COSTS AND BENEFITS OF SPACE DEBRIS MITIGATION

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ABSTRACT

We have conducted a series of simulations of several low-Earth orbit (LEO) missions to examine the cost effect of a growing debris population for several different mitigation scenarios. By comparing the best and worst of these, we find that it is cost-effective to raise mission costs by about 1-1.5% now, and still save money by reducing mission costs in the long run. This compares with 3-4% according to an earlier estimate by Greenberg and Reynolds [1].

We have also made a simple calculation of the cost of end of life (EOL) orbit-raising of geostationary (GEO) satellites.

1. INTRODUCTION

When considering whether to adopt space debris mitigation measures, and to what extent, businesses will naturally want to balance costs with potential benefits. This paper discusses some work we have done in addressing this question, and outlines problems and potential refinements that can be made to the analysis.

2. PREVIOUS WORK

A short description of other work by other researchers will serve to put the ensuing analysis into context.

Reference [2] considers the debris hazard from a broader economic perspective, some points of which are summarised thus:

1. space debris represents a low probability, high consequence event;
2. a catastrophic collision with a manned platform is likely to have serious repercussions on all space programs;
3. even a moderate real (or perceived) impact risk, short of a serious collision, will probably raise mission costs;
4. the cost-benefit tradeoffs of debris mitigation should be balanced;
5. it is probably cheaper to prevent debris from accumulating than to remove it once it is there;
6. some sectors stand to *gain* from a worsening debris problem;
   i) industries in direct competition with space-based applications, e.g., fibre optics, may gain benefit;
7. the non-adoption of mitigation measures by some parties may be due less to a reluctance to implement them than to ignorance of the relevant space debris issues.

In contrast, Greenberg and Reynolds [1] concentrate on the financial effects of space debris on two specific remote-sensing missions: Landsat and Topex. In their simulations, a series of satellites is deployed in orbit consecutively; when one satellite reaches its end of life (EOL) – after about 3.5 years for Landsat, and 4.2 years for Topex – it is replaced by another, and so on for fifteen years. The same mission is then run starting from different points in time, and as a result of debris growth the mission cost gradually increases. The cost penalty occurs mainly for two reasons:

1. more units need to be built, and more launches are required;
2. scheduled launches must be brought forwards in time in the event of an on-orbit failure. Because of the "time value of money" (see below), a higher cost results.

They also included the effects of launch failures and on-orbit failures, with associated delays.

They concluded that satellite recurring costs can be increased by up to 3-4% now to incorporate mitigation measures, and still be cost-effective in the long-term.

3. PLAN

To arrive at an upper limit for cost-effective mitigation, a representative cross-section of missions should be considered. Therefore, we aim to apply Greenberg's and Reynold's analysis to a wider range of missions, particularly to constellations, which are likely to populate the LEO environment in increasing numbers from now on. Owing to space considerations we will consider only two constellation types here, and one mission in sun-synchronous orbit. We also estimate the cost of GEO-satellite EOL orbit-raising separately. The plan for the simulations is as follows:

• Simulate a mission, with all major associated costs: development, construction and launch costs.

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• Include launch failures (from a uniform random distribution), on-orbit malfunctions (randomly determined according to a defined distribution), and space debris collisions (also random determined, but weighted according to the debris impact probability).

• Run the mission a large number of times (2,048), starting every year from 2000 to 2100 to obtain a cost variation with time, and standard deviation, due to the growing debris hazard.

• Use the results from a debris growth model to estimate the debris flux, and therefore the associated cost penalty, for four different mitigation scenarios.

3.1 Assumptions

• The base cost for a given mission, before taking into account the effect of debris, remains constant in time, i.e., the cost of a future mission in terms of today's money, is the same.

• The launch success rate is a flat 95%.

