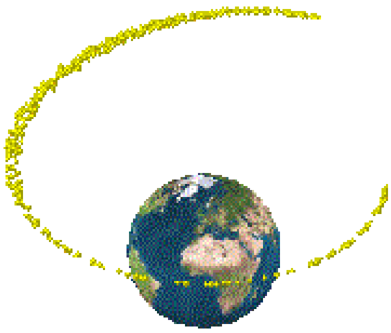
Path to a Sustainable Development in GEO: Environmental Assessment and its implication on Environmental Cost-Benefit Analysis



Thesis submitted in partial fulfillment of the requirements of the Degree of Master of Science at Lund University, Sweden

Prepared by Mari Takagi
LUMES P.O. Box 170
221 00 Lund, Sweden
Email: mari.takagi.127@student.lu.se

Supervised by Prof. Sune Svanberg
Head, Atomic Physics Division
Director, Lund Laser Centre
Lund Institute of Technology
P.O. Box 118
221 00, Lund, Sweden
Email: Sune.Svanberg@fysik.lth.se

May. 2003

Abstract

The importance of space debris research, including on detection, modeling, protection and mitigation measures, has been clearly recognized and a variety of work has been conducted over recent decades. Significant commercial developments have also taken place in space, however there has been a gap between egoistical and altruistic utilization of space environment. This paper makes an attempt to explore the way to bridge this gap by conducting both an environmental and economical evaluation in the specific context of author's proposed mitigation measures, including new legal standards such as lower satellite explosion rates, end of life maneuver, and restrictions on the annual number of launches. The computer model that forecasts the long-term GEO space debris environment, GEO-EVOL, which was developed by T. Yasaka et al at Kyushu University, was used to estimate possible future debris fluxes in GEO over the next 150 years from 2002. In the model, objects in the GEO region are placed into several categories based on their orbital properties (GST, GSY, DRL, DRH) and the orbital population growth is estimated in relation to predicted future space operations, explosions, and collisions based on these categorized objects. The economical evaluation is done within the framework of cost-benefit analysis. Valuation includes both direct and indirect economic values incurred from losses due to collisions, explosions, and space debris mitigation strategies.

Keywords: space debris, GEO, environmental evaluation, economical evaluation, cost-benefit analysis, end of life maneuver, explosion rate, annual number of launches

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List of Abbreviations

CBA: Cost-Benefit Analysis
CLD: Causal Loop Diagram
DRH: Drift Orbit in Higher Altitude
DRL: Drift Orbit in Lower Altitude
ESA: European Space Agency
GEO: Geosynchronous Earth Orbit
GST: Geostationary Earth Orbit
IADC: Inter-Agency Space Debris Coordination Committee
ITU: International Telecommunication Union
LEO: Low Earth Orbit
NASDA: National Space Development Agency in Japan
NASA: National Aeronautics and Space Administration
SGE: Sustainable use of GEO Environment
SNN: Space Surveillance Network
UNCOPUOS: United Nations Committee on the Peaceful Uses of Outer Space

Acknowledgement

I would like to thank Dr.Yasaka for having me at Kyushu University to do research and running GEO-EVOL Model for the scenarios I defined. His comments and advice were also very helpful. Without his help, it would have been impossible to conduct this research. Dr. Collins at Azabu University gave me useful advice on the financial aspect of the work, which enhanced it greatly. Dr. Kato at JSF/NASDA provided me many latest governmental documents necessary to get more background knowledge. Ms. Hayakawa of NASDA helped me obtain the information on annual projected budget for space debris research at NASDA for the economical valuation. Dr. Sune Svanberg at Lund University gave me good feedbacks on my thesis paper.

I would also like to thank Mr. Hirayama and the rest of the members at Space System Dynamics Laboratory at Kyushu University for warm welcome and giving me nice memories. I would like to give my special thanks to my wonderful friends and family who were always there for me to extend a helping hand whenever I encounter any obstacles or worries.

1. Introduction and Objectives

Since the first Russian satellite Sputnik has launched in 1957, more than 5,000 spacecrafts launched into space. Communications, navigations, and earth observation infrastructure provided by satellites have become an integral and indispensable part of modern civilization. Such a valuable space environment, however, is now in danger. As of December 2002, approximately 9,000 catalogued-objects were observed by the SNN, and two-thirds of these objects found to be considered as space debris[1] [32].

Table 1: Number of Objects in Space in Dec. 2002
(Satellite Situation Report, 2002) [32]

Source/Organization	Objects in Orbit			Decayed Objects		
	Payload	Debris	Total	Payload	Debris	Total
Com.Wealth of Ind.S	1356	2532	3888	1797	10654	12451
European Space Agency	39	286	325	5	564	569
Euro.Telec.Sat.Org.	24	0	24	0	0	0
France	32	16	48	8	61	69
Germany	21	1	22	12	2	14
Global	52	0	52	0	1	1
India	23	134	157	8	202	210
Italy	13	2	15	7	0	7
Int.Telec. Sat. Org.	59	0	59	1	0	1
Japan	82	51	133	14	109	123
Orbital Telecommunication	35	0	35	0	0	0
Peoples Rep.of China	37	287	324	39	258	297
Sweden	10	0	10	0	0	0
United Kingdom	21	1	22	9	4	13
United States	943	2801	3744	728	4050	4778
Column Totals	2912	6120	9032	2650	15947	18597
Sum Totals						27629

Inactive payloads and rocket bodies dominate almost 99% of the space debris in weight, but only 0.02% in number [17]. Operational and fragmentation debris generated from collisions and explosions with less than 10cm in size represent most of the rest in number (99% of space debris), which are incapable to detect from the present ground observation facilities. Even for those small-sized debris, they can also bring a catastrophic damage to spacecrafts since they travel with an average speed of 7km/sec in LEO, and 3km/sec in GEO [35].

Although the annual collision probability for an average operational satellite with larger objects (>1m) is relatively small in LEO ($1*10^{-5}$ collisions/yr/m^2), and even smaller in GEO ($1*10^{-7}$ collisions/yr/m^2) at the moment [21], it is crystal clear that the space environment will soon reach a hazardous level for active payloads to operate by the increasing number of space debris.

GEO environment especially has to be treated with a precautionary manner since there is no natural atmospheric drag[2] and the removal of space debris is not yet available with the current technology. Therefore the debris will remain in orbit for thousands of years, and so the potential for debris growth becomes greater than in LEO.

1. Definition of Space Debris: *"Space debris are all man-made objects, including their fragments and parts, whether their owners can be identified or not, in Earth orbit or re-entering the dense layers of the atmosphere that are non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorized."* (UN/STS/UNCOPUS, Technical Report on Space Debris. 1995) [33]

Nonexistence of international legislation or administrative regulations to impose specific debris mitigation requirements, and the lack of awareness and sense of crisis on space debris calamity between public, government, private satellite operators, and manufacturers are other major driving forces that make GEO orbit into a more unsustainable environment. Hence, developed countries are taking advantages for utilizing current space environment on the first come first serve basis, leading to a serious "problem of commons."

To have a better understanding of the present orbital debris environment and to forecast debris accumulation behavior in GEO for a long term, an orbital debris environmental model, GEO-EVOL was developed by T. Yasaka et al at Kyushu University. This paper now attempts to assess the possible future environment over the next 150 years from 2002 in GEO region using GEO-EVOL model, and conduct a Cost-Benefit Analysis under the specific context of proposed mitigation measures, including lower satellite explosion rates, end of life maneuver, and restrictions on the number of launches. The economic analysis will include both direct and indirect economic values incurred from losses due to collisions, explosions, and space debris mitigation strategies. However, the limitation of information and other constraints may restrict this analysis to fully capture all the costs and benefits involved.

The final goal of this study is to understand the threat that space debris poses and to examine the effectiveness of proposed debris mitigations. Cost-effectiveness by the implementation of debris mitigation practices is also examined to seek for appropriate steps to ensure the long-term sustainability in GEO.

2. Analytical Framework

2.1 Space Debris Accumulation Mechanism

There are about 839 catalogued-objects in near geosynchronous region [32] with an average annual launch of 35 [10]. Satellites normally placed in GEO have an average of 10-year lifetime or more depending on the amount of propellant available to keep the station from any physical perturbations. Satellites are originally placed into geostationary orbit (GST), and are recommended to re-boost into higher orbit at the end of life (Refer to 3.6 on recommended distance for re-orbit). However, there are currently about 200 satellites left uncontrolled in the GEO altitude after the mission. Their orbital plane becomes inclined to the equatorial plane up to 15 degrees with a period of 54 years due to perturbation of the Sun and Moon gravitational effects, but their mean radius remains the same. This causes these terminated objects to intersect with other operational satellites twice a day with increased velocities up to about 800m/sec, posing greater hazard to collide [11]. One collision creates hundreds to thousands of small fragments, which increase collision hazard in GEO rapidly.

