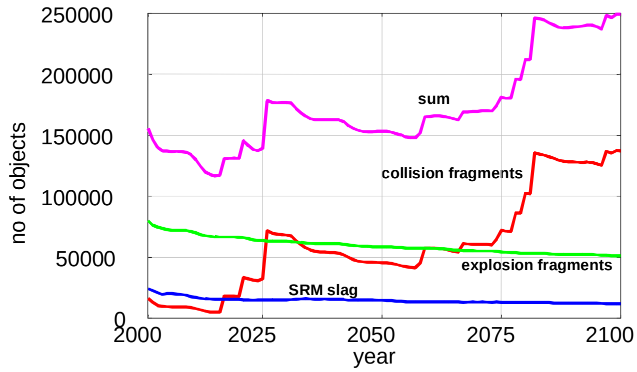

Fig. 12. Example for the future debris population > 1 cm in LEO, immediate explosion and SRM slag prevention

Fig. 13 shows the development of the number of object larger than 1 cm for the above simulation scenarios at 400 km altitude. The effect of an assumed SRM slag prevention can be seen, since slag dominates this altitude according to he MASTER`99 model. Most of the SRM slag contributions at that altitude are due to GTO insertions. Hence, the costs for modifying the related motors would have benefits for GEO spacecraft as well as for low altitude missions.

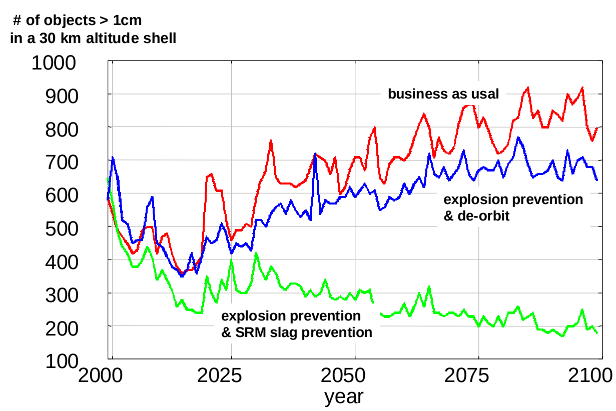

Fig. 13. Population growths at 400 km altitude for the above simulated scenarios

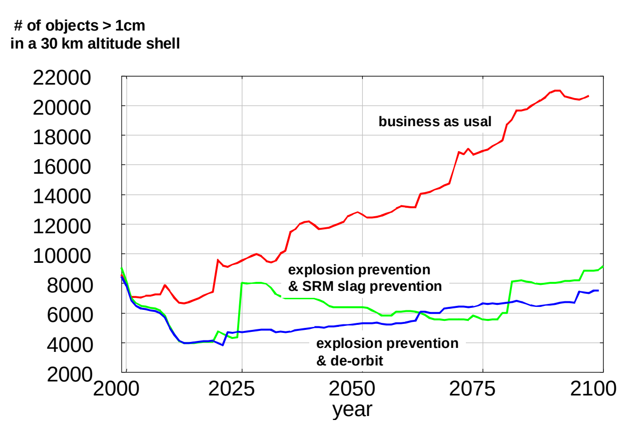

Fig. 14. Population growths at 915 km altitude for the above simulated scenarios

At 915 km altitude, for example, Fig. 14 applies. Here, the effects of both mitigation scenarios analysed are comparable in terms of the benefit of controlling the environment.

4. SUMMARY AND CONCLUSION

The Monte-Carlo results shown in this paper have been randomly chosen from a large variety of traffic model assumptions and stochastic effects. Such individual and even probable scenarios, besides general trends discussed in earlier analysis, should also be taken into account for discussing costs and benefits. However, for the general discussion they are examples. They will be completed and discussed subsequently in connection with analysis concerning the costs and benefits of debris mitigation in the GEO region including a detailed analysis of cost effective debris mitigation related modifications on launcher and spacecraft subsystem level.

But it can be concluded that the break even point of cost and benefit of debris mitigation measures in the LEO region may not be reached within a time frame, which is of any economic concern. However, the necessity of debris mitigation is proven, since business as usual would lead to an unrecoverable overcrowding of the near Earth environment or to collision cascading in a longer time frame. In order to establish effective mitigation a soon as possible, economic aspects are not appropriate to convince space industry and satellite operators. Hence, there is a need for international agreements or even regulations, which should have a binding character as far as achievable.

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