• The probability of a satellite's surviving to time t in orbit without failing (t = 0 at deployment) follows a simple exponential law:

$$P = e^{-\lambda t} \tag{1}$$

where $\lambda = 0.03$ per year in orbit, and t is measured in years. Although this is a simple model, and not strictly correct for redundant systems, its precise form is thought not to affect the final results significantly.

• The damage to constellations will never be serious enough to result in loss of revenue, i.e., there will always be a spare satellite on hand to take over operations without interruption. This allows us to avoid the complications of estimating lost revenue.

3.2 Discount Rate

The present value of future money is determined using the discount rate. Future costs gradually become less and less significant in present-day terms the further forwards they occur.

The discount rate can vary year by year (sometimes greatly), depending on interest rates, other economic factors, and which economist you consult. We have used a value of 5.5% per year, since historically (in the 20th century at least), it appears to be roughly the mean. Greenberg and Reynolds used 10% per year, at which higher value the present value of money diminishes faster with time. A thorough analysis ought to take into account the sensitivity of the results to the discount rate used.

Note that we apply the discount rate to bring all future costs *for one mission* to the present – we are not applying it when considering the present cost of future, *separate* missions.

4. DEFINING THE COLLISION PARAMETERS

The probability of occurrence of an impact capable of causing satellite failure is the most critical parameter, and also a very difficult one to define. Larger debris is obviously more likely to destroy a satellite, but is also rare. The important size range seems to be between 1 mm and 1 cm: 1-mm debris would have a large cost effect (we estimated 30-50% of the mission cost) *if* an impact with an object of this size invariably destroyed a satellite.

Greenberg and Reynolds found that 1-cm debris will have a negligible cost effect on the mission they simulated (because of the rarity of impacts). 6.31-mm and 3.16-mm debris will have respectively greater effects, with the latter increasing mission life-cycle costs by several percent. However, although 3-mm debris is quite capable of causing failure if it strikes a vulnerable component, it is by no means certain that this will be so for any location on the satellite. Therefore, the final cost values may have been overestimated.

We have therefore struck a balance between both limits, and considered 6.31-mm debris mainly, although we try to provide other examples.

5. DEBRIS GROWTH RATES IN LEO

Results from the debris population model EVOLVE have been used to estimate future debris fluxes in LEO. A series of runs were conducted by the EVOLVE team at NASA JSC for the four different mitigation scenarios below:

- S1: business as usual (BAU): same launch and explosion frequency as today, and no end-of-life de-orbiting of either payloads or rocket boosters;
- S2: explosion prevention, mission-related debris prevention, and end-of-life payload disposal within a period of 25 years, starting from 2010 (no rocket booster disposal);
- S3: as S2, but with rocket booster disposal included, also starting from 2010;
- S4: as S3, but with end of life payload disposal and rocket booster disposal starting from 2050 (explosions and mission-related debris eliminated from 2010, as in S2 and S3). This allows the consequences of a late adoption of some mitigation practices to be investigated.

Explosion prevention assumes 100% suppression for all satellites and rockets from the stated year.

Very detailed and useful growth data were obtained for 1-cm, 10-cm and 1-m debris for a variety of orbital inclinations and altitudes. We will concentrate on the 1-cm debris results. Since no growth data are available for smaller-sized debris, we have used the same growth rate as that of 1-cm debris. Typical growth curves at a 700-km, 98.5° inclination orbit are shown below in Figure 1.

For missions running beyond 2100 (for only a few years) we have relied on extrapolating a simple functional fit to each curve, either a second- or third-order polynomial, or a power law.

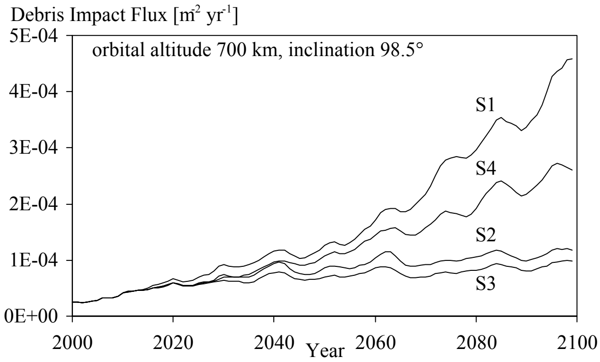

Fig. 1. 1-cm debris growth from 2000 to 2099 for an example orbit, as determined by EVOLVE, for the four different scenarios specified in the text.