By far there is only one breakup detected due to space debris collision in 1996 when French military satellite, CERISE, was hit by the debris from Ariane Rocket produced from its past explosion. However, since the causes for one third of breakup satellites are uncertain, some of these events may include additional number of collisions in space [21].

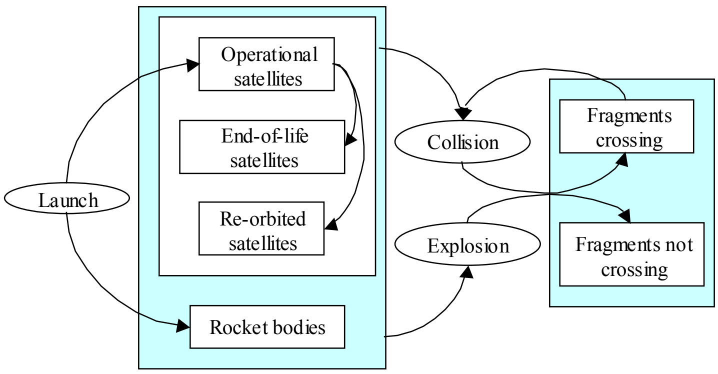
2. One of the most effective mitigation measures in LEO region is de-orbiting into the Earth's atmosphere to burn them down. However, this is not appropriate in GEO due to lack of atmospheric drag.

Spacecraft explosion is another threat for the space environment. Deliberate actions and propulsion-related events have been the primary causes, and make up almost 60% of the total number of 170 satellite breakups known since 1957 [23]. Fortunately, the number of deliberate actions, which are usually taken place for military purposes, has dramatically decreased after the U.S.A and Russia started to cut down on taking this action since 1986 [21]. Propulsion-related breakups however still remains as the most frequent breakups in space, which include catastrophic malfunctions during orbital injection or maneuvers, subsequent explosions based on residual propellants, and failures of active attitude control systems [23].

In geosynchronous region, there were only two breakups known: a spacecraft Ekran 2 (1997-081E), and a rocket body US Titan IIIC Transtage (1968-081E) exploded in 1978 and 1992. The former explosion occurred as a result of nickel-hydrogen battery malfunction. The cause remains uncertain for the second explosion, but this might be due to residual propellants or a collision with a smaller object [19].

An overview of the accumulation mechanism of objects in Figure 1 gives you a better understanding of physical activities in GEO region.

Figure 1: Accumulation Mechanism of Objects in the Geosynchronous Region



(Hanada,T., P. Krisko, et al, 2000) [13]

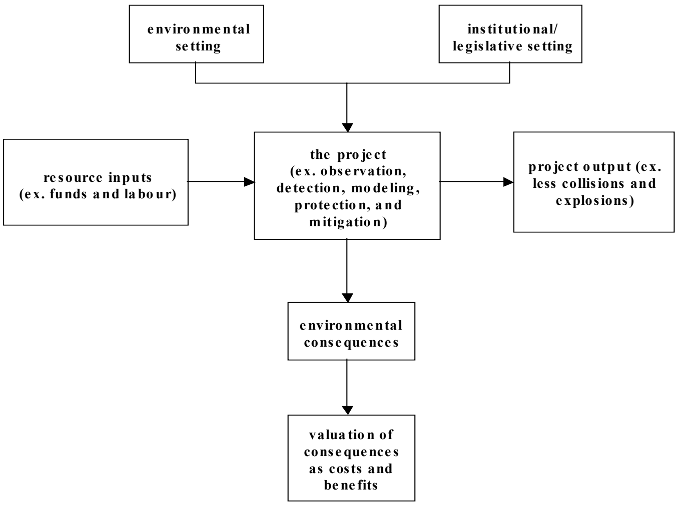
("End of life satellites" refers to disposed satellites left in orbit that intersect with GEO altitude causing further collisions with operational satellites.)

The long-term GEO environmental mode, GEO-EVOL, was made based upon this accumulation mechanism. Further descriptions and algorithm incorporated in GEO-EVOL model for each of these items are given in Section 3.

2.2 From Environmental Assessment to Cost-Benefit Analysis: Methodological Framework

The increase of space junk and threats to commercial space activities in GEO predictably caused concerns for the environmental consequences over the long-term. To assess the impacts, first the environmental impacts are to be identified and measured, and then, the second approach would be to translate them into monetary terms, using information generated by the 'environmental assessment' study for inclusion in the cost-benefit analysis of the project. The principle that underlies such an approach is that unique resources which GEO environment offers for the space commercial development will be efficient if all the effects – direct and indirect, tangible and intangible – are included in the analysis. A schematic representation shown in figure 2 may be useful to understand how environmental cost and benefit can be valuated based upon the current environmental and institutional/legislative settings.

Figure 2: Methodological Regimes for the Valuation of Costs and Benefits



Over the last several years, many space agencies have expressed concerns about the orbital debris environment and called for efforts to reduce space debris generation. A multilateral Inter-Agency Orbital Debris Coordination Committee (IADC) was formed since 1993, consisting of eleven different space-faring nations at present, to exchange ideas or knowledge on space debris as well as to cooperate to reduce space debris generation as an international community. In addition, since 1994 orbital debris has started to become a topic of discussion in the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS). Some governments now have sets of guidelines and methods to limit debris generations, however there are no international legislation or administrative regulations being in place to impose specific debris mitigation requirements[3] yet. The stringent national and international regulatory regimes will be postulated and evaluated both in the environmental and economic impact analysis in this paper.

3. Physical Factors Controlling the Growth of Space Debris in GEO: Algorithms of GEO-EVOL Model

To better understand the current environment and to project the trend of future environment over long terms under different settings, every type of physical actions of objects should be considered and computed into the model. Here all the physical activities contributing to the debris pollution in GEO that correlate with the functions incorporated in GEO-EVOL Model are described.

3. The analysis of national guidelines and the feasibility of international regulations/standards on space debris mitigations will not be discussed since this issue is out of scope in this paper. If you are interested in this issue, interested readers might want to look at ①: "Draft Handbook for IADC Space Debris Mitigation Guidelines" prepared by National Space Development Agency of Japan. Edited by Akira Kato, Oct. 2002. ②: NASDA CFX-99024. 2000

3.1 Model Categories

In the model, objects in GEO region are placed into several categories according to their orbital properties: geostationary orbit (GST), orbits that intersect with GEO altitude by shifting their orbital planes with a period of 54 years (GSY), orbits that are slightly higher or lower orbits than GEO altitude where they have almost no interactions with operational satellites in geostationary orbit (DRH, DRL), and fragmentation debris which remain in GEO altitude and which do not. Table 2 shows how the number of objects in each classified orbit had changed from 1995 to 2002. The model utilizes the number of objects in 2002 as initial number to run the simulation over the next 150 years. Rocket bodies, which usually do not intersect with GEO altitude, are not assigned in this model.

Table 2: Number of Satellites in Categorized Orbits in GEO

	1995	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**
GST	143	158	172	182	188	208	213	228
GSY	190	189	199	199	217	228	235	237
DRH	179	197	210	227	232	246	254	265
DRL	100	103	105	108	105	106	107	109

(Satellite Situation Report)

3.2 Explosion Rate

There were two explosions detected in GEO as described in Section 2.1. Considering the previous number of explosions and the total amount of time that each spacecraft spent in orbit after their launch, the present explosion rate is estimated as $4*10^{-4}$ explosions per year for an object [11]. However, since current optical radars are limited to detect objects smaller than 1m in GEO, other explosion events might have been overlooked. This can be easily assumed from the fact that there is only one debris fragment from these two breakups being catalogued after two decades of the events [19].

3.3 Fragmentation Modeling

In the model presented, a fragmentation model developed by Yasaka and Oda [30] is adopted to estimate the collision probability between satellites and fragmented debris. This model examines a fragmentation process quantitatively, including number, mass, and velocity distributions of breakup fragments. Kyushu University had been conducting a series of low velocity projectile impact tests to describe a collision in GEO, and this model adopts the equation

$$y\,(x) = 0.78(x/m_e)^{-0.68}$$

to represent the fragment mass distribution. X represents fragment mass in grams, y represents cumulative number of fragments greater than x grams, and m_e represents ejecta mass. In addition, incremental velocities of fragments are statistically adjusted to meet momentum and energy conservation laws [10].

3.4 Collision Rate

The debris situation in GEO region appears to be at least two orders of magnitude less than in LEO. Collisions are calculated based on probabilistic occurrences, and collision rate can be estimated once the product of cross-sectional area, spatial density, time, and relative velocity between the colliding objects are known [4, 6]. In GEO-EVOL model, normalized collision rates[4] between objects are calculated based on the method of Yasaka and Ishii [18]. For the rate of collision between fragments and operational satellites, only the number of fragments that reach GEO is considered. Fragments are divided into three categories by the size of a fragment in this model: more than 10cm, 1cm - 10cm, and 1mm - 1cm. The numbers of fragments in 2002 were estimated through simulation from the previous study conducted in 1997 by Yakasa, et al [11].

Table 3: Normalized Collision Rates Between Two Catalogued Objects (10^{-11} collision/year/m^2)

	GST	GSY	DRH	DRL
GST	2.86	-	-	-
GSY	4.17	1.68	-	-
DRH	0.25	0.20	0.12	-
DRL	0.51	0.38	0.01	0.02

(T. Yasaka, et al. 1999) [11]

Table 4: Normalized Collision Rates Between a Fragment and an Operational Satellite (10^{-11} collision/year/m^2)

	Operational Satellite (GST)
Fragment larger than 10cm (1kg)	1.47
Fragment 1cm (1g) – 10cm	1.47
Fragment 1mm (1mg) – 1cm	1.47

(T. Yasaka, et al. 1999) [11]

Table 5: Estimated Number of Fragments in GEO in 2002

	Number of Fragment
Fragment larger than 10cm (1kg)	50
Fragment 1cm (1g) – 10cm	4,545
Fragment 1mm (1mg) – 1cm	45,450

The numbers of normalized collision rates, objects in categorized orbits (Refer to Table 2), and fragments provide the probability of collision in GEO each year. The collision rates between objects in GST and GSY in 2002, for instance, is calculated as $228*237*4.17*10^{-11} = 2.3*10^{-6}$ (collision/yr/m^2). Once having calculated for the others, the probability of collision to active payloads by other objects (including smaller debris) in near GEO amounts to $1.7*10^{-4}$ (collision/yr/m^2) in 2002.

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4. Normalized Collision Rate represents the collision rate of one object in one classified orbit, with another object in another classified orbit.

3.5 Annual Satellite Launch

The number of launches fluctuates every year, however the number of launches including spacecrafts and rocket bodies has been increasing since 1960s. The average number of launches over the past several years is approximately 30-40 launches/year [10].

3.6 Re-orbit Fraction

Since ITU began to address the end-of-life maneuver into higher orbit in 1980s, several space agencies such as NASA, NASDA, and CNES developed national guidelines and recommend different distance for re-boosting as shown in table 6 [20, 25]. Finally in 1997, the IADC sets an international recommendation for the disposal perigee altitude: 235km + [1000*Solar Pressure Coefficient*average cross-sectional area (m^2)/dry mass (kg)] [16]. However, only one third of end-of mission satellites were re-orbited in compliance with the IADC recommendation over the last four years (1997 to 2000): 20 out of 58 spacecrafts were properly reorbited, 16 were reorbited below IADC recommendation, and 22 were abandoned without any end-of-life maneuver [15].

Table 6: Recommendation of Reorbit Distance in GEO for Each Organization

	IADC Guidelines	ITU	NASA	NASDA	US Standard	CNES
Reorbit Distance	235km + (1000*Cr*A/m)	More than 300km	300km + (1000*Cr*A/m)	200km + (0.022*a*Cr*A/m)	Above 36,100km (300km + GEO)	235km + (1000*CR*A/m)

a: semi-major axis = 42,265km, Cr: Solar Pressure Coefficient = 1.5, A/m: Area-to-mass ratio = 0.03-0.05

(IADC: IADC-97-004, ITU: ITU-R S.1003, NASA: NASA Safety Standard 1740.14, NASDA: NASDA-STD-18, US Standard: Orbital Debris Mitigation Standard Practices (draft: Jan. 1998), CNES: MPM-50-00-12) [20]

In GEO-EVOL model, re-orbit fraction is incorporated into debris calculation and expressed in the range from 0-100%: 0% as no re-orbit, and 100% as complete re-orbit maneuver in compliance with IADC recommendation immediately after the end of mission.

4. Environmental Assessment in GEO

4.1 Assumptions for Simulation

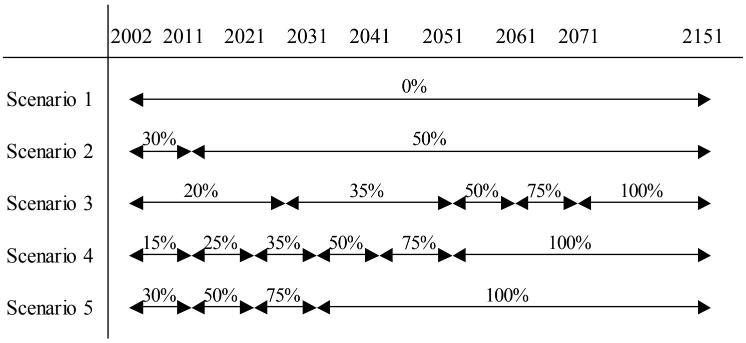
The number of objects depends on the number of annual launch, explosion, re-orbit fraction, as well as the rate of new fragment production. In order to assess long-term GEO space environment, several parameters and assumptions were made, and the model was set to run for 150 years from the year 2002. The summarized parameters and assumptions are shown in table 7.

Table 7: Parameters and Assumptions for Simulation

Annual Launch	Annual launch increase by 1
	Maximum annual launch: 100, 150, no launch limit
Average Satellite Mission Period	10 years
Explosion Rate	$4*10^{-4}$/year/object (present rate) $4*10^{-6}$/year/object (technology implementation)
Fragmentation Migration Ratio from Higher Orbit to GEO	0.5
Re-orbit Fraction	Re-orbit conducted by X % after the end of mission

The annual launch rate is expected to increase by one each year, starting from the present value of 35/year and up to the maximum of 100, 150, or 185(no launch limitation)/year. After ten years of operation, some satellites are assumed to re-boost into higher orbit and others not. Five different reorbit mitigation scenarios are considered and applied for the simulation.

Table 8: Reorbit Fraction Scenarios for the next 150 Years



As for new fragments generated by breakup in higher orbits, some of them reach GEO region and cause physical interactions. The migration ratio was set to 0.5, which represents the number of fragments that reach GEO divided by the total number of created fragments.

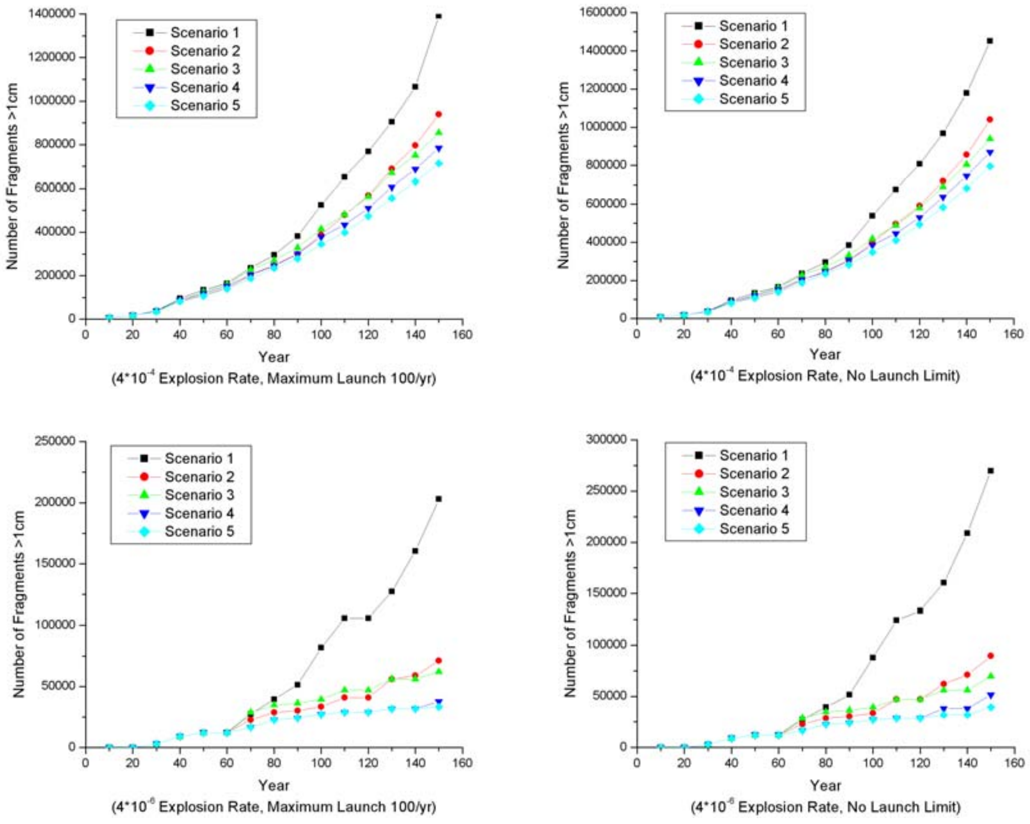
The present explosion rate is $4*10^{-4}$/year/object, however this number can easily be reduced with some technological implementation, which will be discussed in Section 5.5 in detail. Hence, achievable explosion rate, $4*10^{-6}$/year/object[5] was incorporated into the model to compare the accumulation of new debris generation with the present explosion rate.