6. LEO

It is not immediately clear whether constellations stand to lose more or less (financially speaking) as a result of the space debris hazard. On the one hand there is a greater number of satellites exposing a larger total cross-sectional area, but on the other there is (or ought to be) the routine presence of on-orbit spares to deal with the sudden loss of a payload. Perhaps debris hits are so infrequent that not enough satellites are destroyed to require an extra launch. A simulation can clarify the picture.

We have therefore conducted Montecarlo simulations for two types of LEO constellation, as well as for a single satellite in sun-synchronous orbit. Constellation launches are carried out in batches of six, every four to five weeks. Launch and on-orbit failures are also considered. A debris impact is assumed to induce satellite failure in all cases.

6.1 Orbcomm-type mission

The basic details of the Orbcomm-type mission are shown in Table 1. Since the satellite lifetime is four years, we consider four generations of satellites, bringing the total operational period to 16 years.

The net present value of the total mission cost is shown in Figure 2 for scenario S1. From top to bottom the curves are for 1-mm, 1.995-mm, 3.162-mm and 1-cm debris. The 1-mm case is shown only for comparison, since it is not expected to be a hazardous size.

Table 1: Basic details of the Orbcomm-Type simulation.

Discount Rate	5.5%
Development Cost	\$150 million
Recurring Cost Per Unit	\$1.2 million
Satellite mass	33 kg
Satellite bus cross-sectional area	0.5 m^2
Satellite design life	4 years
Launch Cost (for a batch of six)	\$18 million
Insurance	Self-insurance
Total number of units in constellation	32 + 6 spares

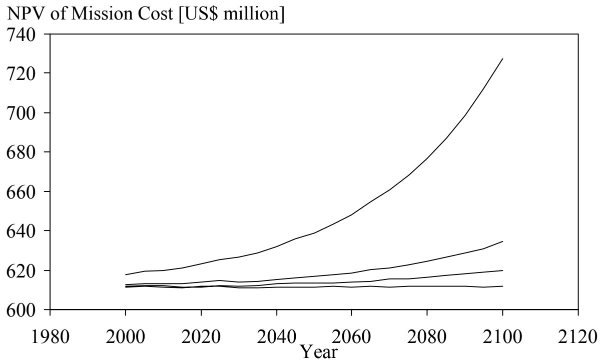

Fig. 2. Net present value of an Orbcomm-type mission with year initiated, for mitigation scenario S1. From top to bottom: 1-mm, 1.995-mm, 3.162-mm and 1-cm debris.

Teledesic-Type Mission[1]

The parameters for a Teledesic-type simulation are described below.

Table 2. Basic details of the Teledesic-Type simulation.

Discount Rate	5.5%
Development Cost	\$180 million
Recurring Cost Per Unit	\$18 million
Satellite mass	750 kg
Satellite bus cross-sectional area	5 m^2
Satellite design life	7.5 years
Launch Cost (for a batch of six)	\$50 million
Insurance	Self-insurance
Total number of units in constellation	288 + 32 spares

Two generations of satellites are considered, bringing the total mission time to 15 years. Once again, it is assumed that any on-orbit malfunctions, due either to debris or component failures, will be dealt with very quickly by replacement by an on-orbit spare, so that no loss of revenue is suffered.

The net present value of the mission as a function of start date for 3.162- and 6.31-mm debris is shown in Figure 3 for scenario S1. There is a negligible effect for 1-cm debris, so it has not been plotted. Scenario S3 also gives a flat distribution, so this case has also not been included.