4.2 Simulation Results: Valuation on Effectiveness of Proposed Political Enforcement

The strong international cooperation and high commitment toward reducing the space debris hazards and pollution is in critical needs, and can greatly influence the future environment in GEO. In this simulation, various scenarios with different level of stringency of the author's proposed legal regulations including lower explosion rate, restricted launch number, and higher reorbit fraction are set to run to examine the long-term GEO environmental consequences.

A. Evolution of Number of Fragments

The combinations of the proposed regulations can effectively reduce the increasing rate of number of fragments. The rate greatly decreased by lowering the explosion rate from the present rate by a factor of two; the reorbit maneuver was second, and then the limitation of launch as third with the least effectiveness. The average growth rate of fragments during the next 150 years is limited to one-seven hundreds and fortieths by lowering the explosion rate (4*10^{-6}), and almost half by the implementation of the most stringent reorbit maneuver policy (Scenario5). Figures 3-6 show the evolution of number of fragments (larger than 1cm) from 2002. Each figure is given under different reorbit mitigation scenarios with a set of fixed explosion rate and annual number of launch.



Figures 3-6: Evolution of Number of Fragments >1cm in the next 150 Years in GEO

5. According to T. Yasaka, reaching to $4*10^{-6}$/year/object for explosion rate is feasible with technical implementation.

B. Future Impact Flux

The simulation results show that the impact flux in 2151 under the most stringent mitigation scenario becomes $9.2*10^{-8}$collision/yr/m^2 by space debris larger than 10cm in size. This will give the probability of collision of 0.000092/object (0.009%) with the average satellite surface area of $100m^2$, and the mission lifetime of 10 years. While the probability of collision with no mitigation measures reaches 0.009/object (0.09%) in 2151. Although both numbers do not satisfactory meet the requirement that NASA Safety Standard[6] [24] sets for the probability of collision for the larger objects, the probability of collision differs as much as one digit by 2151 whether to implement or do without the debris mitigation practices.

C. Number of Re-boosted Objects

The total number of re-boosted satellites after their missions within the next 150 years is estimated approximately 7,000 under reorbit mitigation scenario 2, and 10,000 to 14,000 under the scenarios of 3 to 5 (Refer to Table 8 for reorbit mitigation scenarios in Section 4.1).

5. Environmental Cost and Benefit Analysis in GEO

5.1 Costs and Benefits due to Debris Hazards and Mitigation

The behavior of costs and benefits by the increase of debris hazard, and the preventive measures proposed earlier is now examined. However, many of the economical values are difficult to quantify due to a variety of reasons including lack of information, different government policies, and many other uncertainties. There has also been criticism of the cost-benefits analysis mainly due to the problems of quantifying and monetising all the environmental effects. Here, the author has attempted to evaluate the environmental impacts in GEO within the cost-benefit framework so as to be compatible with the proposed decision making processes with regard to reducing the space debris hazards where feasible. Bendisch and Wegener's study [2] is referred to consider the items for costs and benefits for this analysis.

Mission Cost due to Debris Hazards and Costs due to Debris Mitigation

1. Loss of operational spacecrafts due to collisions and explosions during the mission
2. Damage on operational spacecrafts during the mission
3. Costs for shielding development, mass penalty, and extra operational costs for debris detection for collision avoidance.
4. Mission and spacecraft re-design for spacecraft passivation and minimization of mission related objects
5. End of life maneuver: extra fuel and operational costs for collision avoidance
6. Extra insurance rate

6. NASA Safety Standard provides a general guideline for the probability of collision with larger objects (more than 10cm in diameter) to be in the order of or less than 0.001.

Benefits due to Debris Mitigation

1. Reduced loss of operational satellites due to collisions and explosions during the mission
2. Reduced damage of operational satellites during the mission
3. Reduced shielding mass
4. Reduced number of collision avoidance maneuvers: less operational costs and propellant mass
5. Reduced insurance rate

5.2 CBA Methodology

In cost-benefit analysis, the replacement costs for the satellites that are damaged due to space debris collisions and explosions, and mitigation costs for end-of-life maneuver are considered. The total number of satellite damage is calculated from the long-term impact flux of spacecrafts as well as fragments given from the GEO-EVOL simulation. In addition, the probability of the catastrophic damages out of total satellite damages by the debris fragments in different diameter was estimated from the previous low-velocity impact studies conducted by Yasaka, et al [12], as well as from Interagency Report on Orbital Debris 1995, which describes the probable functional damage of satellite by the different sizes of debris [17].

Table 9: Catastrophic Satellite Damage Possibility

Debris size range	Catastrophic damage failure probability
More than 10cm	100%
1cm – 10cm	75%
1mm – 1cm	25%

To convert the number of satellite loss into a monetary unit and calculate the costs for end-of-life maneuver, the following calculation procedures were applied referring from the previous study conducted by Walker, R. H. Klinkrad, et al [22].

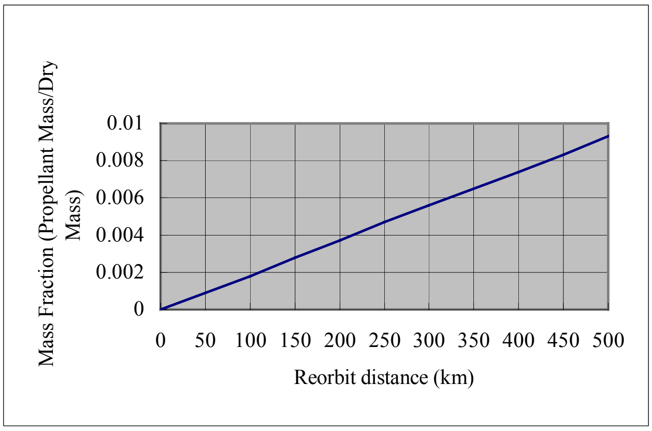
Cost Metric = Mission Failure*Replacement Cost + End-of-life Maneuver Cost

It is important to note that this does not include partial satellite damages by smaller debris assuming that those will not arise any functional damages. Further detailed computation procedures are described below.

Mission Failure = Total Collision Probability*Catastrophic Damage Failure Probability
Replacement Cost = Launch Cost + Manufacture Cost
Launch Cost = Vehicle Mass*Launch Cost per Unit Mass
End-of-life Maneuver Cost = Fuel Mass*Launch Cost per Unit Mass

Replacement cost was estimated $50 Million for the lowest cost mission to 250 Million for the most expensive mission during the ten-year spacecraft mission with the average mass and cross-sectional area of 1200kg and 10m^2. The re-orbit maneuver is to be put into practice soon after their end of missions. The average launch cost per unit mass was set for $30,000 per kg, and the propellant mass necessary for end-of-life maneuver was calculated from the linear relationship between re-orbit distance and propellant mass fraction with parent dry mass (Refer to Graph 1) [26]. As for the re-orbit distance, 300km was applied for this analysis (IADC recommendation in case of Cr*A/m = 0.065).

Graph 1: Propellant Mass Fraction with Dry Mass in Relation to Reorbit Distance



(NASDA CRT98006, 1998) [26]

5.3 Discount Rate

All costs and benefits flows are discounted to convert them into Present Value (PV). The present value of a cost or benefit X received in time *t*, with the rate of discount *i* (which is assumed to be the rate of interest usually), is calculated as follows:

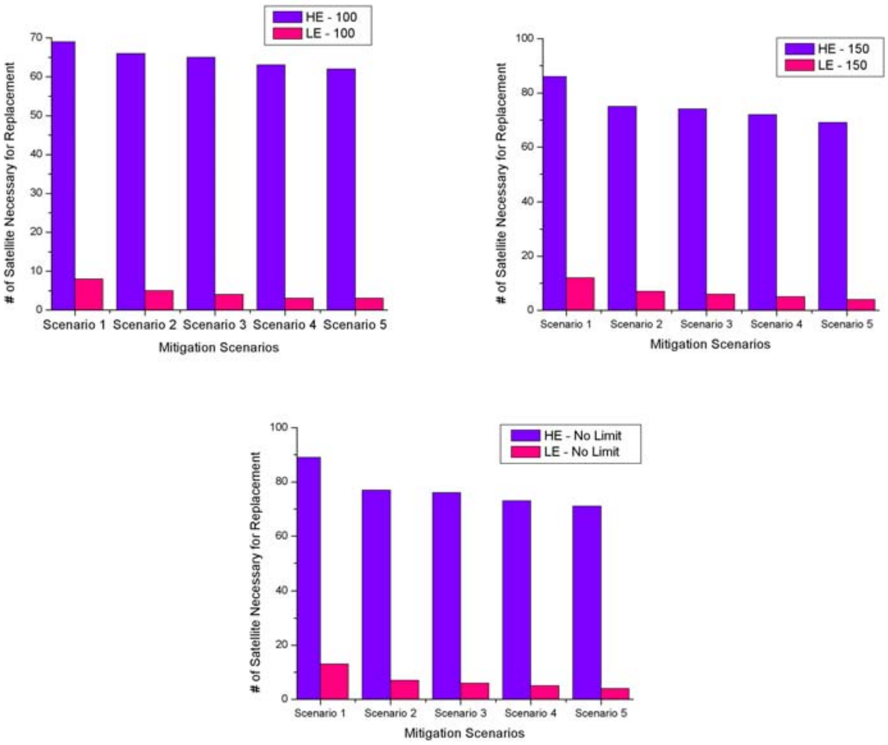
$$PV(Xt) = Xt[(1+i)^{-t}] \ [14]$$

Choosing the discount rate is critical in cost-benefit analysis. Some environmental economists argue that environmental projects should be subject to a lower discount rate than others [34]. Once the useful utilization of human activities in GEO region is viewed as finite environment, a high discount rate can greatly encourage to increase traffic congestions in the earlier years, and leading to a catastrophic destruction of GEO environment within a shorter period of time. While, a number of economists have insisted that there is no unique relationship between high discount rates and environmental deterioration [1]. Thus, it remains unclear how the choice of discount rate effects the future exploitation in the environment.

In the previous studies on costs and benefit analysis for orbital debris conducted by Neish, M. and T. Goka, and Greenberg, J. and R. Reynolds, used the discount value of 5.5% and 10% per year [8, 9]. In this paper, the calculation of net present costs has been subjected to sensitivity analysis by changing the discount rate from 0 to 10 %. Such sensitivity analysis precludes the need for any ad hoc selection of discount rates by the analyst and enables us to leave the choice of appropriate discount rate to the planners and to other decision-makers.

5.4 Replacement Costs of Satellites by Collisions and Explosions, and Costs for End-of-life Maneuver

The long-term debris impact flux in GEO provided from the simulation and the estimated amount of propellant necessary for re-orbit enabled to perform Cost-Benefit Analysis. The analysis uses a cost metric to evaluate the relative mission cost figures for different sets of proposed mitigation scenarios including re-orbiting, explosion avoidance, and restriction of annual number of launch. Figures 7-9 give the projected number of satellites damaged by catastrophic explosions and collisions with larger debris from 2002 to 2151. Each figure is separated by the different maximum number of annual launch (which is 100, 150, and no limitation), and the numbers of satellites damaged are separately represented based on reorbit mitigation scenarios.



Figures 7-9: Number of Satellites Damaged by Catastrophic Collisions and Explosions
(HE: High explosion rate = Present explosion rate, LE: Low explosion rate)

The simulation results show that the numbers of explosions of operational satellite with the present explosion rate are 45, 54, and 57 with the annual launch of 100, 150, and 185 (no limit). While, there is only one explosion within the next 150 years with the lower explosion rate and three different numbers of annual launch. The rest of the numbers shown in figures 7-9 represent the numbers of satellite damaged by collisions. Tables 10-17 show the results of CBA conducted under different sets of mitigation scenarios.

A. CBA Results at the Present Explosion Rate ($4*10^{-4}$)

Table 10: Reorbit Fraction Scenario 1: Maximum Annual Launch 100 (Net Present Value: $ Million)

	T1	T2	Discount rate @ 0%	Discount rate @ 1%	Discount rate @ 2%	Discount rate @ 4%	Discount rate @ 6%	Discount rate @ 8%	Discount rate @ 10%
Costs in 10 yrs	2002	2012	101-503	97-483	93-466	87-435	82-409	77-387	74-368
Costs in 50 yrs	2002	2052	733-3,665	550-2,751	424-2,121	274-1,368	195-975	151-756	125-623
Costs in 100 yrs	2002	2102	1,879-9,394	1,114-5,568	710-3,551	354-1,769	220-1,099	159-797	128-638
Costs in 150 yrs	2002	2152	3,474-17,371	1,582-7,911	852-4,262	368-1,841	222-1,108	160-798	128-638
Costs for end- of-life maneuver	2002	2152	0	0	0	0	0	0	0
Satellite loss	2002	2152	3,474-17,371	1,582-7,911	852-4,262	368-1.841	222-1,108	160-798	128-638

Table 11: Reorbit Fraction Scenario 1: No Limit for Annual Launch (Net Present Value: $ Million)

	T1	T2	Discount rate @ 0%	Discount rate @ 1%	Discount rate @ 2%	Discount rate @ 4%	Discount rate @ 6%	Discount rate @ 8%	Discount rate @ 10%
Costs in 10 yrs	2002	2012	101-504	97-485	93-467	87-436	82-410	78-388	74-369
Costs in 50 yrs	2002	2052	742-3,709	556-2,782	429-2,144	276-1,380	197-983	152-761	125-626
Costs in 100 yrs	2002	2102	1,988-9,938	1,163-5,816	734-3,670	360-1,802	222-1,112	161-803	128-642
Costs in 150 yrs	2002	2152	4,444-22,221	1,867-9,336	943-4,713	381-1,903	225-1,123	161-805	128-642
Costs for end- of-life maneuver	2002	2152	0	0	0	0	0	0	0
Satellite loss	2002	2152	4,444-22,221	1,867-9,336	1,867-9,336	381-1,903	225-1,123	161-805	128-642

Table 12: Reorbit Fraction Scenario 5: Maximum Annual Launch 100 (Net Present Value: $ Million)

	T1	T2	Discount rate @ 0%	Discount rate @ 1%	Discount rate @ 2%	Discount rate @ 4%	Discount rate @ 6%	Discount rate @ 8%	Discount rate @ 10%
Costs in 10 yrs	2002	2012	120-523	115-503	110-483	103-452	96-424	91-401	86-381
Costs in 50 yrs	2002	2052	1,130-4,066	839-3,044	638-2,337	398-1,495	273-1,055	203-810	162-662
Costs in 100 yrs	2002	2102	3,145-10,440	1,819-6,181	1,129-3,929	531-1,941	313-1,193	216-855	166-678
Costs in 150 yrs	2002	2152	5,384-17,749	2,480-8,348	1,330-4,593	552-2,009	315-1,201	216-856	166-678
Costs for end- of-life maneuver	2002	2152	2,292	1,013	515	187	93	56	38
Satellite loss	2002	2152	3,092-15,457	1,467-7,335	815-4,078	365-1,822	222-1,108	160-800	128-640

Table 13: Reorbit Fraction Scenario 5: No Limit for Annual Launch (Net Present Value: $ Million)