[1]The constellation design was taken from the Teledesic Web page, and may have since been modified.

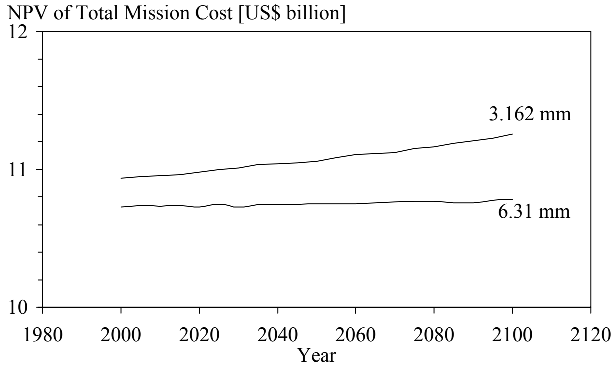

Fig. 3. Variation in the present value of the total mission cost of a Teledesic-type mission with year initiated, for 3.162-mm and 6.31-mm debris, for scenario S1, assuming that an impact with an object of each respective size will induce satellite failure.

6.3 Sun-Synchronous Orbit

The mission parameters are given below

Table 3. Sun-synchronous satellite simulation details.

Discount Rate	5.5%
Launch Insurance	15% of satellite and launch cost
Satellite Bus Cross-Sectional Area	10 m^2
Orbital Parameters	altitude 700 km (circular), inclination 98.5°
Development Cost	$320 million
Satellite Cost	$180 million for the first unit, with a 90% learning curve for subsequent units
Launch Cost	$60 million for a batch of six satellites
Operational Cost	$2.6 million per year
Satellite design lifetime	5 years
Mission Lifetime	10 years

The mission consists of two satellites launched back to back, spanning ten years. Any orbital failures will result in delays while a spare is launched, in which case the simulation continues until the ten full on-orbit years have been completed. If a satellite is half-way through its design life at this point (as would happen after a failure disrupts the schedule) the simulation ends there and then. In reality, the mission might continue if additional funding were found for the extra costs; we do not consider this alternative. The base cost of the mission (no debris, but launch and on-orbit failures included) is US$ 933.05 ± 68.42 million.

The cost impact on the entire mission, including debris, for scenario S1 is shown in Figure 4, and for S3 in Figure 5. The x-axis shows the mission start year (start of actual on-orbit operations). The error bars are not shown because of their size, but are consistently about ±US$65-70 million. Surprisingly, even at 1 cm a small cost effect can be seen, which increases for 6.31-mm debris.

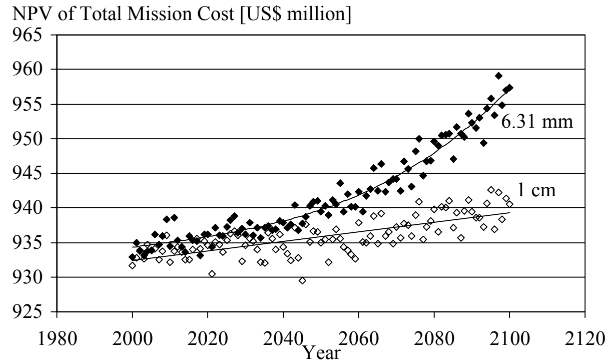

Fig. 4. Net present value of total mission cost as a function of start year, for mitigation scenario S1.

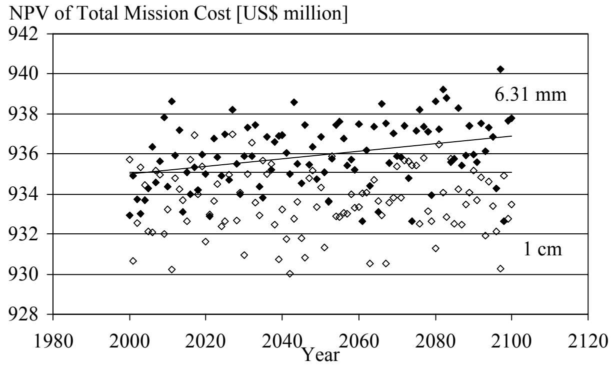

Fig. 5. Net present value of total mission cost as a function of start year, so mitigation scenario S3.