	T1	T2	Discount rate @ 0%	Discount rate @ 1%	Discount rate @ 2%	Discount rate @ 4%	Discount rate @ 6%	Discount rate @ 8%	Discount rate @ 10%
Costs in 10 yrs	2002	2012	120-523	115-503	110-483	103-452	96-424	91-401	86-381
Costs in 50 yrs	2002	2052	1,130-4,066	839-3,044	638-2,337	398-1,495	273-1,055	203-810	162-662
Costs in 100 yrs	2002	2102	3,145-10,663	1,819-6,271	1,129-3,966	531-1,947	313-1,194	216-856	166-678
Costs in 150 yrs	2002	2152	6.389-20,562	2,770-9,148	1,418-4,830	561-2,033	316-1,203	216-857	166-678
Costs for end- of-life maneuver	2002	2152	2,846	1,176	565	193	94	56	38
Satellite loss	2002	2152	3,543-17,716	1,594-7,972	853-4,265	368-1,840	222-1,109	160-801	128-640

B. CBA Results at the Low Explosion Rate ($4*10^{-6}$)

Table 14: Reorbit Fraction Scenario 1: Maximum Annual Launch 100 (Net Present Value: $ Million)

	T1	T2	Discount rate @ 0%	Discount rate @ 1%	Discount rate @ 2%	Discount rate @ 4%	Discount rate @ 6%	Discount rate @ 8%	Discount rate @ 10%
Costs in 10 yrs	2002	2012	0.6-3.2	0.6-3.0	0.6-2.9	0.5-2.6	0.5-2.4	0.4-2.2	0.4-2.0
Costs in 50 yrs	2002	2052	16-69	10-50	7.3-36	4.1-20	2.5-12	1.6-8.0	1.1-5.7
Costs in 100 yrs	2002	2102	110-549	54-269	28-140	9.1-45	3.7-19	2.0-10	1.2-6.2
Costs in 150 yrs	2002	2152	406-2,030	138-692	53-264	11-57	4.1-20	2.0-10	1.3-6.2
Costs for end- of-life maneuver	2002	2152	0	0	0	0	0	0	0
Satellite loss	2002	2152	406-2,030	138-692	53-264	11-57	4.1-20	2.0-10	1.3-6.2

Table 15: Reorbit Fraction Scenario 1: No Limit for Annual Launch> (Net Present Value: $ Million)

	T1	T2	Discount rate @ 0%	Discount rate @ 1%	Discount rate @ 2%	Discount rate @ 4%	Discount rate @ 6%	Discount rate @ 8%	Discount rate @ 10%
Costs in 10 yrs	2002	2012	0.6-3.2	0.6-3.0	0.6-2.9	0.5-2.6	0.5-2.4	0.4-2.2	0.4-2.0
Costs in 50 yrs	2002	2052	16-71	11-56	8.0-40	4.4-22	2.6-13	1.7-8.4	1.2-5.8
Costs in 100 yrs	2002	2102	123-613	59-293	30-148	9.2-46	3.8-19	2.0-10	1.3-6.4
Costs in 150 yrs	2002	2152	653-3,263	207-1,034	72-362	13-65	4.1-21	2.0-10	1.3-6.4
Costs for end- of-life maneuver	2002	2152	0	0	0	0	0	0	0
Satellite loss	2002	2152	653-3,263	207-1,034	72-362	13-65	4.1-21	2.0-10	1.3-6.4

Table 16: Reorbit Fraction Scenario 5: Maximum Annual Launch 100 (Net Present Value: $ Million)

	T1	T2	Discount rate @ 0%	Discount rate @ 1%	Discount rate @ 2%	Discount rate @ 4%	Discount rate @ 6%	Discount rate @ 8%	Discount rate @ 10%
Costs in 10 yrs	2002	2012	20-22	19-21	18-20	16-18	15-17	14-15	13-14
Costs in 50 yrs	2002	2052	409-450	297-327	220-242	128-140	80-88	53-59	38-42
Costs in 100 yrs	2002	2102	1,391-1,592	764-869	448-506	186-208	96-106	58-64	40-44
Costs in 150 yrs	2002	2152	2,505-3,135	1,090-1,318	546-641	196-221	97-108	58-65	40-44
Costs for end- of-life maneuver	2002	2152	2,348	1,033	523	190	94	57	39
Satellite loss	2002	2152	157-787	57-285	23-118	6-31	3-14	1-8	1-5

Table 17: Reorbit Fraction Scenario 5: No Limit for Annual Launch (Net Present Value: $ Million)

	T1	T2	Discount rate @ 0%	Discount rate @ 1%	Discount rate @ 2%	Discount rate @ 4%	Discount rate @ 6%	Discount rate @ 8%	Discount rate @ 10%
Costs in 10 yrs	2002	2012	20-22	19-21	18-20	16-18	15-17	14-15	13-14
Costs in 50 yrs	2002	2052	409-450	297-327	220-242	128-140	80-88	53-59	38-42
Costs in 100 yrs	2002	2102	1,456-1,679	791-904	459-520	188-210	96-107	58-65	40-44
Costs in 150 yrs	2002	2152	3,112-3,932	1,268-1,552	601-712	202-229	98-109	59-65	40-44
Costs for end- of-life maneuver	2002	2152	2,907	1,197	573	195	95	57	39
Satellite loss	2002	2152	205-1,025	71-355	28-139	7-34	3-14	2-8	1-5

5.5 Mitigation Measures, Costs, and Effectiveness

Nations must take immediate actions to reduce hazards posed by space debris, which involve a number of technical steps toward a long-term sustainable environment in GEO. From the technical standpoint, nations and companies in developed countries can easily access to a variety of options to reduce and avoid congestion in space especially for the mitigation measures incorporated in the environmental as well as economical assessments. Here all the possible means of reducing the debris hazard to future space operations are described. These include actions taken during operations (e.g., reducing operational debris such as covers, and wires, or flakes of paints and blankets from degradation), and after its functional lifetime (e.g., depleting energy sources, moving the spacecraft into a disposal orbit, or collecting mission terminated objects). Some methods would cost very little, whereas others might be economically prohibitive for some missions. Their effectiveness also will vary, not only from method to method but also in how well a particular method will work in different orbital regions and with different space systems. Proposed mitigation measures, its potential degree of cost burden for technical implementation, and effectiveness are summarized below in table 18 [7, 28].

Table 18: Mitigation Measures, Cost Burden, and Effectiveness

Mitigation Measures		Technical Implementation	Cost	Mitigation Effectiveness
Minimization of debris release during normal operations	Objects released as design (refer to table 20)	Mostly feasible	Negligible	Small
	Unintentionally released objects (refer to table 20)	Partially difficult	N/A	Small
Preventive measures against accidental breakups	Venting residual propellant	Feasible and easy	Negligible	Large
	Switching off battery charging lines	Feasible and easy	Negligible	Large
	Relieving pressure vessels	None	N/A	Large
Satellite protection against on-orbit collisions		Mostly difficult (Only feasible for small debris)	Expensive	Small
Maneuvering satellite to avoid collisions with larger objects		Difficult (Detection of debris approach & computation for orbit evasion is not yet technically feasible)	N/A	Medium
Reduction of mission terminated objects (satellites & rocket bodies)		Difficult	Expensive	Medium

Re-orbiting from GEO	Feasible, but propellant is required for the maneuver	Medium	Medium

NASDA, for instance, currently aims principally at preventing the additional formation of debris; implementation on satellite protection, and satellite maneuver to avoid collisions are economically and/or technically not feasible at the moment. Several steps should be taken to conduct appropriate measures considering the development of technology, the change of debris environment, and the trend of commitment toward space debris mitigation by the international community.

5.6 Costs for Space Debris Research and Development at Space Agencies

The budget available for space debris research including observation, modeling, prevention, as well as protection differs greatly in each nation due to different political, technical, and economical backgrounds. It is also important to note that the actual cost being spent for space debris research does not always reflect the increasing hazards of space environment.

For instance, NASA Orbital Debris Program does not currently have a solid, long terms guarantee of funding regardless of such an important activity. In the past, NASA Orbital Debris Program had been funded to the tune of $3 million per year by the ISS and Shuttle programs in the U.S., however the funds have been cut in half since 2002. According to Borenstein, the number of workers in the office has been cut from six in 1997 to three in 2000, and then down to two in 2003 [3].

Space debris research activities at the Japanese Space Agency also seem to be on the verge of a crisis by looking at the amount of annual projected budget shown below.

Table 19: Summary of Projected Budget for the NASDA Research Plan (Unit: Million Yen)

Project	1998	1999	2000	2001	2002
Space debris research (Observation)	23	17	83	125	0
Maintenance for facilities to predict the reentry into the atmosphere, to track satellites, etc	3302	4903	6637	4098	3085

(NASDA[7], 1998-2002) [29]

The items of the budget for space debris research at NASDA contain primarily the maintenance cost for the two new observational ground facilities: Kamisaibara Space Guard Center and Bisei Space Guard Center in Okayama, Japan. Kamisaibara Space Guard Centre is still under constructions and will soon be ready to observe and detect space debris and asteroids from 2004 [29].

Hence, it is obvious that more funds and subsidies for space debris research are necessary to ensure the sustainable environment in GEO. However, the amount of funds available for research depends on the seriousness of the problem (degree of awareness), national policy, scientists, and projects itself, so that is it very difficult to speculate the costs for space debris research and development both in short and long terms.

5.7 Environmental Benefit Estimator

Aside from the items listed in Section 5.1 on direct costs and benefits for debris hazards and mitigation, CBA should also consider the environmental value of space (or intrinsic value of space). This environmental economic value is often considered as intangible cost, and therefore tends to be often excluded from the economical evaluation. However, without the existence of space, the current commercial services and activities (ex. telecommunications, navigations, weather forecast, etc) provided from space and all the other potential future projects (ex. space tourism, satellite solar power system. etc) cannot be taken place, and therefore it is important to fully understand the value of space in the economical assessment.

✧Existence Value of Space

When you are asked how much you would like to pay for the existence of space, you may say none because space is something that differs from the natural resources such as fossil fuels that dissipate as we consume, and the existence of space itself also does not directly bring us benefits to our daily lives. It is important to note, however that we are making increasing amount of benefits each year from space indirectly through various commercial activities and services. According to SIA/Futron report, the World Satellite Industry Revenue amounts to $85B in 2000; which includes $41.7B from satellite service, $17.7B from ground equipment manufacturing, $17.2B from satellite manufacturing, and $8.5B from Launch industry. The world satellite industry revenues grew by 23 % in 2000, versus 8% in 1999 [5].

Although space is not something that dissipates even if the space activities are continuously enhanced, there is a physical limit in orbit for further commercial activities and development: once the pollution starts to get more serious in GEO, the orbit suddenly turns into a big junk yard. Unfortunately, this is not yet widely recognized as threats between satellite industries, manufacturers, investors, governments, media and general public. Hence, we tend to forget or to not consider the value of space.

Then, another question will arise: where is the permissive limit for the GEO environment to integrate as close as possible with the space industrial activities? In GEO, the concept of Kessler Syndrome[8] is not applicable since GEO region does not have any atmospheric drag to let debris burn down into the atmosphere, and help decrease the amount of debris in every 11-year[9] by the sun's activity as in LEO [35]. Therefore, the tolerable level for the sustainable GEO environment is placed where the non-polluted GEO environment and space commercial activities go hand in hand closely as much as possible. It would be too late to act upon space debris reduction by the time the intrinsic value of space begins to be recognized and reexamined by the nations as shown in figure 10.

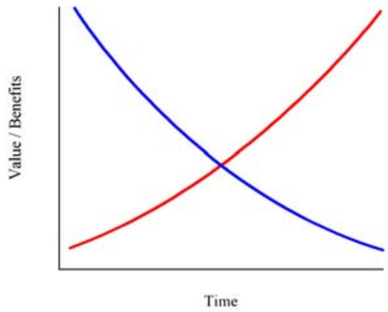


Figure 10: Relationship between Benefits of Commercial Services (Blue) and Intrinsic Value of Space (Red) from the Utilitarian View

On the other hand, when considered from the non-utilitarian view to express the existence value of space, one might assume that such intrinsic value of a natural environment will be extremely high and constant as shown in figure 11, so that the benefits of preservation in GEO environment always surpass the costs. Such perception may just be another way to look at, however such view could help us understand the significance of space environment and effect on future human usage of space to preserve the environment for long terms.

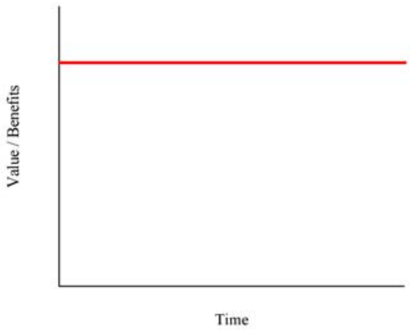


Figure 11: Intrinsic Value of Space from the Non-utilitarian View

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7. Information obtained from Ms. Hayakawa at NASDA in March 2003.
8. Kessler Syndrome: The phenomenon when debris starts to multiply by themselves due to the continuous breakup events even if there are no new launches. [35]
9. The sun's activity changes in every 11 years. When the activity reaches the maximum, the atmospheric layer on earth will expand and the atmospheric density at 500-1000km altitudes will rise twice or three times. Since the atmospheric resistance for objects is proportional to the atmospheric density, more objects will be re-entered into the atmosphere during this period of time. [35]

6. Conclusions

Both environmental and economical assessments were conducted based on GEO-EVOL model to forecast the space debris accumulation behavior and to explore the most sustainable and cost-efficient strategies to preserve the GEO environment over the long term. The analysis was given under different sets of proposed legal regulations to mitigate space debris, which include the limitation of explosion rate, annual launches, and the enhancement of end of life re-orbit maneuver.

The result shows that the number of fragments will increase rapidly with the current explosion rate, and this hastens risks to future satellite operations. Without putting into any actions to mitigate space debris, the collision probability will soon reach a critical level for operational satellites to operate, and hence the cost for mitigation was proved to be urgent.

The most cost effective and sustainable measure to reduce the formation of space debris is to avoid explosive breakups through passivation: venting residual propellant, switching off battery charging lines, or relieving pressure vessels. The re-orbit maneuver is also effective, however the end of life maneuver can only be viewed as a short-term solution considering from the possible accumulated number of reorbited objects within 150 years into higher orbit. The result from the simulation also made clear that the GEO environment wouldn't be able to reach an acceptable level in 150 years unless the limitation of explosion is to be conducted even if both re-orbit maneuvering and the limitation of annual launches were implemented.

Another measure to reduce debris hazards in GEO is to reduce operational debris such as wires, covers or tethers, which seems to be less costly compared to the removal of terminated objects and the extra maneuver to avoid collisions at the moment.

7. Discussions

7.1 One Step Forward Toward a Sustainable GEO Environment: Recommendations by the Author

This paper proposed some cost-effective mitigation measures, and verified the immediate necessity of such mitigation strategies. Although the importance of managing space debris is more recognized by space faring nations, the current use of space still represents the problem of commons, which usually leads to overuse and ruin the environment.

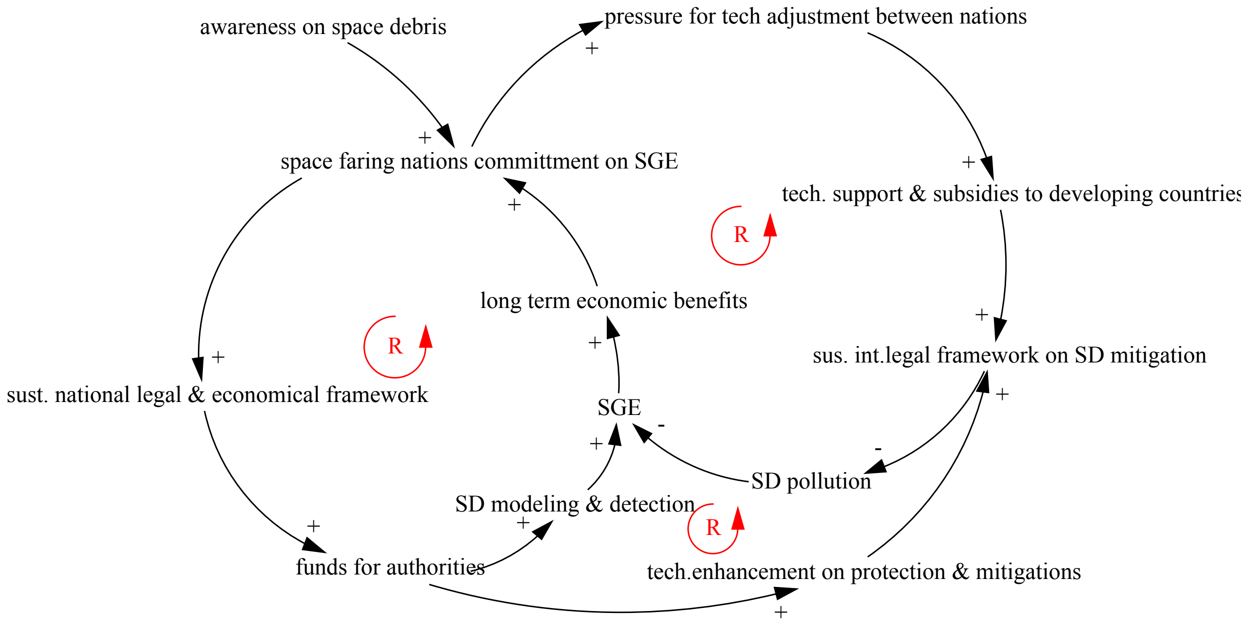
Some of the nations have made national guidelines for space debris mitigations and the fundamental principles for such standards are very similar, however contents of these standards and level of requirements are slightly different from each other [20]. All the proposed measures are not yet applied universally, and mitigation practices are just conducted under voluntary basis.