It is evident that mitigation S3 is very effective in limiting the growth in mission cost.

7. GEO

The present-day collision hazard in GEO as determined by MASTER 99 is around two to three orders of magnitude lower than in LEO, depending on debris size; rocket-motor slag in GTO contributes almost 80% of the flux at 1 cm, and around 85-95% at 3.162 mm and 1 mm. Table 4 shows some typical fluxes.

Table 4. GEO and LEO debris fluxes compared.

	GEO Flux	LEO Flux[2]	Ratio
1 cm	1.005×10^{-7}	1.677×10^{-4}	1670
3.162 mm	3.089×10^{-6}	1.037×10^{-3}	336
1 mm	8.493×10^{-5}	1.668×10^{-2}	196

According to modelling done in Reference [3], the negative consequences of not suppressing explosions and of no EOL orbit raising do not become apparent until about 150 years after the start of the simulation (1993). Even if the 1-cm debris growth rate matches that of LEO over the next century, the financial impact is expected to be small.

[2]For a 98.5° circular orbit of altitude 900 km, with the solar activity option turned off.

We will therefore concentrate only on estimating the cost of orbit raising to the recommended 300 km above the GEO band. The delta-V requirement for this is 10.88 m s^{-1}. Using general values for liquid propellant exhaust velocities [4], and station-keeping delta-V requirements, the reduction in mission life is estimated to be about 2-4 months. Since the amount of remaining fuel near EOL is usually subject to some uncertainty, we will work with the upper limit of this range.

Equation (2) expresses the cost difference between a mission consisting of a series of N satellites of recurring cost C_{unit} per satellite, and design lifetime L (in years), and another identical mission but with the design lifetime of each unit shortened by four months. r is the discount rate expressed as a decimal (e.g., 5.5% is 0.055). This does not include any extra operational costs that might be incurred.

$$C_{unit} \cdot \sum_{i=2}^{N} \frac{1}{(1+r)^{(i-1)L}} \left(\frac{1}{(1+r)^{-\frac{(i-1)}{3}}} - 1 \right) \qquad (2)$$

Table 5. Example costs for GEO satellite EOL orbit raising.

Design lifetime [years]	Discount rate	Cost of original design life [US$ million]	Cost of shortened life [US$ million]
10	5.5%	289.22	292.67
10	10%	230.13	233.46
15	5.5%	247.29	249.59
15	10%	194.51	196.23

Plans by some operators to provide services in the "inclined orbit phase", lengthening a satellite's usefulness by up to three years and generating additional revenue, suggest that calls for mission life reduction for orbit raising will not be well received. The potential loss in revenue by curtailing the possibility of inclined-orbit operations is, however, a subject that ought to be looked at in more detail.

8. COST-EFFECTIVE MITIGATION

How much can we afford to spend on mitigation, and still save money in the long run? Greenberg and Reynolds estimated a value of about 3-4%, depending on debris growth rate, and size considered.

This is, of course, only valid as long as mitigation measures are universally applied!

To estimate the limit of extra expense some adjustment factor, such as the long-term interest rate, is required to convert the future costs of unconnected missions to the present. Greenberg & Reynolds used the "real cost of capital", assigning it a value of 3%. In the absence of better information, we will assume a value of 2%, noting that higher values will reduce the extra allowable cost substantially (by a factor of 3 if a 5% long-term interest rate is used).

Mission costs from 2000 to 2100 in present-day money are summed (assuming a new mission starts every year) for both scenarios S1 (the worst case) and S3 (the best), weighted by a long-term discount factor. The extra allowable cost is the amount by which the S3 curve can be shifted vertically in 2000 so that the sum from 2000 to 2100 just equals that of scenario S1.