One of the biggest problems is that the satellite manufacturers and operators seem to lack a sense of impending crisis on space debris. Moreover, most effective debris mitigation techniques incur a mass penalty, in hardware or in fuel, which reduced the performance or the payload, and it is unrealistic to expect one manufacturer to adopt the most effective techniques if competitors are not obliged to do likewise.

Increasing awareness of space debris hazards and the recognition of the importance of taking precautionary action to prevent further degradation in GEO are critical for satellite industries, manufacturers, space agencies, media, and general public as a first step. Along with this, IADC could give more pressure to each government for an active research on space debris, and hence create more funds for space debris research and enhancement on technical implementation. Increase awareness on debris hazards may also enable to provide subsidies and technical support to developing countries for technical adjustment, which should be actively addressed from the developed countries. This would help make the new international regulations on debris mitigation more feasible.

With the continuation of current mitigation practices, there is no doubt that the GEO environment will soon to be ruined as a junkyard. Some international regulatory body should be established and enforce rules to prevent the formation of space debris to avoid countries and private companies to have an incentive to lower costs by avoiding technical safeguards. Creating international funds to pay compensation for damages caused by non-identifiable space debris, which should be financed by the polluters, might also be effective to encourage nation to adopt national legislation to prevent the formation of space debris, and to impose space industries for responsive strategy. Further commitment to have an international consensus on mitigation practices by IADC and endorsement of UNCOPUOS for the action undertaken by IADC on space debris mitigation would certainly be necessary to ensure safety and sustainable development in GEO. Figure 12 gives an overview to show the path towards a sustainable use of GEO environment. Clearly, three reinforcing loops in CLD make the space environment in GEO orbit very unique. This points out that unlikely to the conditions of Earth, the GEO environment does not have natural forces and technologies to remedy the polluted debris environment (except to reduce the new formation of space debris).

Figure 12: A Path Towards a Sustainable Use of GEO Environment



7.2 Suggestions for Venues for Further Research

A. Environmental Assessment

A1. Observation Technology

The present available telescopes can hardly detect objects smaller than 1m in GEO orbit. Hence further research on improving current observation technology is essential to increase the reliability on data and to have a better model to predict the future environment.

A2. Structural Effects under the Low Impact Velocity

The collision in GEO is dominated by the low velocity impacts at an average rate of less than 0.8km/s, however satellites are not designed to bear enough against collisions so that they can easily be damaged even at the lowest velocity. The previous studies showed that low velocity impacts are thought to have similar fatal effects to spacecraft and the characteristics of fragments are similar to those of the hypervelocity impacts [12]. However, the breakup model, which have adopted into GEO-EVOL has not been validated against actual breakup phenomena, and moreover consequences of such phenomena in space include many uncertainties [10]. Further accumulation of data on physical properties of fragments and structural damage on spacecrafts at low-velocity would provide better understanding on physical damages of operational spacecrafts in GEO. This would result in a better speculation on GEO environment, and hence more reliable data for the economic evaluation.

A3. Distance for Re-Orbit Maneuver

The simulation result has given the large number of spacecrafts re-orbited into higher altitude within 150 years once strict reorbit regulation is implemented at the end of their missions. Considering such potential consequences, the distance IADC has recommended may not be sufficient enough in the future. Since the physical properties of fragments and the actual production rate still remain many uncertainties in higher junk orbit, further studies on distance for re-orbit maneuver may be critical.

B. Economic Evaluation

Some economic values were not appropriate or impossible to include into CBA. However, extra insurance rate due to space debris hazards, as well as additional costs associated with mitigation measures (e.g. cost of hardware development for passivation, shielding, and reduction of operational debris) could be estimated. The author now intends to investigate those values to further enhance economical evaluation.

8. Appendix

Table 20: Sources of Debris

Main	Causes	Debris sources
Mission related objects (Parts released during mission operation)	Objects released as design	Operational debris (fasteners, covers, wires)
		Objects released for experiments (needles, balls, etc)
		Tethers designed to be cut after experiments
		Others (released for military purposes, etc)
	Unintentionally released objects	Flakes of paints and blankets derived from degradation
		Tether systems cut by debris
		Liquid with large density (leaked from the nuclear power system, etc)
		Particles ejected from solid motors
On-orbit breakups	Intentional destruction	Destruction for scientific or military experiments (including self-destruction, intentional collision, etc)
		Destruction prior to re-entry in order to minimize ground incidents
		Destruction to assure security of on-board devices
	Accidental breakups	Explosion caused by failure
		High intensity explosion caused by command destruct systems
		Low intensity explosion caused by residual propellants
	On-orbit collisions	Fragments caused by collision with catalogued objects
		Fragments caused by collision with un-catalogued particles
Mission terminated objects		Systems left in near-GEO, GTO, LEO, and HEO

(NASDA: CRE 01003B, 2002) [27]

9. Glossary

Breakup: Destructive fragmentation of a space objects. Breakups may be either accidental or intentional, which include ① an explosion caused by the chemical or thermal energy from propellants, pyrotechnics and so on, ② a rupture caused by an increase in internal pressure, ③ a breakup caused by energy from collision with other objects.
A breakup during the re-entry phase caused by aerodynamics forces, and the generation of fragments, such as paint flakes, resulting from aging and degradation of a space system are excluded from the definition.

De-orbit: deliberate or faced re-entry of a space system into the Earth's atmosphere to eliminate the hazard it poses to other space systems, by applying a retarding force usually via a propulsion system.

Geostationary Earth Orbit: nearly circular orbit with a period of approximately 1,436 minutes and an inclination close to zero degrees. In such an orbit, the satellite maintains a relatively stable position directly above the equator, at a mean altitude of approximately 35,785km.

(Impact-) Flux: amount of debris passing through a given area in a given time. Area, as well as flux, can be defined in terms of either surface area or cross-sectional area. The debris flux experienced by a spacecraft is directly proportional to the probability of impact.

Low Earth Orbit (LEO): Orbit with a mean altitude of less than 2000km (Orbital debris)

Passivation: The elimination of all stored energy on a space system to reduce the chance of break up. Typical passivation measures include venting or burning excess propellant, discharging batteries and relieving pressure vessels.

Propellant: Rockets work because every action has an equal and opposite reaction (according to Sir Issac Newton's third principle). In order for the rocket to rush forward, something has to rush backwards. That thing is the propellant. The propellant is a material that spews out of the back of the spacecraft giving it thrust, or a push forward.

Re-orbit: intentional changing of a space system's orbit. Typically, this involves putting the space objects in an orbit where it is expected to be less of a hazard.

Spacecraft: orbiting object designed to perform a specific function or mission, (e.g., communications, navigation, or weather forecasting). A spacecraft than can no longer fulfill its intended mission is considered nonfunctional.

Space Debris: Space debris are all man-made objects, including their fragments and parts, whether their owners can be identified or not, in Earth orbit or re-entering the dense layers of the atmosphere that are non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorized.

Space Surveillance Network (SSN): collection of ground-based radar and electro-optical sensors used by the U.S. Space Command to track and correlate man-made space objects.

(The definitions of words listed in the glossary are cited/modified from Orbital Debris by National Research Council 1995, Technical Report on Space Debris by UN/COPUOUS/STSC in 1999, and Draft Handbook for IADC Space Debris Mitigation Guidelines by NASDA in 2002.) [27,31,33]

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