8.1 Sun-Synchronous Mission

The results is a difference of US$5.8 million, or an extra 0.6% of the total mission cost with a discount rate of 2%, which, if concentrated solely in recurring costs, will allow about a US$2.5 million increase per unit, or 1.4% of the satellite construction cost.

8.2 Teledesic-Type Constellation

The extra affordable cost is about 0.24% of the total mission cost (US$25 million), for 6.31-mm debris, or 1.3% (US$ 140 million) for 3.162-mm debris – 0.3% and 1.5% respectively if used only in the recurring costs.

8.3 Orbcomm-Type Constellation

The allowable extra cost is very small. For a long-term discount rate of 2% (and 3.162-mm debris), the extra allowable mission cost is about 0.22%, or 0.3% if used only in satellite recurring costs. For a 5% discount rate this falls to only 0.1%.

The above results suggest an upper limit of 1-1.5%.

Since mitigation practices must be universally adopted to be effective, rocket manufacturers will also have to incur extra costs in modifying existing rocket designs, which will eventually filter down to the customer. So the above figure also places a an allowable limit on the launch portion of the satellite recurring cost.

8.4 Comments

The implicit assumption has been that the frequency of new missions remains the same. If instead this increases progressively over the coming decades, additional weighting will have to be given to later costs.

9. OTHER FACTORS

Several important points not dealt with (and there are surely many others) are mentioned below:

9.1 Future Markets

We have concentrated exclusively on the cost impact on unmanned satellite systems. A more complete financial analysis should also consider the effect on manned missions, including the possibility of rapid growth in commercial space travel, as discussed in [5]. This could increase the value of assets in orbit by orders of magnitude, and would thereby greatly increase the cost of debris mitigation measures that would be economically justified.

9.2 Electric Propulsion Systems (EPS's)

Being highly economical systems, EPS's may be able to provide the required delta-V to de-orbit satellites in high LEO, and to re-orbit GEO satellites cost-effectively.

9.3 Shielding

If the introduction of shielding were to become necessary because of high debris growth at small sizes, extra costs may be incurred as a result of the weight penalty: launch costs could rise, or GEO satellite lifetimes shorten because of extra fuel requirements.

10. CONCLUDING REMARKS

There are obviously severe difficulties associated with extrapolating today's technologies, costs and space activities into the distant future; but it seems inevitable that this should be done if actual cost figures are to be derived.

The issue of lost revenue due to debris has been carefully avoided. Although the near future is expected to see communications satellite revenue growth, advances in competitive technologies could considerably alter the picture.

It is very difficult to obtain real, accurate and relevant cost data for a large sample of satellites. The authors have had to make do with "educated guesses" based on a perusal of the available literature, and the Internet.

As regards constellations, it may be that the optimal construction and launch schedule, and distribution of spares will change as the debris hazard worsens. Although the simulations described here have not taken this into account, it should be investigated as a cost-reducing possibility.

We have not considered the collision hazard between constellation members, which may ultimately be more important than the background debris population. For instance, Swinerd *et al*. [6] showed that the collision probability for a constellation member increases sharply after the on-orbit fragmentation of another member has occurred.

The extra allowable recurring cost for mitigation appears to be very low, around 1-1.5%, and furthermore this occurs after a very long time frame, far beyond the horizon considered by businesses today. This amount is sufficient to cover the cost of small design modifications, but nevertheless suggests that financial arguments alone do not justify mitigation measures (unless there is a large growth in future space asset values, as described in Section 9.1). De-orbiting of LEO satellites from high altitudes using conventional propellants probably exceeds the cost limit, but the introduction of electric propulsion could make it affordable.

Finally, in order to save space, many details concerning the Montecarlo simulations have had to be omitted. Interested parties are invited to contact the principal author for further explanations.

11. ACKNOWLEDGEMENTS

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